ABSTRACT

HARTMAN, NATHAN WILLIAM. Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals. (Under the direction of Dr. Theodore J. Branoff)

The purpose of this research will be to examine the development of expertise in the use of constraint-based CAD tools. There has been a significant shift towards the use of these tools in engineering and design environments in the last ten years, yet without a comparable shift within the academic environment. Engineering graphics within an academic setting should examine industry-based techniques to improve classroom instruction.

Using methods adapted from phenomenological inquiry and cognitive psychology, practicing engineering design professionals were assessed in an effort to gauge their mental models and problem-solving processes to form an initial definition of the domain of constraint-based CAD tools, as well as the experiences that contributed to their development of expertise. Interviews and observations were used to gather data relevant to the experiences of the participants, while a knowledge-mapping task and think-aloud modeling task were used to examine the participants' modeling strategies used in creating a 3D model and their organization of the concepts surrounding this knowledge domain.

The results of this study yielded fifteen constituent themes of expertise based on the data collected from the observations. It also produced seven additional themes related to the personal experiences and conceptions of expertise of each participant obtained by the interview data. These two sets of thematic elements comprised the initial developmental factors of expertise. The think-aloud modeling tasks captured the modeling procedures employed by the participants in creating a 3D model, which looked specifically at their CAD tool usage and how they applied their background knowledge to solve a design modeling problem. Finally, the knowledge-mapping tasks captured each participant's organization of the major concepts related to the use of constraint-based CAD tools. The conclusions drawn from this study provided an initial look at the development of expertise in the use of constraint-based CAD tools. Recommendations for further research were also provided.

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

by
Nathan W. Hartman

A dissertation submitted to the
Graduate Faculty of
North Carolina State University
in partial fulfillment of the requirements
for the Degree of
Doctor of Education

Math, Science, and Technology Education
Technology Education Program

Raleigh, North Carolina

2003

Approved by:

Dr. Theodore J. Branoff Co-Chair of Advisory Committee	Dr. V. William Deluca Co-Chair of Advisory Committee
Dr. Don L. Martin Minor Representative	Dr. Aaron C. Clark Technology Education Program

DEDICATION

To my wife, Heather –

for all of her love and encouragement

BIOGRAPHY

Personal

October 13, 1973	Born: Lafayette, IN
May 1991	Graduated McCutcheon High School Lafayette, IN
December 1995	B.S. in Technical Graphics – Purdue University, West Lafayette, IN
November 1993 – February 1994	Worked in Tooling Design – Fairfield Manufacturing, Lafayette, IN
May 1994 – January 1996	Worked in Engineering Design, Caterpillar Incorporated, Lafayette, IN
January 1996 – May 1997	Graduate Teaching Assistant – Purdue University, West Lafayette, IN
August 1997	M.S. in Industrial Technology – Purdue University, West Lafayette, IN
July 1997 – July 2000	Technical Training Engineer – RAND Worldwide, Schaumburg, IL
July 2000 – present	Graduate Teaching Assistant – North Carolina State University, Raleigh, NC

Professional Affiliations and Awards

Epsilon Pi Tau – 1997 to present
Phi Kappa Phi – 2001 to present
Engineering Design Graphics Division of
American Society for Engineering Education – 1997 to present
Schroff Graduate Student Development Grant – 2000, 2001
Graduate Teaching Assistantship – Purdue University – 1996, 1997
Graduate Teaching Assistantship – NC State University – 2000, 2001, 2002

Fields of Study

Engineering Graphics
Technology Education
Training and Development (Instructional Design)

ACKNOWLEDGEMENTS

I am grateful for the support, encouragement, and assistance of all who aided me in the completion of this study. My colleagues and friends were extremely understanding and gracious in their understanding of my needs during this time.

I am especially grateful for the guidance and support of my committee members, Dr. Ted Branoff and Dr. Bill Deluca as co-chairs, and Dr. Aaron Clark and Dr. Don Martin. They were extremely generous with their time and advice throughout this process without altering the direction of the study. They also kept me grounded, motivated, and realistic in terms of what I could accomplish.

I would also like to thank Dr. Eric Wiebe for his meaningful discussions of expertise and the use of CAD tools in general, as well as his interest in my study. Dr. John Pettitt was of great assistance in discussing ideas I had about data analysis and the results that were generated from this work. Each of these individuals contributed significantly to the final form of this dissertation.

I am indebted to the participants in this study, who must remain anonymous, but gave freely of their time and experiences so that I could complete my tasks in a timely and efficient manner. I believe that because of them, engineering graphics education will be better in the future.

Finally, I could not have completed this endeavor without the self-discipline and dedication instilled in me by my parents. It is from them that I learned to see a task through to the end and to always give my best effort. They taught me the value of a good education, and in many respects, they were my most influential teachers.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

Page

Chapter 4: Findings

Chapter 5: Summary, Discussion, and Recommendations

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

CHAPTER 1: INTRODUCTION

The engineering design graphics curriculum is at a crossroads. Computer technology is enabling engineers and technicians to design and manufacture parts without relying on two-dimensional drawings. The curricula at many universities and community colleges still dedicate a great deal of time focusing on 2D documentation drawings, and this is even more evident at the high school level. There are several possible reasons why some programs have not changed to a curriculum that focuses on constraint-based, three-dimensional solids modeling. One obstacle to this type of change has been the cost of hardware and software (Miller, 1999). Since some 3D modeling programs are as low as $150 and student editions of constraint-based modelers can be purchased for as little as $300, cost can no longer be an excuse for not including 3D modeling into introductory courses (Nasman, 1999).

Another excuse for not revising the curriculum has been that students must understand 2D geometry before entering a 3D environment. A recent survey of NAITTE, CTTE and EDGD members indicated approximately 57% of faculty still use manual drafting equipment in their curricula, most of which is focused in the freshman year (Clark & Scales, 1999). Although many faculty might argue that swinging a compass is necessary to understand tangent geometry, no studies have been conducted to suggest that this is true.

Tradition may be the most prominent excuse for not revising the engineering graphics curriculum. The core of the curriculum, which has mainly focused on engineering drawings, has not changed much over the last 50 years. Computer-aided design (CAD) has changed the way documentation of the engineering design process is produced, but many engineering graphics programs have not critically examined the way computer technology has influenced the design and manufacturing processes. Where in the past drawings were critical components of the design process, today they tend to be ancillary documents (Branoff & Hartman, 2001). These aforementioned reasons for not revising the engineering graphics curricula that are taught within the university environment has left the profession in a position where it is at risk of being surpassed by the rate of technological change. Only recently has the profession developed a mindset of reform. However, the focus of CAD technology is changing; CAD technology is now being used to capture and store more information that is critical to the definition of the product. No longer are Boolean-based primitive CAD systems prevalent in the engineering design process.

Knowledge-based engineering tools are being developed to capture expertise and experience from engineers. As a basis, these tools use 3D CAD models created to capture the geometry of the design. Through the use of geometric constraints, equations and feature relationships, designers can capture the physical characteristics of a product. These new tools allow a person to capture the context in which these products reside (Greco, 2001). Software is now being used that captures some of the “intelligence” that is resident within the mind of the experienced engineer or designer. To do this, the software is utilizing design sketches, research libraries, manufacturing and assembly information, drawing creation, analysis, and expert knowledge in the form of design rules, constraints, and parametrics. Through the use of associative functionality within the software, users are able to drive all of the concurrent engineering processes using the 3D solid model (Greco, 2000), although the transition from 2D CAD to 3D CAD is no longer the same. Parametric, constraint-based CAD tools have pervaded the market place, and they are radically different than the Boolean-based 3D CAD tools that reside in most academic environments (Dean, 2000).

At the national level, several formal and informal curriculum revision activities are taking place to address the need for integration of constraint-based CAD into the curriculum. Barr (1999) conducted a survey of 16 members of the Engineering Design Graphics Division (EDGD) of the American Society of Engineering Education (ASEE) regarding the types of activities that need to be researched relative to the engineering design graphics curriculum. He reported that the most important topics were considered to be developing 3D visualization skills, parametric modeling, 3D solid modeling, manual sketching, and a new generation of teaching materials. Items considered of least importance were lettering, manual construction using instruments, virtual reality, descriptive geometry, and computational geometry. In a review of 3D modeling programs, Ault (1999) concluded that there must be an increased emphasis on solid modeling, parametrics and modern graphical analysis within the engineering graphics curriculum. She also recommended that new teaching methods be investigated to ensure the effectiveness of graphics education. In a review of new technologies for engineering graphics, Miller (1999) lists several topics that every program should emphasize – visualization, problem-solving, design-based exercises, engineering graphics standards, sketching, constraint-based solid modeling, and exposure to the latest engineering, computer-based technologies. He encourages the development of students who have both applied and theoretical knowledge, and suggests that this is necessary for their success in a digital world.

In light of the previous curricula recommendations, many technology and engineering programs have implemented computer-aided design (CAD) technology into their curricula, including the use of parametric, constraint-based CAD tools. In fact, several significant activities are happening at the program level. The faculty at Purdue University has recently revised their curriculum in applied computer graphics. One of their concerns was that students be exposed to a wide range of 3D computer graphics areas at the freshman level, so students will be able to make informed decisions about future careers. With this in mind, one of the introductory courses was revised to include the following: 3D modeling, visualization, 3D coordinate systems, geometric entities, isometric sketching, solid modeling, surface modeling, multiview sketching, the design process, sections, creativity, and lettering (Connolly, Ross, & Bannatyne, 1999).

In a project that has national implications, Cumberland (2001) surveyed 28 companies to identify areas of expertise necessary for the next generation of engineering graphics technicians. Based on the survey data, he concluded that engineering graphics programs should include the following: macro programming, data translation, file and data management, CAD standards, constraint-based solid modeling, web technologies, simulation and animation, internships, collaboration, and a study of current trends and issues.

In addition North Carolina State University has also implemented constraint-based CAD into their Graphic Communications curriculum. The revised introductory course is based on national trends in engineering graphics in both industry and education, and upper-level courses are being edited to reflect those same trends. Although some of the topics look similar to what is currently taught, the material in their revised course will be presented with the idea that the 3D model is the center of the design process. The topics in the revised courses include visualization, solid modeling, constraint-based modeling, and the creation of assembly models (Branoff & Hartman, 2001).

Even with the onset of these new developments in curriculum integration, how are these tools being used? Is there an emphasis on menu selections or comprehensive strategies? Duff (1990) suggested that engineering graphics could be taught as a body of knowledge independent of specific tools. While that may be the case, it is very difficult to apply a parallel constraint to a ruling pen. The tools that exist within the engineering graphics discipline have changed, and just as there were strategies suggested for the use of drafting equipment in most major engineering graphics textbooks, there needs to be effective strategies developed for the use of constraint-based CAD tools. Given that engineering and technology students will likely be employed in a commercial engineering or design environment, effective use of these tools needs to be promoted. By examining practicing professionals, the fundamental components of these strategies can be uncovered. However, industrial and commercial uses of these CAD tools are not beyond reproach either. Hence, the examination of the definition and development of expertise could benefit academic education as well as industrial training.

SIGNIFICANCE

New constraint-based CAD technologies have automated the design-through-manufacture process (Courter, 1999). Even with changes in the academic preparation of engineers and technologists underway, engineers and technologists in a *professional* setting still have their own problems that need to be addressed. This is because users of CAD software typically tend not to use the software in its most appropriate way, and many companies typically do not send their employees to extensive training courses that teach proper techniques. The idea that CAD training classes are a good idea does not get much agreement from many product managers. They see it as taking away from their designers' time and efforts towards developing products. They also see it as a way for employees to potentially search for a better position once they have a new skill set. These notions take away from the overall productivity of the user, because contemporary 3D CAD tools are not easily learned with tutorials, and the 2D experience that the designers have is not readily useable and is often detrimental to their progress. The cost of a CAD training course is often recouped within six months, but that is still a long time to wait for those people who are on a tight production schedule (Yule, 2002). What if this could be reduced to three months by increasing the productivity gain through the use of expert knowledge? The reason that most companies have adopted 3D CAD is its overwhelming advantages over 2D drafting: mass properties, visualization, accuracy, etc. (Dean, 2000). But at the beginning of the transition phase to 3D CAD, many engineers still carried the mindset of using drawings as the basis of their work. They still used slide rules, calculators, and handbooks to find and process much of their needed information (Greco, 2000). Because of the lack of effective education and training in both the academic and professional settings, many constraint-based CAD tool users have not developed effective strategies for utilizing the software. In addition, many third-party training seminars or university engineering graphics courses are not espousing best practices either (Miller, 1999). They are strictly concerned with users developing proficiency with selection of menu picks and software commands.

While some users have become experts at using this type of software, the vast majority of them have not. Some of them do not need to be experts, but most of them should be at a more proficient level than where they are currently (Cumberland, 2001). It has been estimated that certain industries, automotive, aerospace, and consumer products in particular, spend *billions* of dollars a year in manipulating their engineering design process due to errors made in the creation of geometric representations of their products (Computer Aided Design Report, 1998). In fact, many of the new projects being developed for the U.S. government have fallen behind schedule due to the lack of efficient CAD strategies and implementation (Byrum, 2001; Burgess, 2001). So it is imperative that the CAD user develop effective problem-solving strategies to accommodate the fluctuation in design variables which typically affect their design environment. Industry has appeared to stake its claim to the use of these tools, as evidenced by the mold making industry. Solid modeling is becoming the standard for product definition in the mold-making industry. By the end of 2002, it is predicted that 80.5% of mold makers worldwide will be using 3D solid data. They continue to stress the creation of accurate and functional geometry as one of the keys to the spread of 3D solid modeling in their industry (Christman & Naysmith, 2001). While this is only one example, it is a glimpse of a growing trend in engineering and design environments (Greco, 2001).

According to Courter (1999), feature-based, parametric, associative CAD systems have integrated the various components of the engineering design process. Companies need to employ CAD-savvy technicians to deal with these problems. In Cumberland's survey (2001), industry representatives reported they are looking for designers with expertise in the following areas: macro programming, data translation, data management, CAD standards, constraint-based solid modeling, web technologies, simulation/animation, collaboration, internships, and study of current trends and issues. Only by understanding the nuances of parametric, associative CAD systems can these issues be overcome (Izurieta, 1998). Since its inception in 1988, parametric, constraint-based CAD has continued to evolve, and in fact recent changes have been made to take it farther into the realm of capturing design information and linking it to the 3D model.

Companies have to take a smarter approach to product development by implementing a more objective-driven, process-wide view. Behavioral modeling is the next stage in the development of mechanical design automation. It takes advantage of the associative, parametric, and feature-based functionality of previous CAD tools by incorporating smart models, capture geometry, engineering specs, process knowledge, and design intent. Behavioral modeling is also objective-driven design, because it includes feature-based specifications to drive geometry in order to find an optimal solution. In addition, the open environment allows other engineering tools to integrate with the CAD system to promote bi-directional communication (PTC, 2000). While this is the view taken by only one software developer, the move towards more design knowledge being integrated into the CAD model has begun. However, all of these advances are still dependent on the creation of an accurate model that captures the intended geometric relationships. Allowing design problems to propagate throughout the engineering system drastically decreases the benefits of sharing CAD data with down-stream processes (Greco, 2001).

While industry continues to move ahead with the development and implementation of constraint-based CAD and its accompanying technologies, academic institutions have lagged behind in their implementation of these tools. There could potentially be several reasons for this, including cost, size of the academic program, and instructor expertise. However, these factors are beginning to disappear. Within the last several years however, the cost of these modeling systems has decreased significantly, with many software vendors offering substantial academic discounts (Miller, 1999). In fact, many constraint-based modeling vendors offer student editions for around $300, so cost can no longer be an excuse for not implementing these tools (Nasman, 1999). As suggested above, 3D models are becoming the cornerstone of the concurrent engineering design process, and it will be critical that students and faculty are versed in the concepts, methods, and knowledge of the tools that define their creation, manipulation, and archival. Engineering graphics education must find a way to convey the complexity of these tools in a sound manner.

This will require an examination of practicing professionals in order to gauge their expertise in the use of these tools. This information can then be translated into classroom activities and experiences that will promote the use of effective strategies. By examining practicing professionals in their working environment, their strategies for the use of constraint-based CAD tools can be examined, and a structure for the domain knowledge for these types of tools can be obtained. Even though many curriculum reforms have been suggested within the engineering graphics community, examination of the curricula at various institutions reflects a different sentiment. While the prices for software and hardware have decreased with regard to this technology, many schools are still using traditional methods as a means to prepare students (Branoff & Hartman, 2002). They argue that these methods of preparation make students better prepared to use the

CAD tools, however, that has not been confirmed by empirical study. Another reason cited by some faculty members is that industry cannot decide what it wants in the way of CAD tools, so why should academia bother to keep up. On the contrary, it is evident from the sources cited previously that industry has a good idea of where it want to go, it is just lacking proficient and qualified people to help it reach its destination.

These factors, as well as the researcher's personal interest and experience with this topic have prompted the inquiry that forms the basis of this dissertation. Practicing professionals in the field of engineering graphics need to be studied to determine how they process information related to the use of constraint-based CAD tools and how they conceptualize their domain. In addition, these same professionals need to be studied in regard to their past and present experiences to explore the factors that have contributed to the development of their expertise.

PURPOSE STATEMENT

The purpose of this exploratory research study was to explore the phenomenon of expertise in the use of constraint-based CAD tools by examining practicing professionals. In doing so, an initial description of the factors and experiences that contribute to the definition and development of expertise in this area was obtained. At this stage in the research, the social and cognitive theories of expertise in various disciplines, the knowledge of professions, and CAD tool information were used as a background for the development of expertise in the use of these tools. Using interviews, observations and cognitive knowledge elicitation methods, this research sought to examine the definition and development of expertise as determined by practicing professionals through their experiences and practical uses of the CAD tools.

Central Research Question

How does one develop expertise in the use of constraint based CAD tools?

Sub-questions

1. How do professional and social factors and experiences within authentic design activities impact the development of expertise in the use of constraint-based CAD tools?

2. What are the critical concepts that comprise the mental model and the software techniques of expert, constraint-based CAD users?

ASSUMPTIONS

The following assumptions were used throughout the processes and procedures within this study:

1. There is a need to establish a working definition and development procedure for expertise in the use of constraint-based CAD tools.
2. Participants responded truthfully during the interview process in regard to their own experiences and personal levels of expertise.
3. The number of participants chosen for this study was sufficient for a preliminary examination of expertise in the use of constraint-based CAD.
4. Examining authentic practice by engineers and designers working in professional design environments produced information regarding the experience (development) and essence (definition) of expertise in the use of constraint-based CAD tools.
5. Participants possessed expert characteristics in the use of constraint-based CAD.
6. Participants were able to sufficiently verbalize their knowledge in the form of answers to interview questions.
7. Participants were able to sufficiently verbalize their model creation procedures during the think-aloud modeling process.
8. The research methods chosen for this study were appropriate for the exploratory nature of this research.
9. The use of constraint-based CAD tools is becoming prevalent, if not commonplace, throughout engineering graphics curricula within academics and industry.
10. The information gathered in this study is relevant and current with regard to engineering graphics given the curricula changes in the last five years.

Limitations

The following limitations will be considered throughout the processes and procedures used in this study:

1. All participants in this study are practicing professionals within industries that specifically use constraint-based CAD tools, such as manufacturing or product design.
2. Data was collected only from people employed by companies or divisions of companies located in North Carolina.
3. Due to limitations in resources, only five participants were used for this study.
4. Data was collected using observations, interviews, protocol analysis, and knowledge mapping to gather in-depth information from participants and as a means of verifying the information obtained with each technique.
5. Participants were selected as experts based on their years of experience and average hours per week using constraint-based CAD tools and their status as practicing professionals within industry.
6. The results of this study were intended to aid in the development of academic curricula and professional technical training regarding the use of constraint-based CAD tools.

DEFINITION OF KEY TERMS

The following list is comprised of key terms and their definitions as will be used in this study:

1. **Computer-aided design** (CAD) (Majchrzak, et.al., 1987): a design software/hardware package which utilizes interactive computer graphics to assist in the creation, modification, presentation, and analysis of a design.
2. **Constraint-based CAD** (Bertoline & Wiebe, 2002) Constraint-based CAD tools create a solid model as a series of features that correspond to operations that would be used to create the physical object. Features can be created dependently or independently of each other with respect to the effects of modifications made to the geometry. The geometry of each feature is controlled by the use of modifiable constraints that allow for the dynamic update of model geometry as the design criteria change. While terminology within the literature varies, ideas of parametric, associative, feature-based, and dimension-driven will be included in this definition.

3. **Mental model** (Johnson-Laird, 1983; Norman 1983): an internal cognitive representation based on knowledge and beliefs about oneself and the environment, people, and artifacts of technology with which one is interacting. Mental models provide predictive and explanatory power for these interactions.
4. **Information processing theory** (Gredler, 2001; Wickens & Hollands, 2000): Information processing centers on three basic pillars, attention, memory, and problem solving, and their use by humans to exist in a dynamic environment. Attention is used to direct and process the flow of information. Memory is used to code and store this information in useable form. Problem solving is the implementation of stored information to address a deficiency in the current situation.
5. **Expertise** (Mieg, 2001, p. 2-5; Ericsson & Smith, 1991): a set of characteristics that is exhibited by an individual who shows superior performance, more specialized experience, or more extensive knowledge compared to others within a specific knowledge domain or as compared to people in general.
6. **Expert** (Mieg, 2001): A person, either through knowledge or experience, that holds a certain level of expertise; or an embodiment of expertise by a person in their fulfillment of their designated role within a group, such as a society, organization, or profession.
7. **Phenomenology** (Creswell, 1998; Polkinghorne, 1989): the study of lived experiences for several individuals based on a particular concept or phenomenon. For example, the examination of life and work experiences that have led to individuals developing expertise in the use of constraint-based CAD.

OVERVIEW OF THE STUDY

The call for the integration of constraint-based CAD tools into engineering graphics curricula has been made (Miller, 1999; Ault, 1999; Branoff et al., 2002), but there is no clear decision in regard to how to proceed. Many people within the academic setting consider constraint-based CAD simply as another tool with which to document the design process. While that is true to some degree, there is much more to it than that. Those people still stress the importance of traditional documentation and standards (Clark & Scales, 1999) when it is inevitable that they will eventually be passed by.

The question has been raised at several of the previous American Society for Engineering Education's Engineering Design Graphics Division Midyear Meetings about "How do you teach with this stuff?" The answer lies in understanding how constraint-based CAD tools operate, understanding the mindset behind them and teaching those strategies in the classroom. Wiebe (1999) and Hanratty (1995) have argued that there are specific, common elements contained in constraint-based CAD systems. These elements should be the focus of instruction, along with the fundamental strategies and ways of knowing that are unique to this particular domain.

In order to uncover that knowledge base and those strategies, an examination of professional, expert usage was conducted in this research study to examine how these individuals experience expertise within this domain, as well as how they conceptualize it. Constraint-based CAD tools are complex pieces of CAD software that have a myriad of options within them (Bertoline & Wiebe, 2002; Greco, 2000 & 2001) for capturing the knowledge and insight of the individual or collective engineering group. However, with all of those different options for creating geometry and the relationships therein, much of that knowledge becomes "proceduralized" and trapped within the context of professional performance. It becomes, according to Sternberg et al. (2000), practical intelligence.

Practical intelligence can be thought of as a form of developing expertise, and it can be characterized as the development of knowledge, skills, and abilities that lead to successful performance within a domain. Therefore, it is important to understand expertise and how it develops in order to have a good understanding of practical intelligence. A good understanding of practical intelligence, in the case of constraint-based CAD, will lead educators and trainers to the content and process information that they need to develop effective instruction in the use and integration of these tools. Developing expertise is an ongoing process of the acquisition and refinement of skills and knowledge that are needed within a particular domain of life. From the standpoint of using a particular tool, this is often done within collaborative work settings or communities of practice (Wenger, 2000). In this case, it is the application and use of a particular design tool. In order to assess expertise, one must understand how it develops. Much research has been done in the way of analyzing expertise and it various properties

(Ericsson & Smith, 1991; Chi, Glaser, & Farr, 1988; Feltovich, Ford, & Hoffman, 1997). General characteristics of experts have been discovered with regard to memory, problem solving, and knowledge structure with respect to a particular domain, and this study examined these characteristics and their relationship to constraint-based CAD, particularly with regard to possession of these same characteristics by constraint-based CAD experts. Expertise is also viewed not just as an attribute of a particular person, but also by the way a person is perceived by other people within their professional setting (Mieg, 2001). In this case, expertise is a labeling function applied to a person or group by another person or group.

To address the questions regarding the development and definition of expertise in the use of constraint-based CAD, a literature review was undertaken to examine the many facets of expertise, including perspectives from cognitive psychology, sociology, and technology. Given that this study focuses on the use of a technological tool, it is important to understand the history of technology education, one of whose main tenets is the proficient and correct use of tools to affect one’s environment. This is followed by a brief review of the history of engineering graphics, which is the discipline most impacted by the use of constraint-based CAD tools, but which also falls into the realm of communication within technology education. Following the discussion of engineering graphics is a brief history of CAD tools and their development, including a discussion of constraint-based CAD and its common characteristics derived from the literature.

Following the discussion of the technological and professional aspects of this study, an overview of information processing is provided as a basis for the discussion of mental models and expertise. Information processing examines the means by which humans process sensory information and encode it for storage into long-term memory. In the storage of information in long-term memory, people use various techniques, and in the case of expertise, vast stores of domain knowledge are typical. A discussion of mental models follows information processing in the literature review to address the ways in which past experience and previous knowledge affect the development of expertise in a particular domain. In addition, it includes a discussion regarding the means by which mental models act as a collection of vast domain knowledge. The discussion of mental models also provides the basis for the methodologies that were employed to answer the research question regarding the definition of expertise.

A discussion of expertise is also included in the literature review to examine the general characteristics of expertise with regard to depth of domain knowledge, memory, and information processing. In addition, expertise was examined from a sociological perspective due to its attribution to individuals by other individuals within the environment, as well as its tie to practicing professionals. By examining the general characteristics of expertise, the question regarding the similarity of constraint-based CAD and other complex domains in terms of expertise can be answered.

The examination of expertise from a sociological perspective leads to the discussion of technological knowledge and a tie back to technology education. This also addresses the notion of practical intelligence that was mentioned previously and the fact that, in most cases, expertise is gauged within the specific context of a particular domain. Practical intelligence is also linked to the strategic use of tools, and constraint-based CAD is no exception. Several studies (Bhavnani, 1996, 1997, 1998, 1999) have examined the use of CAD from a 2D, architectural perspective, but the study of constraint-based CAD is lacking in this area. Thus, this study is an initial attempt at addressing some of these issues.

To address the definition and development of expertise in the use of constraint-based CAD, this study used several methods taken from a variety of disciplines. While this may seem frivolous, the nature of research regarding expertise and its assessment is eclectic to say the least (Sternberg et al., 2000). Interviews and observations, based on the phenomenological tradition of qualitative inquiry (Moustakas, 1994; Creswell; 1998; Giorgi, 1985), were used to examine the development of expertise. Think-aloud protocols (Ericsson & Simon, 1993; Sternberg et al., 2000; Bainbridge & Sanderson, 1995) and knowledge mapping tasks (Jonassen, 1993; Olson & Biolsi, 1991), taken from the cognitive psychology domain was used to explore the characteristics that comprise the definition of expertise within this domain.

OVERVIEW OF METHODOLOGY

Due to the fact that a localized concentration of experts within a domain is rarely if ever found, this type of research typically uses smaller sample sizes than those used in experimental research designs. Experts were selected using a variety of criteria including their time in a particular job and their status as a practicing professional (Hoffman, Shadbolt, Burton, & Klein, 1995). In fact, Polkinghorne (1989) and Meyer and Booker (1991) recommended the analysis of between five and twenty participants for an exploratory phenomenological study. As a result, five experts were selected based on their experiences and their status as practicing professionals. The observations were conducted within the expert's place of employment to provide a naturalistic setting in which to observe the phenomenon (Creswell, 1998). The field notes for each participant were analyzed to look for common elements that signify their place within the social structure of the group and how their expertise is developed and used. Using the phenomenological research tradition as a guide, emphasis was placed on looking for the meanings of these experiences and how they relate to expertise development.

Interviews were conducted with each participant that center on the experiences that they have had in their academic and professional careers that have brought them to this point. Particular emphasis will be placed on academic and professional employment experience related to technological tools and processes. The focus of the interview analysis was the examination of experiences with the phenomenon of expertise and what it means to each of the participants (Creswell, 1998; Moustakas, 1994). The researcher also discussed expertise in terms of his experiences as a means to bracket the information and guard it from any undue bias. Finally, a rich description of the development of expertise was made in terms of the descriptions given by the researcher, the participants, and the literature.

The knowledge mapping tasks were conducted with each participant in an effort to create a view of their mental model with respect to the domain of constraint-based CAD. This was accomplished by labeling a series of cards with common terms and phrases, taken from constraint-based CAD literature, the experience of the researcher, and the observations of each participant, and asking each participant to arrange them based on their perception of the importance of and relationships between the concepts. The goal of this analysis was to determine critical concepts and their relationships, as well as their structure within the higher-level domain (McGraw & Harbison-Briggs, 1989; Olson & Biolsi, 1991). A graphical representation of each participant's arrangement was created to form a semantic map, which was compared and combined with those from the other participants to attempt to create a common mental model of constraint-based CAD.

Finally, the think-aloud protocol was used as a means to examine the problem-solving process employed by experts in the creation of constraint-based CAD models. In doing so, the researcher attempted to uncover the relationship between the expert's mental model and the actions they actually perform. A form of protocol analysis (McGraw & Harbison-Briggs, 1989) called a think-aloud protocol was used to analyze the transcripts for each problem solving session to determine common language and methods used in the process. The goal of this analysis was to examine the modeling procedures used by the expert participants to create geometry within the CAD tool.

SUMMARY

Engineering graphics education and practice are at a crossroads. While engineering graphics educators have come to realize that they can no longer continue using antiquated tools and methods, the direction in which to proceed is not agreed upon. Many authors have acknowledged the importance of constraint-based CAD in the engineering graphics curriculum, but exactly how it is implemented and to what degree remains to be determined. The documentation of engineering design data will always be important; the only real question that remains is what form will the documentation take? Industry is progressing away from 2D documentation practices and standards and implementing concurrent engineering design processes based on the 3D model. In doing so, they are quickly eliminating the need for large amounts of 2D instruction and increasing the amount of instruction needed in 3D constraint-based CAD tools. While some people in the field may argue that constraint-based CAD is pedagogically challenging, their arguments are equally concerned with tradition and dogma. In order to achieve effective integration of constraint-based CAD tools into the common engineering graphics curricula, new teaching techniques and philosophies are needed. Due to the close alignment of engineering and technology to industry, these tools must be understood from the perspective of their professional use, and that knowledge can be used to define content within engineering graphics curricula. However, it is still the responsibility of engineering graphics educators to adapt this new knowledge so that it is in a form suitable to students at various stages of their academic career.

CHAPTER 2: REVIEW OF LITERATURE

The focus of this literature review is to discuss the critical areas that support the examination of the definition and development of expertise in the use of constraint-based CAD. A brief history of technology education and a brief history of engineering graphics will enlighten the relationship between graphics and technology education and the role that "drawing" tools and processes have played throughout this history. An overview of information processing will then be presented to provide a background for the subsequent discussions of mental models and expertise. Expertise will be examined from two perspectives, cognitive psychology and sociology, due to its nature as a personal characteristic and as a larger abstract role within an organization. Finally bringing all of this together will be a discussion of technological knowledge and its relationship to the strategic use of CAD.

BRIEF HISTORY OF TECHNOLOGY EDUCATION

In ancient times, the Greeks and Romans used slave labor and master/apprenticeship relationships to configure the working, "professional" environment. This practice continued through feudal times to the Renaissance & Reformation period when society in general began to respect the craftsmen and their guilds (Barlow, 1967). One of the most well-known products of the Renaissance period was the artistry and drawings of its myriad inventors and scientists, and it is here that graphics began to be used widely in education, construction, and the military (Bertoline & Wiebe, 2002). The success of guilds and apprenticeship relationships lasted for hundreds of years, and they still survive today in the form of trade unions. The time between the sixteenth and nineteenth centuries was a period of educational reform throughout the world (Barlow, 1967). The numbers of "literate" common people were increasing, and several individuals stood out as key reformers in that movement. Mulcaster used drawing as a means of instruction in his schools (Barlow, 1967). In addition, Pestalozzi, Froebel, and von Fellenberg established schools to teach manual training to the poor as a way to make them employable and self-sufficient (Barlow, 1967). Much of the education at that time focused on the instruction of people in activities that were vocational in nature.

Towards the late nineteenth century, industrial education provided a platform for educational reform in America. As factories in the United States began to expand, they needed a skilled labor force with which to accomplish their mission. The Russian system of manual education, founded by della Vos, impacted the American manual training movement as a result of an exhibit at World Exposition in Philadelphia in1876 (Foster, 1997). The focus of industrial education would now move towards integration into the public schools of the day, and this saw several of the subjects contained in industrial education become popular with students, including mechanical drawing.

At about the same time that John Dewey was advocating educational reform with a more student-centered focus, Congress passed the Smith-Hughes Act to provide federal funding for vocational education. America had now transitioned from manual training to vocational training and job preparation with the advent of the American Industrial Revolution and the impending World War I (Foster, 1997). With Bennett's manual arts program and the evolution to industrial arts by Bonser and Mossman, America was seeing a growing division between industrial arts and vocational training (Foster, 1997).

One element remained strong through all of these transitions, and that was the role of graphics, particularly engineering or technical graphics. Mechanical drawing was seen as a means by which those students who were otherwise destined to become "shop workers" could become involved with a more professional sort of person: the engineer. Students and teachers consistently rated mechanical drawing as a favorable and legitimate subject during this time period. It was proved to be quite transferable to future employment upon graduation (Barlow, 1967).

In the late 1940s, Warner directed the Industrial Arts Curriculum Project as a means for industrial arts education to closely reflect the changing technology in industry. It included four areas of general shop: manufacturing, construction, communications, and transportation. Drawing was included in this new model as a topic for instruction in the communication segment (Barlow, 1967). Olson later advocated a more general approach for industrial arts so that it may be integrated within the general education requirements for school districts around the country. Olson's work continued a theme that was resident within industrial arts since its inception (Foster, 1997), which was integration with the common curriculum in schools. Similar things can be said about the current initiative surrounding scientific visualization.

DeVore initiated a new approach to industrial arts in the late 1960s. It marked a social approach to technology where it was evaluated as a discipline that affects all of society (DeVore, 1964). In addition to the social consequences of technology, DeVore also advocated technology as a discipline, which meant that it had a history, a knowledge base, a method of inquiry, and a means of public recognition (Foster, 1997). In doing so, technology could then be compared to other more formalized disciplines, especially with regard to its body of knowledge and history.

The Jackson's Mill Curriculum Project solidified the underlying principles of technology as a discipline, and it formally introduced the idea of a systematic approach to the teaching of technological concepts. It also kept the four core modules from the former industrial arts programs (Foster, 1997). This also marked the beginning of being able to associate technology and its associated bodies of knowledge to the idea of a profession (Abbott, 1988).

With the new focus in content and application, the former American Industrial Arts Association changed its name to the International Technology Education Association. This action confirmed the change in focus from job-specific and leisure activities to those activities focused on the development of a discipline that permeates general education (Foster, 1997). Through the Technology for All Americans Project, the ITEA developed standards to define technological literacy for all K-12 students. At a minimum these standards encompass the basis for the development and sustenance of technological knowledge in seven core areas of technology (ITEA, 2000)

Graphics is still a strong component in the communications component of the curriculum, and topics are no longer centered on only "drawing". Students can now explore 3D modeling, animation, and scientific visualization. Due to the fact that graphic communications has been a component of technology education from the beginning (Barlow, 1967), it has also gone through an evolution from the days of manual drafting to today's use of high-performance, constraint-based 3D CAD tools (Bertoline & Wiebe, 2002). In many respects, this evolution of drawing to CAD can be traced to the evolution of the tools within the discipline and the professional, vocational nature of many of the industrial arts activities of the time. While the emphasis in technology education is changing to reflect a general curriculum, much of the coursework related to graphics is still very vocational in nature.

Due to the practical nature of many of the activities within these curricula, students often can easily transfer the skills learned in the classroom to tools and processes found in an employment position (Barlow, 1967; Bertoline & Wiebe, 2002). This fits well with two of the basic tenets of technology education: the use of tools to interact with the environment and processes to control the use of those tools (ITEA, 2000).

In doing so, this tends to blur the lines between traditional vocational education and technology education. However, by discussing graphics in terms of a discipline, one can see that it has its own knowledge base and set of tools (Bertoline,1998; Duff, 1990) . While some argue that concepts are independent of tools (Duff, 1990), it is becoming more difficult to differentiate between them due to the automation by constraint-based CAD tools of once manual tasks that required specialized knowledge.

While modern constraint-based CAD tools still employ a few of the traditional characteristics of traditional drafting, they have their own inherent knowledge base that build on these traditional geometry concepts.

In order to fully utilize the advantages of these tools, it is critical to understand their inherent characteristics, common themes, and applications for use (Wiebe, 1999). To do this, practicing professionals must be examined to determine their levels of expertise and the experiences that made them so (Mieg, 2001). In order to understand the body of knowledge related to engineering graphics, a brief examination of its significant milestones is discussed in the following section, including the development of CAD.

BRIEF HISTORY OF ENGINEERING GRAPHICS

Engineering graphics have played a major role in many of the civilizations throughout history, particularly in their ability to convey information about the creation of an object (Bertoline, 2001). Perhaps the earliest known drawing in existence is the plan view design of a fortress drawn by the Chaldean engineer Girdea and engraved upon a stone table. Ancient Egyptian stonemasons made plans for the pyramids and other buildings on papyrus, slab of limestone and sometimes wood. The ancient Greeks and Romans played a very important role in the development of geometry. Pythagoras, Enclid, Marcus Vitruvius Pollio, and Archimedes made mathematical discoveries in terms of geometry and graphical representation, such as parallel and converging lines, that are still with us today. These methods shape our creation of physical objects for our world just as they did in ancient times.

The techniques of drawing advanced rather slowly from the turn of the Common Era and basically on an individual basis until the fifteenth century. However, with the arrival of the Renaissance period, the classic civilizations were rediscovered, studied and imitated. The prominent use of illustrations and images, as well as technical drawings, brought back the use of graphics in mainstream life (Bertoline, 2001).

This stage in the history of engineering graphics was accompanied by the mathematical approach to drawing, which included Brunelleschi, Alberti, and Francesca with their theoretical laws of perspective drawing and painting. It also included Da Vinci's drawings and sketches, which were very easily understood because of his excellent use of perspective, and for this reason he taught others his methods for several years (Bertoline, 2001). Durer was credited with the first basic knowledge of orthographic projection and scientifically formulated it in 1795 in a book written by Gaspard Monge. Desarques was a French mathematician, whose interest in graphics stemmed from problems he faced as a military engineer. Desarques is regarded as one of the founders of modern projective geometry (Bertoline, 2001). Gaspard Monge, considered the "father of descriptive geometry", also lived during this time. He used graphical methods in solving design problems related to fortifications and battlements as a student in a French military academy. History states that he was scolded by his headmaster for not solving a problem using the typical long and tedious mathematical process traditionally used for problems of this type. After studying at the military school, Monge taught mathematics and physics at the Polytechnic School in France. It was during that period Monge developed the principles of projection that are today the basis of our engineering drawing. These principles of projection were recognized to be of such military importance that Monge was compelled to keep his secret until 1795 following which they became an important part of engineering and technical education in France, Germany and later in the United States. His work, Descriptive Geometry, was the first consciously formulated exposition of the science of orthographic projection and descriptive geometry (Bertoline, 2001).

In 1807, engineering drawing classes in this country began to be taught formally when Christian Zoeller was appointed as instructor of drawing at the United States Military Academy. Monge's principles of descriptive geometry were brought to the United States in 1816 from France by Claude Crozet, a professor at the U.S. Military Academy. He had no textbook on the subject, and descriptive geometry could not be taught orally. In 1821, Crozet published the first text on the subject of descriptive geometry in the English language. As is the case today, the use of engineering graphics principles is dependent upon having the proper tools. The first half of the 19th century was filled with many developments that have lasted until today in terms of engineering graphics principles, and this period might well be known as a formative period in the development of engineering drawing (Bertoline, 2001).

In 1850, the Alteneder family established an American factory for the manufacture of drawing instruments. No longer did drafters and engineers in the United States have to buy drawing instruments from European manufacturers. To support the creation and distribution of technical drawings, the blueprint process was introduced in this country at the Philadelphia Centennial Exposition in 1876 (Bertoline, 2001). As stated previously, this is also the time when manual training in the United States began to take on the characteristics of a more generalized curriculum (Barlow, 1967).

Up to this time "draughtmanship" was more or less an art expressing itself in fine lines, shading both by lines and by washes, ornate borders, fancy lettering and the use of colors. Artisans worked many hours to perfect their technique, and professional status and privileges were granted to these people (Abbott, 1988). These techniques became unnecessary after the introduction of blueprinting, and the art of "draughting" was completely lost. The technology of "drafting" was discovered. This was the beginning of modern engineering and technical drawing.

The first half of the 20th century could be characterized as the golden age of drafting. The modern technology of drafting was firmly recognized, and the application of graphics technology was found in engineering, design, manufacturing, production, architecture, etc. Engineering, technical and vocational training in the area of drafting was greatly increased. Vocational programs at the high school level were being funded by the federal government to promote workforce development (Barlow, 1967), a it was common for large companies to have rooms full of drafters who did nothing else but create and edit technical drawings. Due to the proliferation of technical drawings and the emergence of the United States as a manufacturing power during the first half of the twentieth century, the need for standards to support mass production had arisen (Bertoline, 2001).

In all of the engineering graphics textbooks, there has been a tendency to standardize the characters of the graphic language and to give industry, engineering, and science a uniform, effective graphic representation. The American National standards Institute (ANSI), along with the American Society for Engineering Education, the Society of Automotive Engineers, and the American Society of Mechanical Engineers, has been at work since 1926 to establish standards for drafting and to bring such standards into agreement (Bertoline, 2001). While this has contributed greatly to the effectiveness of the American manufacturing enterprise, it has also perpetuated the focus of engineering graphics instruction on drawing standards and documentation practices instead of wholesale adoption of more robust and powerful graphic representation.

In 1950, the first computer-driven display attached to MIT’s Whirlwind I computer was used to generate simple pictures, and the dawn of computer graphics had arrived. By the late 1950’s, MIT’s TX-0 and TX-2 interactive computing systems became feasible, and interest in computer graphics began to increase rapidly (Bertoline, 2001; Orr, 1995). In 1962, Ivan Sutherland’s Ph.D. thesis "Sketchpad: A Man-machine graphical communication system" proved that interactive computer graphics was a viable, useful, and exciting field of research, and Sutherland also used constraints to aid in part creation, but did not use them to control geometry (Hanratty, 1995). Although, up until this time, no attempts had been made to use computer to generate graphical representations of complete product geometry.

In the mid-1960's all of that changed when large computer graphics research projects were begun at MIT, GM, Bell Telephone labs, and Lockheed Aircraft. D. T. Ross of MIT developed an advanced compiler language for graphics programming (Bertoline, 2001). Coons, at MIT, and Ferguson at Boeing, began work in sculptured surfaces. GM developed their DAC-1 system and other companies, such as Douglas, Lockheed, and McDonnell, also made significant developments. These companies began to invest a great deal of money into the notion of using computers to generate graphical representations of geometry that could be used in the engineering design process (Orr, 1995).

In the 1970's, academic research groups began to produce interactive computer graphics systems. Developments in the mathematics of parametric geometry were developed by Coons and Bezier for the control of 3D surfaces of objects (Orr, 1995). Wireframe and polygonal modeling schemes began to develop, as well as the development of the first 3D solid modeling systems. Requicha, working at the University of Rochester in New York, began using directive graphs to represent the relationships between dimensions and geometry (Hanratty, 1995). As part of his Master's thesis at MIT, Gopin used directed graphs to define and modify geometry in an interactive CAD system (Hanratty, 1995). These were the first attempts to control geometry with mathematical parametric constraints in an interactive fashion. In 1980, Light and Gossard, working through MIT and ACM:SIGGRAPH respectively, showed that generalized dimensional constraints could be used to control geometry through large shape variations, and that geometric properties could be used to constrain geometry (Hanratty, 1995). While these developments were exciting, it would be nearly another decade before parametric controls made their way into interactive CAD systems in a wide spread fashion.

In the early 1980s, Apple and IBM PC's popularized the use of bitmap graphics. This resulted in an explosion of easy-to-use and inexpensive graphics-based applications, including CAD software (Hanratty, 1995). By March 1982, solid modeling functionality was now included in seventeen CAD systems (LoPiccolo, 2002). While this was a huge step for the blossoming CAD software industry, some vendors had mixed feelings; was solid modeling a novelty, or was this functionality here to stay? Later that year, solid modeling systems were able to work with primitive shapes, but they had difficulty with objects that contained internal features. Support for free-form surface generation was limited, and in most cases, it was considered a future concern (LoPiccolo, 2002). In late 1983, the Romulus solid modeling system was developed, and it was able to show internal geometry of parts. This was a significant development in the usability of the software, but it was confounded by the lack of computing power available to perform the complex software operations that were required (LoPiccolo, 2002).

In May 1988, parametric constraints used to control geometry behavior in CAD tools debuted with the release of Pro/ENGINEER from Parametric Technology Corporation (LoPiccolo, 2002; Hanratty, 1995). This produced a flurry of activity within the CAD software market, and several large companies adopted this software for use in their engineering design processes. While the promise of parametric constraint-based modeling technology was great, it is open for debate, even fifteen years later, as to whether or not companies have become as efficient as they can be in using this new type of software. As parametric, constraint-based CAD applications began to be developed by more than one software vendor, companies began to use CAD models to drive downstream engineering processes, such as visualization, CNC machining, and assembly (LoPiccolo, 2002). This trend continues to this day with a higher degree of integration between the CAD software and related technologies.

By 1994, there were at least seven significant dimension-driven, parametric CAD tools in the marketplace with more appearing every few months (Hanratty, 1995). Nearly all CAD systems that remain today have some form of dimension-driven, constraint-based, or parametric functionality included in them. While this flurry of activity in CAD tool development has increased the functionality and complexity of the tools, it has also affected the ways in which companies conduct their business operations and the way engineering and technology programs educate their students. With slight variations between them, it is not always possible to learn or use one CAD tool and transition smoothly to a different one without some loss in productivity. Those involved with the engineering graphics profession are searching for a solution to this problem still today. To address this issue, in March 1998, Chrysler became the first company to standardize on one CAD system for the design of its vehicles, and it requires that all of its suppliers use the same CAD tool in order to continue to do business with Chrysler. Other large original equipment manufacturers have followed suit, and it is now somewhat common to have entire segments of a company's supply chain centered on one brand of CAD system. This works well if everyone is capable of using the CAD tool effectively to communicate their design intentions, but if not, then the entire system can be hampered by inefficient CAD usage and poorly created CAD geometry that brings downstream processes to a standstill.

As engineering graphics evolved from carvings on stone tablets, to ornate drawings on linen, to 3D, mathematically accurate electronic representations, one idea have remained the same. Each practitioner, within their own time period, had a body of knowledge that surrounded their work. Whether it was the angle at which to strike the chisel to carve the tablet, the way to hold or fill the ink pen to gain consistent line quality, or the manner in which features are related within a constraint-based CAD tool, each type of practitioner has a method and a manner in which they go about their work. As mentioned by the aforementioned histories, the evolution of engineering graphics has paralleled the transition from manual training to industrial arts to technology education and the creation of complex, interactive computing systems.

As humans have gained and transformed their technological knowledge in the development of their artifacts through specialized tools, graphics has been one of the domains that have experienced that transition firsthand. In doing so, the relationships between graphics tools and their inherent techniques become more interrelated, particularly with regard to modern constraint-based CAD tools which take advantage of geometric inference algorithms to capture the intentions of the user. In addition, the geometry created by these systems is now being used to drive other processes within the concurrent engineering environment, which means that the geometry must be correct as well as robust enough to handle likely design changes. In order to obtain robust and correct geometry from constraint-based CAD tools, it is important that the user has a full understanding of the relationships that control and influence the operations of such tools.

CONSTRAINT-BASED CAD

Today's commercial brands of 3D modeling tools essentially contain many of the same types of functions. They are dimension-driven, parametric, feature-based, and constraint-based all at the same time, and these terms have come to be synonymous when describing modern CAD systems (Bertoline et al., 1997). For the purposes of this study, the term "constraint-based" will be intended to include all of these many facets. In addition, many of today's modern CAD tools also operate on similar interfaces with similar geometry-creation command sequences (Wiebe, 1999).

Generally, most constraint-based CAD tools consist of software modules that operate interdependently to control the modeling process. They include the Sketcher, the solid modeling system itself, the dimensional constraint engine, the feature manager, and the assembly manager (Hanratty, 1995). In most cases, there is also the presence of a Drawing tool. These various modules of the CAD tool are used both simultaneously and separately to define the 3D representation of the object, and in doing so, they have a particular way in which geometry is created.

Many of the modern 3D CAD tools combine constructive solid geometry (CSG) and boundary representation (B-rep) modeling functionality to form hybrid 3D modeling packages (Bertoline & Wiebe, 2002; Hanratty, 1995). Traditionally, CSG used mathematical primitives to create 3D models. They were efficient for the storage of the database, but they had difficulty with sculpted surfaces and editing the finished model. B-rep modelers use surfaces directly to represent the object three-dimensionally, so they tend to be very accurate. But, they also tend to have large database structures. Hence the development of hybrids to capture the best characteristics of both B-rep and CSG.

Constraint-based CAD tools create a solid model as a series of features that correspond to operations that would be used to create the physical object. Features can be created dependently or independently of each other with respect to the effects of modifications made to the geometry. If features are dependent, then an update to the parent feature will affect the child feature. This is known as a parent/child reference, and these references are typically at the heart of most modeling processes performed by the user (Hanratty, 1995).

The geometry of each feature is controlled by the use of modifiable constraints that allow for the dynamic update of model geometry as the design criteria change. This dynamic editing capability is also reflected in assembly models that are used to document the manner in which components of a design interact with each other. Modifications to features contained in a part will be displayed in the parent part as well as in the assembly that contains the part. Any working drawings of the part or assembly will also update to reflect the changes. This is known as associativity.

A critical issue in the use of constraint-based CAD tools is the planning that happens prior to the creation of the model (Bertoline & Wiebe, 2002). Much of the power and utility of constraint-based CAD tools is derived from the fact that users can edit and re-define part geometry as opposed to deleting and re-creating it. This requires a certain amount of thought with respect to the relationships that will be established between and within features of a part and between components in an assembly. The ways in which the model will be used in the future and how it could potentially be manipulated during design changes are both factors to consider when building the model. The manner, in which the user expects the CAD model to behave under a given set of circumstances, and the effects of that behavior on other portions of the same model or on other models within the assembly, is known as design intent (Bertoline & Wiebe, 2002; Hanratty, 1995). The eventual use and re-use of the model will have a profound effect on the relationships that are established within the model as well as the types of features that are used to create it, and vice versa.

Given the use of modern CAD tools and their place within the larger body of communications technology, it is important to discuss both the specific nature of constraint-based CAD and how it relates to technology as a discipline. Constraint-based CAD, with its own knowledge base comprised of the conceptual relationships regarding the design intent of the user and specific software controls that enable them, requires the use of an object-action interface model and metaphor on the part of the user in order to be effective (Wiebe, 1999). This interface model correlates the objects and actions used in the software with those used in the physical construction of the object being modeled. If a person is to effectively use the CAD tool, these two sets of models should be similar. In relation to the object-action interface model is the idea of a user's mental model of the software tool (Wiebe, 1999). This mental model is comprised of semantic knowledge of how the system operates, the relationships between the different modules and commands, and syntactic knowledge that is comprised of specific knowledge about commands and the interface.

The development of effective mental models in any given knowledge domain can generally be explained in terms of information processing theory borrowed from cognitive psychology. Specifically related to the use of technological tools and processes, in this case constraint-based CAD tools and their usage, are three derivatives of the information processing model: the development of mental models, the cognitive and social psychological roles of expertise, and strategic knowledge in the use of those tools. However, a basic description of the central tenets of information processing according to cognitive psychology is provided as a basis for further discussion.

OVERVIEW OF INFORMATION PROCESSING

Humans interact with information in visual, textual (verbal) and aural (sound) forms, and their information processing capacity is influenced by three basic cognitive systems: attention, memory, and problem solving (Wickens & Hollands, 2000). In their interaction with complex systems, such as interactive, constraint-based CAD tools, these functions operate on two levels: semantic, which entails the relationships between concepts, and the syntactic, which entails the use of language and lower level controls to interact with the concepts. Information processing theory was developed as a means to inform and explain this interaction (Gredler, 2001).

Memory

Information processing theory evolved from the study of human memory and cognition using a computer systems approach. However, these approaches did not account for the humanistic construction of meaning based on context (Gredler, 2001). The cognitivist perspective to learning uses information processing theory as its central theme: the receiving, coding, and remembering of information. Individuals transform much of their sensory input into memory codes for later use. Based on the process of perceiving, comprehending, and storing information, an individual uses their prior knowledge to organize information to be learned (Gredler, 2001; Driscoll, 2000). Two basic assumptions underlie the cognitivist perspective: (1) memory is an active and organized processor of information, and (2) prior knowledge plays an important role in learning (Gredler, 2001; Johnson-Laird, 2000). Related to these assumptions are ideas about the basic nature of human memory, the ways that particular knowledge items are represented in long-term memory, and the way that bodies of knowledge are organized in long-term memory.

Human memory actively selects the stimuli that it will process and retain, and information processing theory literature recognizes four different perspectives on the functioning of human memory. The multistage approach (Broadbent, 1958) considers memory to be a series of stages through which stimuli pass. The sensory registers receive incoming stimuli, and pass it to the short-term store to begin the encoding process. Working memory further transforms the information by encoding it into a particular format, and long-term memory stores the information as assimilated knowledge to be recalled as necessary in the future. The executive control function manages and directs this entire process.

This particular version of the theory of memory was disputed by Edelman (1987) due to the fact that it lacks a definitive capacity for each structure and that it favors constancy of processes over the wide variations that naturally occur in humans. Tulving (1985) also advocated a long-term store of memory, but it was comprised of different systems, each with its own purpose and procedures. Episodic memory is composed of personal or autobiographical information that is associated to a particular time or place in a person’s life experiences. Procedural memory deals with the individual’s ability to adapt to the environment through the performance of tasks. Semantic memory is composed of general knowledge and facts. Semantic memory allows a person to construct mental models of the world around them (mental models will be discussed later in this literature review). Also, by combining procedural and declarative knowledge (semantic plus episodic), one is able to employ strategic knowledge to perform complex tasks and operations (Wickens & Hollands, 2000). Strategic knowledge will be discussed later in terms of technological knowledge and its relationship to CAD tools.

The state concept of memory describes working memory as the active state of memory (Gredler, 2001). This is where stimuli are encoded and meaning is constructed. This view of memory also describes long-term memory as inactive; it is only a warehouse of information. The focus of this approach is not the act of processing information, but the change of state when information is recalled from an inactive to an active state. This perspective also has the ability to handle automatic as well as working memory tasks at the same time.

A third perspective on memory is known as levels of processing (Craik & Lockhart, 1972). In this case, memory is a by-product of perceptual analyses that occur in sequential, hierarchical levels: sensory analysis, pattern recognition, and semantic association. Individuals are assessed according to their "depth" of understanding, but this is a qualitative measure. One cannot determine "depth" of understanding independently of the amount of information remembered (Neath, 1998).

The fourth modern conception of memory is the connectionist (neural) network. These consist of simple processing units, known as nodes, with links between them (Neath, 1998). Memory is a series of these interdependent networks, and knowledge is embodies in the links between them (Schneider & Graham, 1992). Processing occurs in simple elements as the links transfer knowledge between the networks.

The multistage concept, however, still remains the dominant perspective in the description of human memory (Gredler, 2001; Wickens & Hollands, 2000) and will be used throughout the remainder of the discussion in this section. While the mechanisms of human memory are important for the understanding of how information gets processed, it is the storage format and subsequent organization of that information in memory that is critical in the performance of daily activities, including the operation and effective use of a constraint-based CAD tool.

Knowledge Representation in Long Term memory

Representation of knowledge in long-term memory typically takes some type of symbolic form. Early views of long-term memory describe the storage of information as specific items, whereas later views of long-term memory discuss that storage in terms of larger bodies of knowledge. The stored form of the information is not identical to the stimulus because signals received by the senses are not perfect representations of the physical world. The information is transformed so that it is remembered, either in a dual code approach suggested by Paivio (1986) or in a verbal-only format.

The dual code model suggests that information can be stored in nonverbal or verbal form: abstract concepts and events are stored in verbal form, and sounds, actions, and concrete concepts are stored in the nonverbal form (Paivio, 1986). Some objects and events are actually stored both ways, and the particular recall depends on the stimulus, instructions, and context at the time. The dual code model incorporates the additive effects of imagery and verbal codes. However, opponents argue that visual image storage would overload the brain capacity and it would require a separate, internal "perceiver" in order to comprehend the images. Visual encoding theorists stipulate that the stored codes are not pictures per se, but that they are analog representations that are only manifested with the proper combination of stimulus and context, similar to a lock and key. There is only one form of key for a any given lock.

Verbal theorists do not necessarily question the validity of visual imagery as a means to process knowledge, but they maintain that the imagery is a reconstruction of verbal codes (Anderson, 1990). Two types of knowledge are generally represented by verbal coding schemes: declarative knowledge and procedural knowledge. Declarative knowledge tends to be factual items composed of base strings of meaning and comparative information that places it in context. It becomes the smallest unit of meaning used within a structure called a propositional network. These networks allow a person to test what they are experiencing in the current situation against what they have experienced as fact in the past using the context of the aforementioned comparative information (Anderson, 1990). Procedural knowledge is comprised of coded information that describes a process, and it is enabled through condition-action pairs, which take the form of if-then statements (Anderson, 1993; Newell & Simon, 1972).

Once information has been represented as knowledge in the form of verbal and nonverbal codes, or as a propositional network in long-term memory, it is then organized in a useful way for the individual. There are many different terms for the way knowledge is organized, but they all focus on the ability of the individual to recall the stored information and use it in a meaningful way in everyday life activities. Some of those terms are domain knowledge, schema, content-specific knowledge, mental model, and topic knowledge (Alexander, 1992; Alexander, Schallert & Hare, 1991; Johnson-Laird, 1983). Although explicit definitions are lacking in many cases, analyses of the typical implied usage have determined certain relationships between some of the various terms (Alexander et al., 1991). The term “mental model” will be used for the purposes of this study and will be explained in detail in a following section. Generally, two broad categories are used to describe the knowledge stored in long-term memory independent of the structure in which it is stored (Gredler, 2001): tacit knowledge and explicit knowledge, with the latter being divided into conceptual and metacognitive knowledge.

Tacit knowledge is generally known as implied knowledge. It operates below the level of consciousness usually, and it is highly indicative of those individuals that exhibit expertise within a particular domain (Gredler, 2001). Its relationship to expertise will be discussed in a later section. In addition, those that have a high level of tacit knowledge regarding a particular subject tend to have difficulty expressing that knowledge verbally due to the fact that they do not often think specifically about the actions that they use to perform a task (Anderson, 1993; Ericsson & Smith, 1991). Tacit knowledge is an area where procedural and declarative knowledge begin to merge to form a higher-level knowledge, such as a script, template or prototype (Gentner & Stevens, 1983). A script is an example of tacit knowledge, and humans use scripts as guides in common, familiar situations, such as school, work, or social functions. Tacit knowledge will be further described later in this review in relation technological knowledge.

Explicit knowledge, on the other hand, is available to the consciousness of a person and it is the object of their active thought process. One type of explicit knowledge is metacognition. Metacognition encompasses an individual’s strategies for learning new information and the knowledge of oneself as a learner (Alexander, et al., 1991), and it typically focuses on the regulation of one’s own learning methods. For example, if one encounters a word that he or she does not understand, they are often able to figure out the meaning based on context of the sentence. The strategy that they use is an example of metacognition.

Metacognition is affected by three internal states of the learner: domain knowledge, goal orientation, and self efficacy (Zimmerman, 1995). For learners that are well versed in a domain (experts), metacognition only serves a minor enhancement function in their development. If a person is actively trying to achieve mastery of a body of knowledge, their metacognitive strategies will be enhanced. If they are only trying to "pass", then they will not develop effective metacognitive strategies. Differences in metacognitive strategies occur between older and younger people and experts and novices within a particular domain. The differences between experts and novices will be discussed in a later section of this literature review.

The second broad category of explicit knowledge is conceptual knowledge, and it is comprised of concepts, their accompanying context, and the meaning to the individual (Gredler, 2001; Alexander, 1992). Conceptual knowledge is topic-related and relevant to knowledge about communications, and it is one of the items that form the basis of mental models that will be discussed in the next section. Conceptual knowledge is divided into two parts: content knowledge and discourse knowledge (Alexander, 1992). Discourse knowledge concerns language and its use, and it may be formal or informal. It includes text-structure knowledge, which is the understanding of the frames and forms of text; syntactic knowledge, which is the conventions of language and its use; and rhetorical knowledge, which is the sense of audience and style that accompanies language and its use. Content knowledge is information about one's physical, mental, and social world, and it too may be formal or informal. Content knowledge, as will be discussed later, helps to form the content of an individual's mental model and their understanding of a particular topic area. Concept knowledge is composed of domain knowledge and discipline knowledge (Alexander, 1992). Domain knowledge is specific to an area or discipline, such as constraint-based CAD; where as discipline knowledge is extensive academic knowledge in a particular field, such as engineering graphics or technology education. Domain knowledge tends to be very specific and narrow in scope compared to discipline knowledge.

One particular form of knowledge organization that helps individuals cope with situations in which information might be missing or vague is a schema. Schemata are knowledge organizations based on past experiences, level of knowledge within an area, and future expectations (Neath, 1998; Driscoll, 2000). They provide a framework to accommodate new information, and they serve as a guide for future activity. They tend to fill in gaps when current information is incomplete. However, they tend to be vague and are not necessarily useful for making wide-ranging predictions (Neath, 1998). There are many debates about what the schemata for a particular situation should or should not include.

While schemata are not included as essential types of knowledge because the term has multiple interpretations and no fixed definition (Alexander, et al., 1991), they are useful for educators as a way to explain how students may assimilate information. Schemata help explain the process of acquiring information and organizing it according to events or knowledge from the past, which is relevant to this study from the perspective of the experiences that lead to the development of expertise in constraint-based CAD. Although schemata often tend to be vague in their description of a particular topic, they take advantage of a person's tacit, procedural, and declarative knowledge to aid in the processing of new information based on what one has encountered previously. A schema is not an image or specific instance of a phenomenon per se, but it is the model that underlies the ability to form an image (Johnson-Laird, 1983). Mental models are representative samples of the sets of knowledge that they typify (Johnson, Laird, 1983), and they are often (mistakenly) used interchangeably with the concept of schemata. Educators tend to prefer the term "schema", while cognitive psychology tends to prefer the term "mental model" (Johnson-Laird, 1983. p.x-xi; Gredler, 2001, p. 180), but they are in fact slightly different.

A schema is a hypothetical mental structure for representing generic concepts stored in memory. It is a sort of framework, plan, or script. According to Stein and Trabasso (1982), schemata are thought to have certain distinctive features. Schemata are composed of generic or abstract knowledge used to guide encoding, organization, and retrieval of information, and they reflect prototypical properties of experiences encountered by an individual, integrated over many instances. A schema may be formed and used without the individual's conscious awareness, and although they are assumed to reflect an individual's experience, they are shared across individuals within a culture. Once formed, schemata are thought to be relatively stable over time. Driscoll (2000) suggests that a schema is analogous to a play, in that it has a basic script, but each time it is performed, the details will differ. It is also analogous to a theory, in that it enables us to make predictions from incomplete information, by filling in the missing details with "default values", but this can be a problem when it causes us to remember things we never actually saw. And finally, it is analogous to a computer program, in that it enables us to actively evaluate and parse incoming information.

The previous discussion relates to constraint-based CAD from the perspective of human-computer interaction. Interactive CAD tools are complex systems that require a user to process a great deal of incoming stimuli and transform that into usable information (Majchrzak, et al., 1987). If the way a designer processes information can be determined, then automated systems to carry out more mundane tasks can be created. While automation is not necessarily the focus in this study, acquisition of the schemata used by constraint-based CAD experts will aid engineering graphics educators in the selection of content for their lessons.

Cognitive theories center on how people store information, retrieve it for use, transform that information to solve problems and make decisions, and carry out particular responses (Gredler, 2001; Wickens & Hollands, 2000). This is often thought of as a bottom-up and a top-down process. It is bottom-up in the sense that we receive sensory inputs to be manipulated by the rest of the cognitive system, and we use prior information and cognitive processing to determine which sensory inputs will be selected for further processing. In the use of CAD tools, experts are able to operate between these to levels with relative ease (Bhavnani, 1997).

According to Majchrzak et al. (1987), a CAD user tends to process information in four steps: attending to graphic stimuli which appear on the screen, recognizing familiar patterns while acquiring and integrating new information, assessing the new design with respect to needed modifications, and deciding on a response as to change or keep the design. However, this is rather simplistic for constraint-based CAD use considering the internal and external considerations which must be accounted for, and the notion of “modify” and “redefine”, as opposed to “delete and recreate” (Hanratty, 1995; Bertoline & Wiebe, 2001).

Majchrzak et al. (1987), also states that decision making can be divided into three categories with respect to CAD: prediction, choice, and diagnosis. In choice decision making, the human makes a decision between two hypotheses. However, with the use of constraint-based CAD, it is likely that there would be more than two alternatives. In addition, humans tend to become anchored to their first choice without giving alternative hypotheses their just consideration (Wickens & Hollands, 2000). In diagnosis decision making, the operator must consider several hypotheses to determine the cause of the problem. This is particularly evident when a designer must correct a design. Especially in the use of constraint-based CAD, it can be precarious given the nature of the parent/child references that have been built into the model. This is because humans often tend to use non-optimal decision making strategies that are supported by the heuristics that they develop in natural environments (Wickens & Hollands, 2000). These can often lead to problems, because people tend to stop processing information once the conditions for the heuristic have been met, although heuristics do allow experts to work quickly (Gredler, 2001; Wickens & Hollands, 2000). Expert CAD operators spent 96% of time on physical operations and 4% on mental operations. Novices devoted considerably more time to mental operations because they needed more time to think about what they were doing (Bhavnani et al., 1997, 1998).

The previous discussion of the information processing models forms a basis for the remaining portion of this literature review addressing the definition and development of expertise in the use of constraint-based CAD. Tacit knowledge and content knowledge, typically embodied in relevant schemata or mental models, form the basis for identifying incoming information. Tacit knowledge and content knowledge also control the inferences made about new information. Recall that the components of content knowledge are domain and discipline knowledge that address the processing, organization, and use of knowledge relevant to specific areas of study. According to

DeVore (1964) and Herschbach (1995), technology is a discipline that contains many domains in which to employ technological knowledge. The remaining portions of this literature review will examine mental models in greater detail followed by a discussion of expertise from the viewpoint of cognitive psychology and sociology. Finally, a discussion of how these topics relate to technological knowledge and the strategic use of CAD will follow.

MENTAL MODELS

Mental models go beyond schema theory to include perceptions of task demands and task performances. Mental models include how people perform tasks and solve problems in specific contexts (Driscoll, 2000). In addition, the scope and depth of a person's mental model is in large part affected by their experiences within a particular domain. The characteristics of their mental model aid them in their problem solving abilities, and there are marked differences in the literature between individuals with varying levels of expertise in a particular domain (Gredler, 2001). Mental-models combine a schema or mental representation with a process for manipulating the information in the schema. Solving a problem requires the learner to not only have the appropriate knowledge representation (schema or knowledge structure) but he or she must also have algorithms or heuristics for manipulating these knowledge components in order to solve problems (Merrill, 1999). While there are many views as to the notion of the human mind, all of them have as a central tenet the idea of a "representation".

Individuals construct models of the world as a way to cope with the continuous input that they receive (Gardner, et al., 1998). While there are various cultural applications, the underlying meanings remain the same. A competing theory, connectionism, maintains that the mind is composed of neural networks made up of a collection of nodes and the meaningful links that associate them (Churchland, 1989; Hinton, 1993). Both theories tend to agree that various cognitive patterns or models have emerged, including domains, frameworks, cognitive maps and patterns. The differences simply lie in the way and to what extent each one is used (Gardner, et al., 1998). For this study, the concept of mental models will be used due to their close alignment with information processing.

Mental models were first postulated by the Scottish psychologist Kenneth Craik (1943), who wrote that the mind constructs "small-scale models" of reality that it uses to anticipate events, to reason, and to underlie explanation. Human beings construct mental models of the world, and they do so by employing tacit mental processes (Johnson-Laird, 1983). Mental logic, the relationship of mental representations and language, the grammatical relationships that govern the conveyance of ideas through sentences and their parts, the meaning of discourse and language, and the nature of self awareness are all governed by the concept and scope of a person's mental models. This concept entails recursive mental processes that enable human being to understand discourse, to form mental models of the real and imaginary, and to reason by manipulating such models (Johnson-Laird, 1983).

As stated previously, mental models are representative samples of the sets of knowledge that they typify (Johnson-Laird, 1983). They are unique to each individual in that they represent a "typical" instance of a concept. For example, one could have a mental model of a constraint-based CAD tool. While there are many different types and vendors of this type of software, contemporary CAD tools tend to operate in a similar fashion (Wiebe, 1999). This same type of similarity can be found in many of the technological devices people use on a daily basis, such as cars, appliances, and tools. Johnson-Laird (1983) proposes mental models as the basic structure of cognition. Mental models play a central role in representing objects, states of affairs, sequences of events, the way the world is, and the social and psychological actions of daily life. They are comprised of certain common characteristics that apply to all examples of a given classification of a concept. Therefore, constraint-based CAD tools could be said to have certain common characteristics that could be used to explain their operation (Wiebe, 1999).

When examining mental models, one should account for four different things: the target system, which is the system that the person is learning or using; the user's mental model of the target system; the scientist's or designer's mental model of that system; and the conceptual model, which is invented by teachers, scientists, or engineers to be the accurate, consistent, and complete representation of the target system (Norman, 1983).

Mental models are evolving all of the time, and people form them through interaction with a target system. They do not necessarily have to be accurate, but they do have to be functional. Through continued interaction with the system, a person will arrive at a model that is workable for them.

However, mental models are constrained by the user's technical background, previous experiences with similar systems, and the structure of the human information processing system (Norman, 1983). According to Norman (1983), mental models in any domain tend to have the following general characteristics:

- Mental models are incomplete.
- A person's ability to "run" their models is severely limited.
- Mental models are unstable; people tend to forget the details if they do not use it for a long time.
- Mental models do not have firm boundaries; similar devices and operations get confused with one another.
- Mental models are unscientific; people maintain suspect behavior patterns even when they know they are unneeded because they have little physical cost and conserve mental resources.
- Mental models are parsimonious; often people do extra physical work in lieu of doing extra mental planning so as not to expend cognitive effort. This is especially true when one simple rule can apply to many devices, thereby reducing some of the potential confusion.

It is true that people often feel uncertain about their level of knowledge, even when it is complete and accurate, and their mental models will include statements about their degree of uncertainty (Norman, 1983). When individuals construct mental models they make explicit as little as possible and they focus on that information which is explicit in their models. Concomitantly, they fail to consider possibilities that lie outside their models. The consequence is that they may overlook the correct possibility. Many of the cognitive errors that have contributed to real-life disasters have exactly this form (Three Mile Island and the English Channel ferry).

In order to model a person's target system, one needs a good understanding of the conceptual system on which it is based (Norman, 1983). With respect to constraint based CAD, Bertoline & Wiebe (2001), Wiebe (1999), and Hanratty (1995) offer summary explanations of the conceptual characteristics of constraint-based CAD tools. Since conceptual models are devised as tools for understanding or teaching physical systems, and mental models are what people have in their heads as a working representation of that system, ideally there should be a direct and simple relationship between the conceptual model and the mental model. A major purpose of the mental model is inference or prediction so that a person does not necessarily have to "run" their model to obtain a particular state or result (Norman, 1983).

Ideally, when a system is constructed, the design will be based on the conceptual model (Norman, 1983). This conceptual model should also govern the human interface with this system, so that the system image seen by the user matches the conceptual model. Any instruction given to the user should then match the conceptual model so that the potential mental model formed by the user will match the conceptual model and the system image.

The conceptual model according to the previous point should fulfill three criteria: learnability, meaning that it should not be too difficult to learn; functionality, which means that it should closely correspond to the conceptual model; and usability, which means that it should not tax the human information processing mechanism (Norman, 1983). All too often though, there is not such correspondence between models. Mental models are often developed in a mechanistic fashion to aid in the understanding and troubleshooting of complex machines and systems or physical phenomena. This entails the development of a qualitative simulation "in the mind's eye" of how one expects the system to work. Through the evaluation of ambiguities within the systems, humans are able to develop a causal model of how the system operates. This causal model is linked to structural patterns that humans already understand and are also evident within the system being examined (de Kleer & Brown, 1983).

While not perfect in all situations, the mental model theory has been extensively tested, and the experiments have corroborated several obvious and common signs of the use of mental models. A mental model represents one possibility, capturing what is common to all the different ways in which the possibility may occur. Mental models also represent explicitly what is true, but not what is false. These characteristics lead naive learners into systematic errors. The greater the number of models that a task elicits, and the greater the complexity of individual models, the poorer performance is. Learners focus on a subset of the possible models of multiple-model problems - often just a single model - and are led to erroneous conclusions and irrational decisions. Procedures for reasoning with mental models rely on counterexamples to refute invalid inferences; they establish validity by ensuring that a conclusion holds over all the models of the premises. These procedures can be implemented in a formal system; however current psychological theories based on formal rules (and most artificial intelligence programs) do not use them (Johnson-Laird, 2000; Byrne, 1990).

Mental models also provide a unified account of deductive, probabilistic, and modal reasoning. People deduce that a conclusion is necessary if it holds true in all of their models of the premises. They also infer that it is probable or likely to be true if it holds in most of their models of the premises. They infer that it is possible - it may be true - if it holds in at least one of their models of the premises (Johnson-Laird, 2000; Byrne, 1990). The classical theory of decision making, whatever its status as a specification of rationality, does not begin to explain the mental processes underlying decisions. On the one hand, the theory is radically incomplete: it has nothing to say about when one should decide to make a decision, or how one should determine the range of options and assess the utilities of their various outcomes. On the other hand, the theory conflicts with the evidence on how people reach decisions in daily life: their conspicuous failure to maximize expected utility has led some theorists to worry about human rationality and other theorists, notably Simon (1959), to argue for a different criterion for human decisions.

Mental models form the basis for the organization of knowledge that humans have regarding a particular phenomenon or system. While they may be incomplete in some cases, they provide a sufficient description in most cases for effective interaction between the individual and the target concept or phenomenon. Some mental models are more elaborate than other models, which leads to a better and deeper understanding of the phenomenon in question (Gredler, 2001), and that is characteristic of an expert individual in a particular knowledge domain.

As stated in the Introduction, one of the research questions for this study involves the definition of expertise in the use of constraint-based CAD. This definition will likely be a result of the examination of many characteristics of expert CAD users, and one of those characteristics is likely to be an elaborate mental model of the constraint-based CAD domain (Gredler, 2001; Bhavnani, 1999). However, before discussing CAD-specific domain knowledge, a discussion of expertise is warranted not only from a psychological perspective related to the characteristics of an individual, but also from the perspective of the social role that experts play within an organization.

EXPERTISE

General Characteristics of Expertise

Expertise began to be studied as an aside to the development of expert computing systems. Investigations into the mental processes and strategies of chess players (deGroot, 1966; Newell & Simon, 1972) are seen as the seminal knowledge-based studies into this area. It was obvious that specialized knowledge structures existed within the minds of the chess grandmasters, but the chunks that the experts used needed to be identified and quantified. Expertise research became more about knowledge-based research and the mapping of the search process that an expert must engage in to operate in a highly specialized knowledge domain (Glaser & Chi, 1988).

Expertise has been studied and assessed in a variety of domains and disciplines, including medical diagnosis, business management, software design, finance, typewriting, waiting tables, solving mathematics and physics problems, and the judicial process (Chi, Glaser, & Farr, 1988). The following points characterize the general characteristics of expertise across the domains that have been studied. They are robust, and they exhibit robust predictive capabilities (Chi, Glaser, & Rees, 1982; Posner, 1988).

- Experts excel primarily within their own knowledge domain. Their depth and breadth of knowledge in one domain make it difficult to transfer that knowledge to another domain whose structure is likely different. A person cannot know everything.

- Experts perceive large, meaningful patterns within their domains. This is not necessarily related to their perceptual abilities, but to the organization of their knowledge base. They are able to chunk information in larger, more conceptual chunks.
- Experts are fast; they are faster than novices at performing the skills within their domain, and they solve problems quickly with few errors. This speed comes from many hours of practice, greater ability to chunk information in memory, and less time spent searching for information due to their extensive domain knowledge.
- Experts have superior short- and long-term memory. They do not have *more* memory; they just use their memory more efficiently, especially in regard to the chunking strategies mentioned previously.
- Experts represent problems within their domain at a deeper, more principled level. Experts' categorizations of problems typically are based on semantics and not on syntactic information.
- Experts spend a great deal of time analyzing a problem qualitatively. They tend to develop an understanding and scope of the problem right away. Experts build a mental representation (model) of the problem so that they can evaluate relationships and constraints of the situation. This is especially helpful in ill-defined or non-routing problem situations.
- Experts have strong self-monitoring skills. They are more readily able to determine when they have made an error and to select an appropriate course of action to address that error. This is typically due to their greater domain knowledge and a motivation for attainment of expertise in a particular domain.

These characteristics of experts tend to show that there is a relationship between knowledge structure and processing abilities and problem solving. They are reflective of an expert's high level of conceptual and procedural knowledge that can be readily accessed and used with superior monitoring skills. All of these areas have deduced that expertise has several common characteristics. But can these characteristics be translated to *all* other domains and disciplines? In the final section of this literature review, technological knowledge and the effective use of CAD strategies will be discussed. But, as one of the research questions asks, do experts in the use of constraint-based CAD exhibit similar characteristics as experts in other domains? If so, then the domain of constraint-based CAD may be able to be assessed and studied to the same depth as these other domains. To aid in making that determination, a brief discussion is provided for several of the characteristics that describe an expert within a given domain.

Learning and Metacognition

One of the underlying themes of the development of expertise from a cognitive perspective is the performance of an individual in a complex learning environment. These environments are quite prevalent, especially in the physical sciences and technology domains (Gredler, 2001; Feltovich, et al., 1997). As discussed previously, metacognition plays a key role in the way an individual establishes and maintains their learning methods. An individual defines the task and generates a perception of the given situation. They then proceed to setting goals and defining a plan. Next, they enact the strategies of their plan, and finally they adapt according to the results of their current actions (Winne & Hadwin, 1998).

Differences in metacognitive abilities generally occur in younger versus older children and experts versus novices. While the differences between younger and older children can be attributed to physical maturation and increasing experience in an academic environment (Gredler, 2001), they are not the focus of this study. When learning a new topic, experts tend to have different tactics than do novices. For example, in reading tasks, experts tend to revise their hypotheses for the problem scope, devote more time and effort to difficult tasks, address difficulties before they become major problems, use available resources effectively and efficiently, and employ more flexible strategies (Rohrer, & Thomas, 1989). By having such command of their capabilities, experts ultimately become better problem solvers than do novices.

Problem Solving

In general, problem solving involves dealing with new and unfamiliar tasks when the relevant solution methods are not known (Schoenfeld, 1992, p.354). A problem typically consists of three components: the givens, a goal, and the allowable operators (Dominowski & Bourne, 1994). The givens are the elements of the problem, the surrounding conditions, and the relationships among the two of them. The goal is the desired outcome, and the allowable operators are the steps or procedures that transform the givens into goals. Problem scenarios often include obstacles, which are characterized as those things that prevent the transformation of the givens into the goals.

Another factor to consider according to Mayer & Wittrock (1996) is the degree to which given problems lie along the continua of definition and frequency. Well-defined problems are those that contain information necessary to address the givens, goals, and operators. Ill-defined problems are just the opposite; they are missing all or part of that information. In addition, problems may be routine, which are those problems that have been solved in the past, or non-routine, which are those problems that have not been solved in the past and are not immediately recognizable. Many CAD scenarios correspond to the non-routine, ill-defined types of problems (Majchrzak, 1987; Bhavnani, 1998), and this is only further exacerbated by the advent of constraint-based CAD.

In the 1970s, much of the problem solving literature focused in three areas: the general problem solver (GPS) (Newell & Simon, 1972), use of heuristics (Polya, 1973), and artificial intelligence research (Bereiter, 1991). The GPS system used means-end analysis as a way to analyze sub-goals of a problem to maintain progress towards the specified goal. Heuristics were rules-of-thumb that tended to lack any real specificity when it came to actually solving a problem. They were intended to only reduce uncertainty within a setting. And artificial intelligence research, while it typically was domain-specific, never was able to capture the most complex human thought processes; only the simple ones were captured with any regularity. All of these problem-solving methodologies lacked sufficient domain-specific knowledge.

According to Chi, Glaser, and Farr (1991), expertise requires the use of domain-specific knowledge, not heuristics, and the focus of expert problem solving has shifted towards the examination of metacognitive strategies based on mental models and long-term memory. The following elements encompass the basis for metacognitive problem solving (Mayer & Wittrock, 1996; Davidson & Sternberg, 1998) (metacognitive skills are in parentheses):

- Represent the problem: identify the most relevant features and create a “mental map” of the situation. This would include selective recoding, combination and comparison when necessary, which would result in a new mental representation of the problem (access content or intuitive knowledge about the domain or metacognitive knowledge about particular problem approaches or strategies in long-term memory).
- Planning: consider tactics and strategies *before* implementation to gauge potential consequences (review and select plans and strategies; access long-term memory when necessary to aid in plan construction).
- Overcome obstacles: potentially, inability to generate plans or procedures or fixation on a specific (usually incorrect) solution (access long-term memory for analogies, metaphors, or models that may provide a new perspective on the problem; initiate selective recoding, combination, and comparison procedures).
- Execute the plan: requires self-monitoring of the situation to stay on course (use of metacognitive strategies to stay on course and to evaluate one’s own progress).

Efforts in the 1960s to simulate human thinking capabilities in a computer program led to the research in an area known as artificial intelligence (AI) and an increased interest and awareness in the development of human expertise (Chi, Glaser, & Farr, 1988, p.xv). This research as led to the general characteristics of expertise listed in the first part of this section. However, the characteristics of expert problem-solvers, with respect to their depth of knowledge and their problem-solving strategies, are summarized in the following paragraphs (Chi, Glaser, & Rees, 1982; Greeno, 1978; Glaser & Chi, 1988; Larkin, 1980; Sternberg, 1998).

The knowledge structures of experts are organized around the phenomena in a domain in relation to higher order principles. The organization of experts’ domain or discipline knowledge has implications for problem solving. Experts, particularly in the sciences, use specific schema to classify and code problems and their solutions. With time and experience, the problem and its solution become so closely attached within the problem schema that future activation of the problem-solution strategy pairs becomes automatic. For experts, strategies become part of the knowledge base in their respective domain. Experts are also more efficient in their short- and long-term usage, because their memories are “chunked” at a conceptual level as opposed to a factual level. Experts do not have more memory capacity; they simply use what they have more efficiently.

Experts also have increased metacognitive skills and strategies for monitoring their own performance. Experts tend to spend large amounts of time developing and constructing representations for the problems they encounter. By having an elaborate model as a guide, experts are able to insert the given information more efficiently. Experts also tend to represent problems at the basic conceptual levels of their domain, as opposed to using superficial details to determine a solution. Experts also tend to work forward from the given information by applying their well-developed problem schemata. This allows them to expend little mental effort on problems that they have seen and solved previously. In working towards the unknown entities in a problem description, experts also employ the context of the situation as an aid.

Experts also tend to spend more time planning their approach and tactics for a problem solution, as well engaging in the use of self-monitoring strategies from the beginning. They rigorously test potential schemata for their problem situation, and they evaluate and discard those that do not seem to work in any given situation, as well as adjust those that do seem to have worked in a given situation.

Decision Making and Expertise

An expert is considered to have experience at making predictions and performing processes within a specific domain and one who has some type of professional or social credentials. While experts are often credited with superior memory, planning, mental models, and problem solving abilities within a particular domain, they also have several faults (Camerer & Johnson, 1991).

Experts are not as accurate at prediction as statistical models, and in fact only slightly more accurate at prediction than novices (Camerer & Johnson, 1991). But they have the ability to assess and correct their own inaccuracies in judgement, which gives them an intuition as to how “accurate” they are when making a prediction. Experts also tend to fixate on a solution given their use of heuristics, while less-outstanding performers will work through a problem step-by-step. Experts have a speed advantage this way, but they also make a trade-off with potential inaccuracy (Gredler, 2001).

When experts evaluate information to make a decision, they often use more elaborate search and analysis processes than do non-experts. They also have to search less, because they have greater knowledge stores organized in memory (Camerer & Johnson, 1991). Experts use configural rules to scope a problem and decision space. They do so because configural rules are easier to process which leads to less cognitive resources being expended. In addition, configural rules are often used to explain and store past experiences. However, they can be inaccurate due to their incorporation with heuristics in applying the rules to a larger class of situations. This can take the heuristic and the configural rule out of its original context. This can result from slow, inaccurate, or non-existent feedback. While experts may not necessarily be better at prediction than non-experts, they are extremely useful for measuring variables in a situation or for discovering new ones (Ericsson & Smith, 1991).

While there has been a great deal of discussion and research concerning the cognitive aspects of expertise, there is also a social side to this phenomenon. In this case, expertise is based on the attribution of expert characteristics from one individual to another individual within their group or organization. Expertise established in this manner is not as concerned with the embodiment of expert traits in a person as it is the exchange of knowledge from a person who has it to a person who needs it.

SOCIAL ASPECTS OF EXPERTISE AND THE PROFESSIONS

Professions are knowledge-based occupations and therefore the nature of their knowledge, the socio-cultural evaluation of their knowledge, and the occupation’s strategies of handling their knowledge base are of central importance (Macdonald, 1995). Society makes distinctions between occupations based on their degree of “certified and credentialed” knowledge (Weber, 1978). Typically this is done through the awarding of a degree or certificate to attest to one’s attainment of a certain level of professional knowledge. This places value on the knowledge held by these individuals. In many cases, this formal action leads to the informal adoption of those people as experts within a particular field (Macdonald, 1995).

The tasks of professions are generally performed by experts, the degree of which and the knowledge required for performance varies from time to time and place to place (Abbott, 1988). Most problems eventually shift from esoteric knowledge bases to information that is widely distributed among the laypeople. This shift, however, tends to be slow in the realm of objective problems (those characterized by natural phenomena or technological advances). Generally speaking, advances in technology has provided professions with a new opportunity for advancement in their work, and this advancement tends to occur on the fringe of the jurisdiction of the profession where a practitioner once relied on a service provider and now relies on an expert system (Macdonald, 1995). By embracing this type of technology, the practitioner survives and maintains the jurisdictional boundaries of his or her profession.

Societies tend to structure their expertise within a professional domain, and the basis for this is personally held resources, whether of knowledge or wealth. A profession is always vulnerable to changes in the objective character of its central tasks (Abbott, 1988). However, Macdonald (1995) contends that it is the constant pursuit of the professional project by practitioners that holds at bay the competitive forces that might be willing to overtake the professions as the chief repository of knowledge and expertise for a particular domain. This can be seen with engineering graphics and the integration of CAD. When 2D CAD was introduced, in many cases, it was no more than just an electronic drafting board. However, with the inherent intelligence and complexity of constraint-based CAD, industry and academia are seeing the need for a new breed of professional technologist to use this system (Branoff & Hartman, 2002). Abbott (1988) contends that computers and the advent of the computing technology have transformed certain professions by creating new areas of work and merging old ones. This is indicative of engineering graphics and graphics in general. Computing technology and associated software has led to the rise of animation and simulation, finite element analysis, and 3D modeling in engineering graphics, while all but eliminating the status of the detail drawing.

Subjective changes also have an impact on the need for and degree of expertise within a given profession (Abbott, 1988). An immediate example of this is the taxonomy of engineer-technologist-technician that is evident within engineering and technology education today as discussed by the Accreditation Board for Engineering and Technology (1977). Each of these disciplines use constraint-based CAD tools, but the debate within professional and academic circles is over the extent and degree of use for certain subjects and technologies.

Academic knowledge, with its organization along abstract lines, allows for the generation of new lines of inquiry and inference methods. Academic knowledge excels at invention; while it may make predictions that seem nonsensical at first, they can eventually re-shape professional knowledge altogether (Abbott, 1988). Hence the importance of examining the mental model of expert constraint-based CAD users – to gain insight into the structure of the professional knowledge base, and to use it as a basis for academic knowledge.

Based on the discussion of expertise in terms of Ericsson and Smith (1991), one question still remains. Does the cognitive psychology explanation of expertise encompass all there is to know about experts and their development of expertise? In many cases, the experts, according to the cognitive psychology frame of reference, were the ones with high task performance, the best performance, or professional status within a particular domain. This leads one to ask whether all professionals are experts that exhibit outstanding performance, and are there any professions without any experts or expertise (Mieg, 2001)?

Based on a discussion of experts-in-context, Agnew, Ford, and Hayes (1997) suggest that an expert and their expertise are actually the embodiment of a social *role* that needs to be fulfilled within a group or organization. There are two traditions for studying expertise: psychology, as discussed previously, and the sociology of the professions. This leads to a shift in the discussion of expertise in terms of professionalism, instead of performance. Scribner (1984) wrote about working intelligence and concluded that expertise is a function of experience. The specialty of experts can now be attributed to superior performance based on specialized experience (Mieg, 2001). There is a difference between experience and knowledge. An expert-by-experience must be an expert *in* a field, but an expert-by-knowledge can be an expert *about* a field, which is all too common in the field of academics (Mieg, 2001). Hence, to extrapolate to the domain of constraint-based CAD, it is imperative to capture the knowledge of practicing professionals in order to provide more accurate and timely instruction. According to Hoffman, Feltovich, and Ford (1997), the "minimum unit of analysis" is the "expert-in-context".

This social role is based on one basic premise: There is someone who seems to have knowledge that someone else is in need of (Simmel, 1971). The interaction is essentially based on an exchange of information from the person who is asked to the person who is asking. However, the person being asked (the expert) rarely gets an equal value of information in exchange for their answer. Social psychology is concerned with the interactions between persons and situations, and, in some cases, groups, organization, and personal relationships define the situations. The same is also true for experts (Mieg, 2001).

In his study of the sociology of science, Collins (1985) found that it takes time and experience to become capable of conducting a scientific experiment – "…like a skill, it cannot be fully explained or absolutely established" (p.73). According to Clancey (1997, p.263), "To understand the idea that knowledge is inherently social, as well as inherently neural, we must first understand that human action is inherently social." Knowledge is an instrumental means to social activity, and knowledge is given a value within those socially constructed activities (Clancey, 1997). This notion underscores Clancey's idea of situated cognition. According to the situated cognition approach, experience strongly depends on a physical environment; in particular, it involves the use of instruments and artifacts, such as in the case of constraint-based CAD. Expertise is not easily attributed to stable characteristics of a person as advocated in the empirical cognitive psychology approach; it is more appropriate to have an expert-in-context (Mieg, 2001). This indicates that an increase in experience equates to an increasing adaptation to a specific work setting.

Expertise is relative to a particular time and place and body of knowledge, and others use it only in that particular context. This context is defined not only by the expert themselves, but also by the individuals who make use of others' expertise, the type of problem to be addressed, and the role of knowledge with that organization. Expertise in a sociological setting is not a type of person per se, but it is a form of interaction involving an attribution to a person – in this case, an attribution of expertise – thus, the term "expert-interaction" (Mieg, 2001). The social form of "the expert" defines a class of possible relations between members of a society, and the expert knowledge is the object of a social act (Mead, 1925). The social control through information is two-sided: Not only may the non-expert try to put into practice the expert's advice, but the expert has to check what kind of information can serve as expert advice.

Expertise is also a phenomenon concerned with the interpretation of knowledge within a particular context. Typically experts are people that are considered *qualified* in some respect, and according to Heider's (1958) philosophy regarding interpersonal relations, this occurs through attribution theory in which one person attributes certain characteristics to another person. In this case, those characteristics are related to a particular knowledge domain. Hence, the person acquiring the information applies truth to the "expert-interaction". It is a necessary presupposition to the "expert"-interaction. They expect that the knowledge will be interpreted in their best interest (Mieg, 2001), and that it will be objective in the social sense. Their reason for soliciting the help of the expert is to realize a gain in speed and efficiency. It is likely they would have come to the same conclusion *if* they had time to have the same experiences as the expert. This requires that a person balance their need for control versus their willingness for a degree of uncertainty.

If people access experts for their knowledge, then why do they not just reference a book for what it is that they want? The answer refers to the *leistung* of the expert (Mieg, 2001). This concept summarizes the knowledge, status, and personal characteristics of the expert, which is what the non-expert is addressing with their inquiry. In general, people want to use an expert for their compressed experience and their ability to filter knowledge into a form that is usable in a specific situation. It is a time-efficient use of knowledge

(Mieg, 2001). Nearly everyone can be an expert in something at some point in time. It is likely that an expert in one area will be asked a question by an expert in another area, and vice versa. Knowledge is not information. Information requires interpretation, and that is what makes an expert useful in a social context (Mieg, 2001). Hence, when an expert has exhausted their domain knowledge and strategies in one area, it is likely they will ask another so-called expert for some help (Mieg, 2001).

As practicing professionals participate within a particular profession or industry, specific ways of knowing and strategies for understanding the business at hand are selected and reinforced. This is because they prove over time to have an effect on accomplishing important goals (DiBello & Kindred, 1992). Over the course of time, the culture of practice is passed on to new workers as they learn the norms of the profession or organization (DiBello, 2001). This particular set of goals and skills comprise the culture of any workplace. How workers understand their work and their role in the workplace affects how they do their job and what actions they take at various decision points (DiBello, 2001).

Even though expertise is based primarily on experience from a social perspective, some type of training or schooling is required. Ericsson and Charness (1997) described this as deliberate practice. Professionals are often considered experts; however, a professional's *leistung* is not the same as that of an expert in all respects. Professionals are often reluctant to explain matters in great detail, and they often serve multiple functions within their organizations (Mieg, 2001). Abbott (1988) described the following sequence of professional work: diagnosis, inference, and treatment. Diagnosis assembles the client's relevant needs into an image of the situation and then places the image in the proper diagnostic category. It not only seeks the correct category, but it also removes extraneous information. The inference stage uses information from the diagnosis stage, and it recommends a range of treatment based strictly on professional knowledge. Treatment involves the individual consultation with each person and their particular problem, and it tends to impose a rather subjective structure. While these examples happen to be in terms of medicine, it has a parallel within the realm of cognitive psychology. Anderson (1990) and Newell and Simon (1973) describe a three-step sequence for problem solving that is similar to the professional version suggested by Abbott: definition of the problem space (diagnosis), selection of operators (inference), and controlled execution (treatment).

Professions also contain academic knowledge, which is organized, abstract knowledge that ranges from common to esoteric and is available to all practicing professionals within the domain (Abbott, 1988). Academic knowledge also allows most professions to have an inherent knowledge base, such as that surrounding engineering graphics (Duff, 1990). Academic knowledge legitimizes professional work by clarifying its foundations and tracing them to major cultural values. Similar arguments are made by DeVore (1964) in his declarations of technology as a discipline. Professional work implies, in general, the interpretation of problems within a particular professional knowledge domain, and professionals engage in much more than just providing information, as can be seen by the fact that most of their information provision is tied to the making of a decision (Mieg, 2001). These decisions are not only made at the individual level, but also at the level of the organization.

Abbott (1988) also suggested that information should not only be institutionalized within individuals, but also within commodities and organizations. In doing so, institutions and organizations take on the social role of the “expert”. While “experts” are generally defined in terms of specialized knowledge, the knowledge that an expert provides is also relative. It depends on the social situation of the “expert”-interaction. However, “expert” knowledge depends on the knowledge background of an age. For example, in the domain of engineering graphics, an expert might have been consulted because of their knowledge of proper drawing techniques using an ink pen on linen paper. Now, an expert might be considered due to their knowledge of the concurrent engineering environment with respect to the creation of assembly models in a constraint-based CAD tool. But, there are various types of experts. Williams, Faulkner, and Fleck (1998) stressed the role of scientific uncertainty in experts’ disputes within a given domain. This generally occurs under the auspices of limited information and inadequate theoretical models. Luce and Raiffa (1957) note three decision-making situations: certainty, in which each action is known to lead to a specific outcome; risk, in which each action leads to a known outcome of specific probability; and uncertainty, in which each action leads to specific outcomes of unknown probabilities. In most cases, probabilities are unknown.

Models of decision making provide tools to capture uncertainties and structure to guide the decision-making process. From these, we can distinguish two uses of expert judgement. One is when expert judgement is simply part of the decision base, and the other is when expert judgement structures and guides the actual decision-making process (Otway & von Winterfeldt, 1992). Both of these uses for expert judgement appear in the domain of constraint-based CAD. By applying models of expert decision making, Mieg (2001) has advocated a typology of experts who might be addressed by the "expert"-interaction. This typology operates on the premise of dispositional attribution, which means that the attribution of expert characteristics presupposes expertise in the form of objective personal knowledge. Objective personal knowledge may be based on experience or academics. This particular dispositional attribution identifies experts with their expertise such that the role of the expert remains socially contingent (Williams, Faulkner, & Fleck, 1998). The typology also differentiates between domain-specific knowledge and formal knowledge, which is general knowledge to which everyone has access. There are also several types of domain knowledge: practical, scientific, exclusive, and local. The following list is a summary of this typology.

- Expert X is a single person with exclusive knowledge. Expert X appears when an expert attribution cannot be standardized (this happens often in smaller companies in terms of system integration and constraint-based CAD).
- Scientists are the pure forms of knowledge embodied in a person and used just for the sake of knowledge.
- Professionals are concerned with the practical application of knowledge with respect to specific uses. Abbott (1988) points out that the core element of professional work is to make an inference for a treatment from a diagnosis. This is generally done according to levels of acceptance among the various professions that have established them (Macdonald, 1995). Scientists tend to focus on causes and reasons, whereas professionals have expectations for procedural information.

- System experts have a sense of history and of the current state of the system. They provide the “what” explanations
- Decision experts do not necessarily know much about the problem content. They simply provide the “how” explanations and the procedures.
- Whatever the type of explanation might be, all experts act as interpreters of knowledge. This leads to the notion of using “experts” as heuristics – rules of thumb by which to make a decision and solve a problem (Margolis, 1996).

Based on the previous discussion, what is really the difference between a job and a profession? In most cases, a job is a singular event; something that a person does. But a profession is larger; it is something that a person participates in. According to Moore (1970, p.56), there is a distinction between a profession and an avocation. An avocation is based on customary activities and modified through the trial and error of individual practice. A profession involves the application of general principles to specific problems. Professions are highly specialized occupations that entail a highly substantive body of knowledge and the techniques of production or application of knowledge over which the specialist claims mastery. Such is the case in engineering graphics; technologists and engineers have knowledge of its underlying fundamentals and wield the tools to put that knowledge into practice.

While many disciplines are time-tested, those related to any kind of technology often find themselves in a state of flux. According to Schon (1983), however, the systematic knowledge base of a profession has four qualifying characteristics: specialization, bounded, scientific, and standardized. All of which characterize engineering graphics and the larger body of technological knowledge. In addition, Schein (1973, p.43) states that professional knowledge consists of an underlying discipline or basic science, an applied science or “engineering” component, and a skills and attitudes component. In addition, the format of technological schooling is such that the basic and applied sciences come first, and the practice follows. This allows a student to learn something to put into practice. The basic science of engineering graphics still centers around graphic science, visualization, and various projection theories, but the applied sciences portion of the profession deals with the tools and processes that manifest the embodiment of those basic scientific principles.

As stated previously, Moore (1970) considered there to be a difference between a profession and an avocation; professions examined solutions to problems, while avocations simply consisted of day-to-day occupational activities. One of the basic tenets of technology education is its search for solutions to problems between human kind and its environment (ITEA, 2000). In addition, Schon (1983) stated that the underlying knowledge base of any profession is comprised of four common elements. It is bounded to clearly delineate itself from other professions, and it is specialized so as to have jurisdiction over its own principles and techniques. Professional knowledge is also scientific in that it is simply more than trial and error; it is also troubleshooting and the development of solutions according to the constructs of the professional discipline. And finally, professional knowledge is standardized, so that each member of the profession understands his or her duties and obligations.

Technology education embodies all of the characteristics of a profession. It is bounded, standardized, and specialized according to the curriculum standards defined by ITEA (2001). Given its role in the development of solutions to problems, it is also scientific. The same things can be said for engineering graphics (Duff, 1990), which is a component of the communications portion of technology education.

The next section of this literature review discusses the idea of technological knowledge from two perspectives: its link to psychological aspects of expertise with regard to tacit and descriptive knowledge and problem solving and its relationship to practical knowledge and the practice of professional activities.

TECHNOLOGICAL KNOWLEDGE

In terms of technology, expertise can be defined as the knowledge or competence that a person can bring to bear on a situation (Hollnagel et al., 1995b). Often this competence, and the cognition that brings it about, is situated within a given context. An operator's competence with a technological system comes from basic education, training, and direct experience in working with the system (Hollnagel et al., 1995a). However, it only through extensive training and experience that the operator truly becomes familiar with the systems and its behavior (Samurcay, 1995).

According to Ihde (1997), there are several dimensions to technological knowledge. There is knowledge *about* technology; for example engineers and technicians understand how a machine functions. There is also *theoretical* technology knowledge, which consists of physical, electrical, or chemical laws. There is also knowledge *through* technologies, otherwise known as *praxical* or use knowledge. Much if not most domain knowledge is technologically dependent, whether that technology takes the form of tools, processes, or ideas, and it is constructed through the use of these instruments. This notion corresponds quite closely to the ideals of technology education where one of the emphases is on “learning by doing”.

Ihde (1997) argues that, in a very structured way, any “interesting” technology “non-neutrally transforms” the project or object towards which the technology is directed, and in a reflexive fashion, it also alters the human user of that technology.

CAD technology has transformed the way technologists and engineers work, as well as the knowledge based behind engineering graphics. Whatever knowledge we gain through the use of these tools also impacts our abilities and the ways in which we use the tools. The inclusion of praxical knowledge in the taxonomy of technological knowledge forces a much more critical approach to the results of experimentation. Pragmatism is necessary to constantly improve upon instrumentation and tools of the profession. Such is also the nature of engineering graphics; many authors have suggested improvement in the curriculum that includes the use of constraint-based CAD tools.

According to Herschbach (1995), there is a belief among technology educators that technology constitutes a formal discipline with its own knowledge base. However, universities are devoted to the distribution and production of fundamental knowledge in general. They are committed to a particular epistemology that fosters inattention to practical artistry and professional artistry (Schon, 1983). As such, technological knowledge is potentially subject to all of the same constructs that govern other disciplines in terms of the cognitive and social psychology and the professional control of knowledge unless it is brought to bear in a specific scenario intended for its use.

The defining characteristic of technological knowledge is its relationship to activity in real, applied contexts. It is useful in that we study professionals within their own domains to assess their level of expertise and technological knowledge. This coincides with Mieg's account (2001) of expert knowledge in that it is based on an applied, social context in which its meaning is attributed by a person or organization to another entity. According to Skolimowski (1972), technological knowledge makes use of formal knowledge that is common to all, but the application is multidisciplinary. In fact, technology and "technique" are typically represented as the study of the discipline and the application to real situations respectively, but not combined to make up technological knowledge.

Technological knowledge has three forms (Herschbach, 1995). Descriptive knowledge provides the statements of facts and common information, which provides the framework within which people work. It also provides information about things as they are, and often is the application of scientific knowledge. This corresponds closely to content knowledge from the cognitive psychology perspective (Alexander, 1992). Prescriptive knowledge results from the incremental effort to achieve greater effectiveness, and it is altered through experience. It is not readily based on scientific knowledge, and it is generally comprised heuristics and generalizations. This is similar to one of the components of semantic memory known as procedural knowledge (Alexander, 1992). Finally, technological knowledge also includes tacit knowledge, which is implied knowledge based in large part on experience and practice. It is most often attributed to experts and outstanding performers within a domain.

Through the combination of descriptive (content), prescriptive, and tacit knowledge, technology and technological knowledge correspond to the description of a discipline as defined by Alexander (1992). Graphic communications, and specifically constraint-based CAD, embody a domain of knowledge within that discipline; hence the relationship between the conceptual mental model of an expert constraint-based CAD user and its role within the technological domain.

Just as expertise is a context-dependent phenomena and is based on domain-specific knowledge (Mieg, 2001; Chi, Glaser, & Far, 1991), so is technological knowledge.

According to Herschbach (1995), technological knowledge loses much of its meaning and identity when taken out of context and removed from activity. Technological knowledge acquires much of its form and purpose through human activity, which similar to the professional domains described by Abbott (1988). Wu, et al., (1996) have also concluded that the technological domain also has its own unique problem solving style that is different from other academic disciplines. This finding is consistent with arguments made by Abbott (1988) and Mieg (2001) in that professions, and experts within them, develop problem-solving and knowledge-application skills and tactics that are specific to their own disciplines and domains.

Thus, the link between information processing, mental models, expertise, and problem solving, through the auspices of professional and technological knowledge has been established. Engineering graphics, with its own knowledge base (Duff, 1990), is a form of technological knowledge, and is thereby included as being able to have its own domain knowledge examined. Within the larger engineering graphics domain lies constraint-based CAD, and according to Alexander (1992), this domain knowledge would consist of conceptual and tacit knowledge as well. And it would be elicited from practicing experts (Moore, 1970; Schon, 1983; Abbott, 1988) within this domain to form the content and procedures used within academic and industrial education environments.

Competent practitioners tend to know more than they are capable of saying, and this knowledge is usually embedded in a tacit form (Schon, 1983). The use of CAD tools is no different. It involves strategic knowledge, which according to Wickens and Hollands (2000), is comprised of declarative and procedural knowledge, as well as the idea of tacit knowledge. Technological knowledge consists of declarative, procedural, and strategic knowledge in the use of tools and processes as a means to an end, and it forms the bridge between constraint-based CAD tools and the larger body of knowledge surrounding information processing, cognitive psychology and the development of expertise. The final section of this review examines the study of 2D CAD and the strategies for its effective use. While these strategies work well in certain environments, the shifting focus of academic and professional engineering graphics will soon make these techniques obsolete.

ASSESSMENT OF 2D CAD STRATEGIES

Prior to the research conducted by Bhavnani et al. (1996, 1997, 1998, 1999) in the use efficient use of 2D CAD tools, the majority of the research related to CAD centered on the social and organizational impacts of the use of CAD. According to Majchrzak, et al. (1987, pp. 182-196), much of the research done from 1960 to 1987 focused on the effects of CAD on the workplace, employee relationships, employee performance, power, wage structure, and perceived stress.

However, in four related articles, Bhavnani, John, and Ulrich (1996, 1997, 1998, and 1999) have addressed the efficient and effective use of CAD. In their case, the domain was 2D CAD in an architectural setting with no reference given to 3D modeling, let alone constraint-based CAD. Undergraduate and graduate students were selected from the enrollment in an architectural program at a university in the eastern United States. The participants were examined with respect to the problem solving and geometry creation strategies they employed while solving an architectural design problem. The major points of the tasks centered on the creation and manipulation of geometry and patterns typical of an architectural detail drawing. In fact, at the time of these writings, constraint-based CAD tools had been on the market for about eight years. The problem is that no research of this type had been done during those eight years.

In spite of the lack of research on 3D constraint-based CAD, in the arguments made by Bhavnani and John, one can see the extensive coverage given to the 2D CAD domain and the need to now begin exploring the 3D, constraint-based CAD domain. Bhavnani and John (1996, 1997, and 1998) also used a combination of methods for their assessment of 2D CAD strategies. In all of their articles, they used knowledge elicitation methods that were consistent with cognitive psychology research, as well as ethnographic qualitative methods to examine practicing professionals and their use of 2D CAD (Bhavnani et al., 1998).

Sub-optimal strategies for use of 2D CAD tools stems from a lack of recognizing the potential uses for certain commands and a lack of efficient and effective execution of the commands (Bhavnani et al., 1999). While traditional drafting textbooks supply strategies for effective use of appropriate tools, much of the CAD-related literature does not. They focus instead on command knowledge. Drafting textbooks had to focus on technique, as well as quality, because it was easy to identify incorrect or sub-optimal strategies on a hand-made drawing; it is not so easy with electronically created drawings. As long as the finished drawing looks like it is supposed to look, no one can really tell what kind of strategies were used to create it (Bhavnani et al., 1996). The same can be said for constrain-based CAD models. Unless one knows the strategy employed and the mental model used by the designer, it is impossible to tell how the model was created without examining the electronic file. Even worse are times when someone does not examine the file in the engineering group and the CAD model is then used for something else, such as analysis, manufacturing, or inspection. Due to the nature of constraint-based CAD systems, it is possible that the model then behaves in an adverse fashion, thereby causing cost increases and time delays as the problems are addressed and fixed (Computer-aided design report, 1998, June).

Strategic use of CAD must be made explicit in education and training settings to avoid this type of scenario. In order to do that CAD strategies must be examined in context, and they must be evaluated in regard to the concepts and actions they employ in the creation and relation of geometry (Bhavnani et al., 1998). This is critical given the multiple methods to decompose the same design task within a CAD system, especially with regard to constraint-based CAD systems. Bhavnani and John (1996) suggested a strategy involving the detailing, aggregation, and manipulation of 2D CAD entities when creating a drawing. However, when the design problems are more complex, this strategy may not be enough by itself. While the design of the software and the methods upon which it works may be enough for sufficient usage of the tool, it does not necessarily foster efficient usage (Bhavnani et al., 1997).

In regard to the previous point, the study conducted by Bhavnani and John (1997) employed experts and skilled novices. While both groups completed the experimental tasks in relatively the same amount of time, the compelling differences lied in the methods they chose to complete the tasks. The experts completed the tasks in fewer steps, which corresponds to their capacity for chunking information in memory (Ericsson & Smith, 1991; Chi, Glaser, & Farr, 1982). Bhavnani and John (1997) suggest that this difference is also due to the strategies employed by the experts with respect to their knowledge of multiple methods to determine a solution within the CAD tool. Using their mental model of the situation, the experts were able to decompose the task more efficiently than the novices (Bhavnani & John, 1997), hence the importance of determining the experiences and factors, which are not related to the CAD system, that contribute to the development of expertise. Bhavnani and John (1997) allude to the technology of aggregation in creating 2D CAD drawings, which involves the creation of geometry, any pattern required inside the bounded areas (to denote product materials), and the eventual manipulation of the group. However, these strategies do not readily apply in constraint-based CAD due to the nature of creating geometry in those tools; they use an additive mindset for the creation of features (Bertoline & Wiebe, 2001). In addition, the concepts of parent-child references and associativity do not promote the use of a detail-aggregate-manipulate philosophy.

To espouse the promotion of their theory, Bhavnani and John (1997) suggest that CAD training should include these types of strategies in addition to the knowledge of commands. However, constraint-based CAD tools require more than that; they require an estimation of external customer requirements as well as knowledge of downstream processes in which the model might be used (Branoff & Hartman, 2001). While 2D CAD drawings might be thought of in a similar mindset, the level of complexity of the system increases drastically with the use of constraint-based CAD tools. While they have advocated the use of strategies as being important in the effective use of tools, Bhavnani and John (1998) also advocate a more systematic approach to understanding the relationship between computer tools and strategies. In dong so, they examined the historical developments that brought about the creation of new tools and new constraints and problems that were inherent with those new tools. They cite CAD tools as no exception.

To overcome certain limitations in these strategies as a result of the nature of the CAD tools themselves, Bhavnani and John (1998) suggest a combination of delegation and circumvention. In this case, delegation refers to allowing the CAD tool to automate simple components of the drawing creation task, and circumvention refers to the process of determining alternate solutions to design problems when the initial strategy chosen using the CAD system is ineffective. Use of constraint-based CAD tools is similar in that many commercial constraint-based CAD brands automatically apply geometric constraints to features and sketches created within the system. While this certainly saves time, it is not always the optimal application of references; it is then imperative that the user know enough about the relationships of the fundamental components of the system and the geometry it creates to be able to adjust what the system has created automatically.

In their 1999 article describing the development of a course to teach strategic uses of CAD, Bhavnani, John, and Flemming suggest a bi-directional approach to teaching those strategies: learning to see and learning to do. The goal of this course was effective and efficient software usage. As these tools become more prevalent in professional and technological environments, their effective use is essential. Learning to see involves recognizing opportunities when efficient strategies can be put to use based on the nature of the task. Learning to do involves implementation of the strategies based on the operation of the CAD tool. Because the strategy employed by students was not readily apparent by just inspecting the finished drawing, so the researchers asked the students to verbalize their plan for constructing the model. This makes the action process public and available for analysis. Creating a 3D model with a constraint-based CAD tool is similar; students' models cannot be evaluated merely from a printout. They must be assessed in terms of their strategy and modeling procedure, thus it is critical to understand efficient strategies from the standpoint of expertise. Several studies have shown that strategic knowledge is not readily acquired by command-based training exclusively. It requires instruction in the recognition and selection of efficient strategies (Bhavnani & John, 1997; Cragg & King, 1993; Doane, et al., 1990; Nilsen, et al., 1993).

The authors mentioned above believe that strategic knowledge holds the key to the use of these strategies, and they advocate exposing students to this approach using a realistic context so that students may learn to recognize the appropriate instance for application (1999). The key to this strategic knowledge is expertise and determining the mental models and experiences that define and develop it (1996 and 1998). Complex computer applications, such as CAD, offer a user more than one way to complete a task

(Bhavnani, et al., 1999). **Strategic knowledge** refers to knowledge of such methods and how to choose between them. Knowledge of how to use a particular strategy is rather abstract, because it does not include knowledge of explicit commands. These are generally used in combination with concrete strategies that do include knowledge of CAD commands and how to execute them.

The mental model(s) of the users and the nature of the representation that they include also govern the use of such complex systems (Samurcay, 1995). Mental models can potentially be different for each user depending upon their context and past experience, and some portion of user training and education should focus on the development of such models to include strategic knowledge of the CAD system. By giving constraint-based CAD users the proper mental model from the beginning, it is potentially possible to improve performance (Hollnagel et al., 1995b), and this performance gain is influenced by the mental model of the expert user.

SUMMARY

In discussing the matter of expertise, it imperative to understand the cognitive psychology point of view with respect to information processing. It is through this process that humans transform raw stimulus inputs into meaningful knowledge that can be used at a later time. It is also this process that provides the support structures for the creation of mental models. By being able to process information quickly and efficiently within a domain and by being able to create highly organized and deep representations of their domain, experts are able to out-perform novices.

Expertise also relies on a social structure to propagate its existence. An expert would be useless without a situation in which to exercise the knowledge that they hold. Through the mechanisms of social psychology another person or entity often attributes expertise to some person or entity. In doing so, value is placed on the expert’s knowledge by those who desire it. While anyone can be an expert in regard to almost anything, expertise usually resides within professional domains, hence its relationship to technological knowledge. Technologists and engineers are highly proficient in the use of physical and mental tools that allow them to perform better in relation to normal people. It is this performance that has been examined with respect to 2D CAD due to its lengthy existence relative to constraint-based CAD, but those tools are being phased out of both academic and professional environments.

CHAPTER 3: METHODOLOGY AND ANALYSIS

It is critical that strategic use of 3D constraint-based CAD be examined, and in order to do that, the definition and development of expertise within that domain has to be assessed. In order to make an initial inquiry into this area, four different methods were used in this study (Olson & Biolsi, 1991). Interviews and observations will be used to examine the experiences that aid in developing expertise, and card-sorting tasks and think-aloud protocols were used examine expert constraint-based CAD user's mental model development and problem-solving strategies.

On the most basic level, the study of expertise seeks to understand and account for what distinguishes outstanding individuals in a domain from less outstanding individuals in that domain, as well as other people in general (Ericsson & Smith, 1991). The attribution of expertise to an individual was initially based on stable characteristics of the person or the environment, and not in regard to singular or random events that occur. However, focus in expertise research has shifted towards an applied focus of not just what the unique characteristics are but also how they were acquired (Ericsson & Smith, 1991). What is it that experts actually acquire? Previously studied domains have given many clues about memory, practice, and speed of experts, but each domain is specific. This accounts for the variability and exploratory nature of these studies in domains that are relatively unexplored. In this instance, it is important to distinguish between mere exposure and practice with feedback.

However, in the constraint-based CAD domain, there has been no determination of standardized tasks or conditions. In addition, it is likely that there are many mediating influences that would make these types of analyses difficult. Hence, these are the reasons for an exploratory study into this domain. Are there typical experiences that expert constraint-based CAD users have? Do they perform the same tasks regardless of the professional domain in which they work? Answers to these questions could potentially lead to standardized assessment instruments within the area of expert analysis (Ericsson & Smith, 1991).

The assessment of outstanding performance is typically conducted within two dimensions: inherited versus acquired and general versus specific (Ericsson & Smith, 1991). Initially, expertise was assessed according to general, inherited characteristics, but eventually these could not be used to explain certain phenomena. General abilities include such things as intelligence and personality, and they are typically assessed according to personality inventories and intelligence tests. Specific abilities are found in regard to a particular characteristic of a person, such as musical or language ability, and they are typically assessed with specific measures of such ability. Acquired abilities include general learning and experience in the forms of cognition and general knowledge, which are typically assessed using common processing strategies. On the other hand, and of particular interest in the examination of constraint-based CAD, is domain-specific training and practice focused on domain- or task-specific knowledge, which are typically assessed using an analysis of task performance. Assessment of this nature focuses on acquired, specific characteristics and skills. This final area is by far the largest in terms of active applied research. Many studies of experts in various domains have accounted for the use of their mental model as an important element in their ability to plan and strategize within their domain. It is typically found to be critical with respect to their development of a problem solution (Chase & Ericsson, 1982; Holding, 1985; Charness, 1989).

Branoff and Hartman (2001), Miller (1999), Ault (1999), and Barr (1999) have suggested that modern engineering graphics curricula should include constraint-based CAD tools, but no agreement has been reached as yet to the extent and depth of its coverage (Branoff and Hartman, 2001). It is this researcher's contention that, in order to effectively integrate constraint-based CAD into the engineering graphics curricula, one must understand the fundamental nature of such a tool. While literature does exist concerning its operation (Bertoline & Wiebe, 2001; Hanratty, 1995), only by examining expert users in their professional context will a notion of its core concepts and their relationships be developed. Much research has been done with respect to the usage of 2D CAD (Majchrzak, et al., 1987; Bhavnani, 1996, 1997, 1998, 1999), but given the relatively brief existence of constraint-based CAD compared to 2D CAD, no substantive research has been conducted regarding the development of expertise in this area. No consensus has been reached concerning its core competencies, standards for its applied usage, or techniques for its instruction in engineering graphics courses. Hence, this is not the time to conduct an empirical study due to lack of professional consensus regarding the variables involved.

The goal of this dissertation was two-fold: to determine an initial definition of expertise in the domain of constraint-based CAD and to describe the experiences that led to the development of expertise in this domain. As stated previously, research into expertise in knowledge-based domains is eclectic, so the nature of this research methodology was dichotomous. With respect to the determination of a basic definition of expertise in constraint-based CAD, knowledge acquisition techniques, including verbal protocols and card-sorting tasks were used to examine experts' mental models. Once the mental model and its related experiences have been determined to form a basic definition of expertise in the domain of constraint-based CAD, future quantitative studies can be performed to determine the relative significance of the concepts contained in the definition. To determine the experiences that have fostered expertise in this domain, phenomenological qualitative research techniques were used to analyze interviews and observation of experts with respect to these topics. Based on the information provided by the experts, a suitable pedagogical process to convey that information in education and industry will need to be determined at some point in the future.

BRIEF COMPARISON OF RESEARCH PHILOSOPHIES

Different traditions of qualitative research have developed in different academic disciplines, with the majority of the work being done in sociology, anthropology, and psychology (Glesne, 1999). In the 1920s, a group of sociologists at the University of Chicago began doing what they called *fieldwork*. This became known as the Chicago School, and it spread the methodology of using participant-observation techniques throughout the realm of sociology between 1920 and 1960 (Tesch, 1990).

In the 1960s and 1970, the rise of phenomenology began based on the works of Edmund Husserl. He contended that human consciousness actively embodies the notion of experience (Holstein & Gubrium, 1994; Creswell, 1998). Alfred Schutz then developed social phenomenology as a research mode by arguing that the social sciences should focus on the experiences and productions of everyday people which are normally taken for granted (Holstein & Gubrium, 1994). Phenomenology is now often used in psychology as a way to enhance psychological knowledge elicitation techniques (Young, 1983; diSessa, 1983).

Anthropologists are credited with the development of ethnography by Malinowski (Glesne, 1999; Creswell, 1998). Ethnography focuses on the immersion of the researcher into a particular culture to study it in fine detail. Its initial goal was to examine cultural development in a way that was different from those European-based cultures, and in the 1960s anthropologists began to critically reflect of their relationships with those people that they were studying. They were trying to avoid the impression of colonialism as seen by other research disciplines (Glesne, 1999).

According to Creswell (1998), qualitative research is a process of understanding based on methodological traditions of inquiry that address social or human problems. The researcher builds a picture of the problems that is complex and holistic in nature while conducting the study in a natural setting. “Natural setting” in this case means the context or location in which the problem manifests itself.

The research methods chosen for a particular research project say something about the way that the researcher views reality. It is this ontology that dictates whether a researcher believes in a fixed, measurable, quantitative reality (positivism) or in a socially interpreted, qualitative (interpretivist) reality that is ever changing (Glesne, 1999). Interpretevist is also known as constructivist in many research circles. The view of this study is that reality, and the conditions that exist in it, is constructed based on the participants’ meanings for certain phenomena.

The interpretevist mode of inquiry assumes that reality is socially constructed and variables are complex, interrelated and difficult to measure. It is based in the meanings that people construct of their realities and tends to ask, “how did things come to be this way (Gall, et al., 1996)?” The positivist assumptions are that social facts have an objective reality, and that variables can be identified and measured (Glesne, 1999). Qualitative researchers tend to ask questions in the form of “how” or “why”, where as quantitative researchers typically ask questions in the form of “what” (Creswell, 1998).

Positivist researchers seek explanations and predictions that will generalize to other persons and places, whereas the constructivist researcher intends to explore a phenomenon in depth for a particular group or context (Glesne, 1999). A qualitative researcher typically deals with few subjects but many variables. The researcher becomes the main research instrument through which data is filtered. The qualitative researcher typically is a participant at some level within the research environment and has a natural empathetic understanding of the issues at hand. The quantitative researcher however is exemplified by detachment and an objective stance to the research project (Glesne, 1999). Qualitative research results tend to be somewhat subjective given their relationship to the researcher, however, it is important to acknowledge the perspective of the researcher as probably being the impetus for the research project in the first place (Gall et al., 1996).

To understand the nature of this reality, qualitative researchers will observe and interact with their participants about those particular perceptions and ways of knowing (Gall et al., 1996). They will search for patterns and common themes in the data using an inductive reasoning process, and they will use a “thick” description when delivering the narrative of the story. They tend to include quotes from participants to give an indication of the problem in the words of the participant (Creswell, 1998). Quantitative research begins with a hypothesis and a relationship to a theory. It uses formal experimental instruments and a deductive thought process to analyze the data. Abstract language and numerical indices will be common in the final report of the findings (Glesne, 1999).

It is common in the qualitative research environment to find data collection methods that put the researcher and the participant in contact with each other, such as interviews and observations (Glesne, 1999; Gall et al., 1996; Creswell, 1998). However, in a quantitative research scenario, researcher and participant contact is kept to a minimum using tools like experiments and simulations (Gall et al., 1996; Glesne, 1999). While each particular research format views the other with a certain amount of disdain - such as quantitative research viewing qualitative research as advocates, and qualitative research viewing quantitative research as focusing on topics that are easily measured – it is important to select methodologies that are suitable to the questions at hand and the interests of the researcher, including the integration of both types of research when warranted (Gall et al., 1996). Exploratory research typically does not have formal guidelines and procedures for conducting the study, and what few it does have, tend to evolve over the course of any particular study (Creswell, 1998).

OVERVIEW OF EXPERT ANALYSIS AND KNOWLEDGE ELICITATION

There is a wide range of methodological approaches covered in the analysis of expert performance, including task analysis and cognitive tasks analysis. Each one comes from a different perspective of analyzing a particular task and the context that accompanies it (Annett, 2000). Classical methods of task analysis involved the use of scientific means to assess the amount of time and effort an operator was putting into a task. Information theory and the accompanying depictions of human information processing suggested that the human operator could be characterized as a processor of information with a fixed bandwidth that was measurable (Annett, 2000). All of this new information eventually led to concept of mental workload. Any subject matter that had to be taught was broken down into its component elements, thus creating an analysis of the task.

Among other things, cognitive task analysis referred to a means of structuring course materials based on the way a person might employ problem solving techniques (Annett, 2000). Cognitive task analysis closely matched Newell and Simon’s (1972) problem solving theory and its basis of information processing systems within human cognition. These analyses were intended to reveal the problem path and heuristics employed by experts and novices in their development of a problem solution (Annett, 2000). Not only were they looking for error detection, but also for explanation. Due to the procedural and declarative nature of long term memory within most experts in any given domain, eliciting tacit knowledge about the expert’s problem solving processes and abilities without corrupting the reliability of such data was no easy task. Methodologies are diverse when it comes to finding out what a person knows and how they have come to know it, and many of those methods developed by early cognitive researchers are still in use today, such as interviews, observations, verbal protocols, and semantic task analysis (Ericsson, and Smith, 1991).

Parallel to the emergence of cognitive task analysis were further developments in the area of human problem solving due to the increased use of computer-controlled environments within industrial systems. The basis of many of these new problems solving measures was the collections of compiled and procedural knowledge taken primarily from experts within a domain for the purposes of analyzing a cognitive task (Annett, 2000). Cognitive task analysis is concerned with the decision-making tasks performed by operators within a particular domain (Annett, 2000), and in doing so, cognitive task analysis has been influenced by literature relating to learning, mental models, and cognition. However, simply observing an individual perform a task can give a superficial understanding of what is happening; one must use multiple methods to assess the procedural and declarative knowledge that is embodied within an expert's mental model in order to develop effective training procedures (Annett, 2000).

Mental model research has developed along two major lines of research that have merged together in this regard to produce a rather productive relationship. The first line includes cognitive psychology and its associated disciplines of linguistics, anthropology, and philosophy. The second line of research is that of artificial intelligence, which has provided explicit theories of human knowledge and processing (Gentner & Stevens, 1983, p.3). Typical examination of mental models is done by a careful investigation into the ways that people understand a particular knowledge domain (Gentner & Stevens, 1983), which focuses on the applied utility of this type of knowledge – understanding human knowledge about the world. Modern task analysis is heavily influenced by the group conducting the analysis, and the effects that each type of field makes on the process as a whole depends on the way in which their field is organized, and the methods of cognitive task analysis they choose are based on the questions they are trying to answer. Depending on the questions to be answered, the examination of the cognitive task could be aimed at description or analysis or a combination of both, and the methods used should be adapted accordingly (Annett, 2000).

In determining the basic definition of expertise in constraint-based CAD, think aloud protocols and knowledge mapping tasks were used to acquire the information necessary. Think aloud protocols were used to examine the expert's thought process when solving a problem or conducting an activity representative of those in the domain (Lu, 1994; Ericsson & Simon, 1993). By doing so, the researcher could obtain an example of how the experts used the procedural and declarative knowledge stored in their mental model. To obtain a depiction of the mental model and the relationships between the concepts contained therein, a knowledge mapping task was used (Jonassen et al., 1993). The knowledge mapping task allowed the researcher to provide the participant with initial concepts from the domain, and the participant could then arrange those according to their mental model by using the given terms, adding more, or removing those that did not fit.

OVERVIEW OF QUALITATIVE RESEARCH TRADITIONS

Qualitative research, as one of its basic tenets, strives to explore and expose the underlying factors of human experience (Anderson, 1998). Given the eclectic nature of this type of research, a predominantly qualitative methodology was chosen for this dissertation. The reason for this is that qualitative research tends to be exploratory in nature, as opposed to explanatory and predictive (Borg, Gall, & Borg, 1990; Glesne, 1999). In addition, the phenomenological tradition in qualitative research most closely aligns with the naturalistic decision making line of inquiry in cognitive psychology in terms of its methods and purposes.

Naturalistic decision making attempts to focus on how people use their knowledge and experience to assess complex situations and take action (Beach, et al., 1997). According to Zsambok (1997), naturalistic decision making involves four themes: the task and setting are filled with ill-defined problems, uncertain and dynamic environments, and shifting goals, time pressure, and high stakes; subjects are experienced participants in that particular setting; locus of interest is on situation awareness, diagnosis, and plan generation rather than attending to the particular moment of choice; and the purpose of the research is to describe the strategies that people use and not the strategies they *ought* to use. Due to its nature, naturalistic decision making encompasses many areas of inquiry, including problem solving, cognition, information processing, and decision making (Zsambok & Klein, 1997). In addition to these, one of its many phases of exploration is the development of expertise related to a myriad of phenomena, including warfare training, programming, healthcare, and business management (Salas & Klein, 2001), all with an eye towards the progression from novice, to advanced beginner, to competence, to proficiency, to expertise. It is with this mindset that professionals practicing in the field of engineering design, and who use constraint-based CAD tools, were used for evaluation in this study. While many of the methods employed in analyzing mental models of individuals are comprised of psychological experimentation, there are a growing number of researchers tapping the qualitative domain of research in the area of psychological phenomenology (Stevens & Gentner, 1983). Their methods include observations within natural settings of the participants and protocol analyses (Williams, et al., 1983; Young, 1983; diSessa, 1983).

Creswell (1998) suggests that there are five typical methods used in current qualitative research environments: biography, phenomenology, grounded theory, ethnography and case study. While nearly any topic could be researched using any of the five basic qualitative traditions, each one has its own unique characteristics that will make it better in certain situations. Biographies are most useful when examining individuals in order to explain the significance of their life experiences. Phenomenology is useful when the researcher wants to examine a phenomenon in terms of people's lived experiences, as well as their own experiences. Grounded theory studies are generally used when the researcher needs to generate a new theory, based on existing information, about a phenomenon that they have encountered. Ethnography is used to examine cultural characteristics often using a very broad definition of the word culture. Finally, case study research is used to examine a group of people or organizations that have a particular characteristic in common. While people often confuse case study research and grounded theory, they are in fact different. Case study research has a bounded quality to the geography and organization of the case, whereas information in a grounded theory study may be elicited from anywhere the characteristic is observed.

Despite the aforementioned differences, each of the general qualitative traditions do have some similarities, particularly in regard to their origins, their data collection methods, their analysis techniques, and their final narrative form (Creswell, 1998; Moustakas, 1994). Each of the five traditions has its roots in sociology, psychology, or anthropology. This accounts for the very humanistic nature of the methods. The goal is generally a search for meaning and essence, as opposed to measurement and explanation. Research questions are formulated based on the interest, involvement, and commitment of the researcher, and methods are chosen based on these characteristics. Each one emphasizes people's ways of knowing within a particular context; hence the need for generalization beyond the current sample is not necessary or intended. The focus is on experience, and not solely on the objects or parts of the research.

Other than case study research, the qualitative traditions use interviews and observations as their primary sources for data collection, with the emphasis given to long interviews in most cases (McCracken, 1988). Long interviews provide a means of collecting vast and rich amounts of data from which to identify emergent themes and meanings. The emergent themes are determined based on some type of coding or analysis process applied to the interview transcripts. Depending on the qualitative tradition process being used, these codes may be simple phrases, words, or ideas that continually appear within the transcript. In a more exacting fashion, the codes may be more formally determined by comparing those common entities to existing theory in order to link the research to a particular knowledge domain (Creswell, 1998). Finally, the results are written in a narrative form in most cases. It is done in this manner to apply a vivid description to the phenomenon in question. In doing so, the researcher paints a picture of life in those exact circumstances. Phenomenological research methods seek, above all else, to illuminate the nature of human awareness and experiences (Anderson, 1998). It is with this approach that the experiences of expert constraint-based CAD users were examined in order to expose the experiences that led to the development of their expertise.

PHENOMENOLOGY

Phenomenological research methods are often used to examine the fundamental concepts or experiences surrounding a particular phenomenon, such as the representation of physical or mathematical quantities when problem solving or the design of interactive devices like computer software (diSessa, 1983; Williams, Hollan, & Stevens, 1983; Young, 1983). The primary focus of phenomenological research and the knowledge that is produces is an understanding of the meaningful, concrete relations implicit in the original description of experience within the context of a particular situation (Moustakas, 1994).

Human experience is metaphorical in nature, and metaphor is an essential structure of human experience (Romanyshyn, 1981). Part of the meaning of any experience is elusive, and it is the use of metaphor that helps to formulate this missing part of meaning. Phenomenological research is guided by a quest for the true essence of a phenomenon and the conditions that bring it about and support it (von Eckartsberg, 1998). Mental models are an embodiment of human experience with the addition of context- and task-specific features. They help to assimilate and make sense of that which cannot be explained from physical observation (von Eckartsberg, 1981).

Husserl, the founder of phenomenological philosophy, regarded consciousness as the primary theme for phenomenological inquiry (Moss & Keen, 1981). Husserl (1931) states that natural knowledge begins with experience, and while the leap to expertise in context might seem great, it is not much of a deviation from Husserl. Expertise, according to Hoffman et al. (1997), is developed and used within a naturalistic setting and context, and through experience within this setting, Mieg (2001) contends that expertise is conceived and recognized. It is this relationship between the context, moment in time, and knowledge domain that makes up the essence of "knowing" within a given domain. Consciousness is not just a thing or event, but an opportunity. Phenomenology is concerned with articulating the organizational principles that govern the relationship between the conscious organism and the world in which it exists. Phenomenology is a description of an individual's experience in the terms and concepts that are appropriate for the context (Moss & Keen, 1981), and it relies on the supposition that people name and identify their experience in a consistent and shared manner. The "intentionality" of the relationship between the human and their environment is a function of the "mind", which is a fundamental tenet of existential phenomenology (Moustakas, 1994). Experience and behavior are directed towards an object, goal, or situation in the world; however, this is not the same as free will or expression of the human onto the situation. The nature of the relationship is reciprocal. Intentionality contends that the human is oriented towards any given situation, and that the situation organizes the human's awareness and behavior, which in turn helps to organize the situation (Moss, 1981).

Phenomenological psychology employs a concept known as epoche, which means that all questions or doubts about the reality of a phenomenal, experiential world are suspended. It assumes a consciousness based on immediate, lived experience and an assertion of human activity with an orientation outward towards the world (Moss & Keen, 1981; Moustakas, 1994). As a researcher studying a particular phenomenon, one must "bracket" his or her experiences with regard to the phenomenon and keep them separate from the research interaction. In that way, the true meaning of the phenomenon in its own lived space will become apparent by not describing it in terms of what the researcher already perceives, knows, or wants. (von Eckartsberg, 1998; Moustakas, 1994). The data that comes out of the interviews with the participants yields a fresh look at the phenomenon, because any preconceived notions that the researcher may have do not taint it. The researcher approaches the project with an attitude of openness rather than an attitude of knowing things in advance.

Consciousness is not necessarily equated with knowledge or cognition. If anything, these are a function of our consciousness and its interaction with the world around us. Through language, science, mathematics, and other domains, we are able to transcend the immediate concrete entities that surround us into an abstract state of meaning (Moss & keen, 1981). This is often the case when describing mental models; they are an abstract relationship of concrete entities with which we interact daily. The texture of consciousness is the texture of the human world; this is the epitome of the phenomenological perspective. The fundamental roots of consciousness are derived from the articulation and coherence of a time, place, language, and person (Moss & Keen, 1981). This same arrangement can be extrapolated to form the basis for mental models; the application of specific contexts and tasks to a schema to form the template by which people interact and work (Stein & Trabasso, 1982).

To address and make meaning from these elicited experiences, phenomenological research employs a process of explication. Explication involves the capturing of the essence of the phenomenon as it is described in terms of what it is to those who live it and how it is lived by those people in their particular context (von Eckartsberg, 1998; Moustakas, 1994). This data is typically collected through interviews or protocol analysis and analyzed in terms of obtaining a general structure for the phenomenon in question (Ricoeur, 1979; Moustakas, 1994). The resulting picture of the phenomenon is then applicable to those people interviewed within that particular context. Given the use of the phenomenological perspective for the interview and observation portion of this study, a phenomenological component of a research study generally has several components (vonEckartsberg, 1998; Colaizzi, 1973).

The first stage is problem and question formulation. In this study, the question centered on the development of expertise in the use of constraint-based CAD tools. The second stage is the data-generating situation, or what is sometimes known as the protocol life text. For example, each participant might list significant experiences related to their learning/development of expertise in constraint-based CAD. This protocol would then serve as the basis for a follow up interview. The third stage of the general phenomenological research process is data analysis, known as explication and interpretation according to Moustakas (1994). The protocol life text and the subsequent interview would be analyzed for configurations of meaning and common elements and terms used by the participant. This process is guided by a general question in the form of: "How is what I am reading relevant to the meaning of [expertise in the realm of constraint-based CAD]?" The researcher is looking for what this question helps to inform about the essence and situated structure of the phenomenon in question.

Giorgi (1985) suggests a four-step process for the analysis of these results. The first step involves the reading of the protocol life text to get an impression of the statement as a whole. One is trying to understand the scope of the experience as it relates to the subject. Moustakas (1994) would term this step bracketing, which involves creating boundaries around the phenomenon in questions to maintain a sense of focus. The second step involves the researcher reading the account a second time, only now he or she is looking for "meaning units" from within the perspective of the participant, and with a focus on the phenomenon in question. This is also known as "horizonalizing", which means taking each statement individually as a measure of truth (Moustakas, 1994). It is common that the “meaning units” derived by the researcher correspond to psychological criteria surrounding the phenomenon. It is also imperative that the researcher adopts a psychological attitude while deriving the meaning units so as not to interject unnecessary preconceptions contained within the epoche of the researcher. It is a process carried on within the context of discovery and not within the context of verification; content analysis in this case is more a methodology, free to be dynamic and flexible as the conditions warrant. The third step has the researcher examining each “meaning unit” in turn to attempt to express the psychological underpinnings contained within, especially for those meaning units most closely related to the phenomenon in question. According to Moustakas (1994), this would involve clustering horizons into themes and imaginative variation, which focuses on synthesizing a larger meaning from the multiple units. Allowing the general category to emerge from the concrete, yet cryptic, protocols of the participants accomplishes the discovery of the relationship to psychological categories surrounding the phenomenon. As a manner to overcome the multiple realities present in the raw protocols of the participants, reflection and imaginative variation are at the heart of the meaning unit transformation. Finally, the researcher transforms all of the elaborated meaning units into a cohesive statement regarding the phenomenological experience, which corresponds to Moustakas’ notion of textural description, which is a robust, vivid description of the phenomenon in question. While all meaning units may not be explicitly stated, those that are not should at least be implicitly present within the final description of the phenomenon in question. The final stage of the phenomenological design suggested by Moustakas (1994) is presentation of results. The formulations made with regard to the phenomenon are reviewed with the participants, via the exchange of the transcript information or by one-on-one meetings, to ensure that they have been stated properly and accurately according to the experiences of the participants.

COGNITIVE KNOWLEDGE ACQUISITION METHODS

In identifying knowledge representations of the expert, a major goal for the initial interview and observation process is to identify the abstract nature of the knowledge involved in the task (Chipman, Schraagen, & Shalin, 2000). From this point, further knowledge elicitation activities can be employed. When examining a task that involves procedural and conceptual information, it is important to use techniques that will elicit both types of information (Chipman, Schraagen, & Shalin, 2000). Constraint-based CAD could be considered one of these types of tasks, and structured interviews, field observation, and protocol analysis are all methods that could be employed in this type of analysis (Chipman, Schraagen, & Shalin, 2000).

Development of some form of semantic network of concepts is often involved in the examination of expertise. There are a variety of methods to conduct this type of analysis of an expert's mental model, including knowledge mapping (Olson & Biolsi, 1991). However, novel approaches to the acquisition of knowledge from experts may need to be created in order to address the deficiencies being examined, especially in a domain that has not been examined (Gray & Kirschenbaum, 2000). These contrived techniques often are variations of techniques already in place, but others are new. These new techniques can often be just as efficient and effective as the more established techniques in yielding rich information (Hoffman, et al., 1995).

The goal is to determine the user's mental model of the system by comparing it to the conceptual model of the system (Norman, 1983). To do this, the researcher must observe and assess the user in action. There are three key dimensions that characterize research on the mental models of individuals: the nature of the domain studied, the nature of the theoretical approach, and the nature of the methodology (Gentner & Stevens, 1983, p. 2).

Initial efforts to obtain naturalistic human knowledge must center on the simplest domains possible. Domains should be chosen for which there exists some type of normative knowledge that is relatively simple to detail. In this regard, mental model research tends to focus on physical systems or devices as opposed to complex human relations. However, one might be saying, "why examine expertise and constraint-based CAD then?" The idea is that the mental model of an expert user can be examined rather directly in light of cognitive psychology research relating to expertise in other knowledge domains and disciplines. In addition, the focus is on technical domains because these areas tend to have the most explicit normative models, such as the common elements within constraint-based CAD systems (Bertoline & Wiebe, 2001; Wiebe, 1999).

Before beginning any knowledge elicitation activities, Lu (1994) recommends that experts are made aware that they are not being replaced, but simply called upon to provide information that will ultimately help the organization, and to explain to them the following points. Every domain has its own laws and regularities, and experts tend to use those in order to solve problems. Domains also have laws, which are “fuzzy” and non-deterministic, and it is expertise that is required to work within those constraints.

As stated by Cordingley (1991) and Hoffman et al. (1995), there are many techniques designed to elicit information from people, including interviewing, focused talk, sorting tasks, teach back, laddering, protocols, simulations, and others. In an effort to determine the map of the mental model of an expert in the constraint-based CAD domain and the experiences that developed it, the methodology used for this study included several techniques. Observations and interviews were used in order to obtain a characterization of the expert’s past and current experiences that contribute to their expertise in constraint-based CAD. In addition, protocol (think aloud) reports and knowledge mapping (structural knowledge elicitation) were used to determine the core concepts and their relationships that define the expert’s mental model of the constraint-based CAD domain. Characteristics of these four techniques are explained below.

Observations

One of the most functional and simple ways to observe a person’s interaction with their environment is to observe them in action. Observation is also one of the most common data gathering techniques in exploratory research (Mieg, 2001; Creswell, 1998). Observation is the passive action of noting and recording features and events that occur naturally in the environment in question (Cordingley, 1989). Observations involve selecting a site to be observed and identifying who or what will be observed. It is also important to record an accurate description of the participant, the physical setting, any particular event or activities that occur, and one’s own reactions and insights with regard to the process (Creswell, 1998).

While observations can yield a great deal of information about a participant and their overtly obvious characteristics, they tend not to give much information in the way of cognitive processes on the part of the participant. This usually requires some amount of inference on the part of the researcher (Creswell, 1998; Olson & Biolsi, 1991). To safeguard against too much inference, the researcher can interrupt the participant when they observe something that does not fit the conception of the situation, which is a particularly useful when a great deal of the expert's behavior is already accounted for. A second alternative is to videotape the session and review it with the participant immediately afterward to clarify any questions that the researcher may have regarding the activity of the participant.

To successfully accomplish observations with regard to expertise and mental models, representational and functional issues from the perspective of the participant must be considered (Johnson-Laird, 1983 & 2000). A person's mental model reflects their beliefs about the physical system that have been acquired through observation, instruction, or inference. The relevant parts of the belief system should be contained in the conceptual model of the system. In addition, the parameters and states of the mental model should be observable in the physical system. In the conceptual model of the user's mental model there should be correspondence between the parameters there and in the user's mental model. Finally, the resulting mental model description of the user's mental model should reflect the relationships between the concepts and procedures that are contained within to gain an accurate description of the physical system. These characteristics can form the basis of any analytical technique applied to the observational transcript, namely the search for common themes that emerge from the observational field notes that will later be compared to the results from the mental model representation tasks.

Observation typically occurs on a continuum between full participant and full observer. With researchers who are particularly familiar with the domains they are studying, they may find themselves "walking a fine line" with respect to how much they become involved with the research scenario (Glesne, 1999). Field notes are taken in a descriptive as well as analytic fashion. Dialogue between the participant and other individuals in the setting is also included, as well as sketches if necessary to elaborate on the physical make up of the setting. Analytical memos written by the researcher tend to elaborate as well as synthesize the emerging themes uncovered by the observations

(Glesne, 1999). When used later in the knowledge elicitation process, observations are a means to assess whether or not the expert performance is consistent with the expert description. (Trimble, 1989).

Long Interviews

Long interviews comprise one of the major knowledge elicitation methods for a phenomenological study (Creswell, 1998; Moustakas, 1994; McCracken, 1988) and for a knowledge acquisition exercise in cognitive psychology (Firlej & Hellens, 1991; Cordingley, 1989; Olson & Biolsi, 1991). The term “interview” in this sense is meant to describe a technique and not an event. In this case, the researcher is asking a person with domain knowledge specific questions related to that domain in an attempt to gain insight to concepts that are not readily available (Cordingley, 1989).

Interview questions are often formulated by themes revealed in the observation of the environment and interaction with the participants (Glesne, 1999). These questions tend to be more specific and set within a particular context, as opposed to research questions that are broad and general. According to Patton (1990), interview questions can come from six general areas: experience/behavior, opinions/values, feelings, knowledge, based on sensory information, and background/demographics.

Cordingley (1989) also suggests direct versus indirect questions and explicit versus implied questions. Direct questions are intended to elicit specific information that the researcher thinks the participant possesses and will be able to verbalize. Indirect questions are used when the researcher wants to allow the participant to suggest categories of knowledge of which the researcher may be unaware or if asking directly would tend to induce a specific answer.

Interviews potentially allow for a great deal of expansion on the part of the participant depending on the type of interview that is conducted, although the researcher generally approaches the situation with some type of guide so as to avoid becoming disorganized. Cordingley (1989) suggests three styles: structured, semi-structured, and unstructured. Structured interviews tend to be used in settings when the questions and answers need to be in the same order for each participant or when the answers can be anticipated and coding begins ahead of time. These types of interviews generally are considered “closed” due to their rather restrictive nature and are often not used in knowledge elicitation. The opposite type is the unstructured interview, which gives the participant most of the control over the situation, because the researcher typically has no guide prepared. They may start with an initial question, but after that, the interview tends to flow on its own accord. In between those two types is the semi-structured interview, and that is the method to be used for this study. It combines the structure of a few prepared questions, but it does not require the researcher to ask them in a specific order and gives him or her the liberty to add or remove questions as necessary.

Through conversation analysis suggested by Creswell (1998), Cordingley (1989), and Olson and Biolsi (1991), transcripts of the interviews are analyzed for common terms, attitudes, experiences, and themes that are consistent with the domain. These themes should reflect the notions alluded to in the research questions. Structured and semi-structured interviews have the advantage of providing results quickly, and they are appropriate when the researcher already has an adequate understanding of the domain (Trimble, 1989). Semi-structured interviews can be quite productive in gathering rich data, but they can also be time consuming when done well (Hoffman et al., 1995).

Think Aloud Protocols

Verbal protocols can be one of the most effective techniques used to obtain rich data in a domain that has not been extensively researched previously. This is especially true if functioning within that domain is a function of past, present, and future experiences and knowledge (Bainbridge & Sanderson, 1995, Ericsson & Simon, 1993; Hoffman et al., 1995). To assess expertise, Simon and Chase (1973) used verbal, “think aloud” protocols and a series of performance tasks to assess expertise in chess. This combination allowed them to form an initial definition of what differentiated expert chess players from other chess players.

Further revision of this process led Ericsson and Simon (1993) to distinguish four different types of protocols: think aloud, talk aloud, eidetic reduction, and retrospective. All of them operate on the assumption that there is a link between what a person has in memory and what they are saying in any given situation. The think aloud technique involves asking an expert to perform a task within their domain and to verbalize their thought and problem solving processes from start to finish. Generally, this is about as close as a researcher can get to an actual working situation. Talk aloud protocols ask the participant to say aloud whatever they might say to themselves silently, and to keep that flow of speech going until the activity is finished. The eidetic reduction activity involves the participant "removing themselves from the situation" and viewing what they have done critically and reporting to the researcher. Retrospective protocols ask the participant to tell the researcher everything they can remember, including any uncertainties, about what they were thinking during the problem solving process. Their goal is not to repeat the problem scenario, but only to verbalize what they were thinking. While think aloud, talk aloud, and eidetic reduction protocols are performed real-time, the retrospective protocol is performed immediately after the event has taken place.

Think aloud protocols are often conducted later in the knowledge elicitation process, because they can serve as a way to check data that has already been gathered. By revealing particular sequences of events, these protocols expose the expert's problem solving process (Firlej & Hellens, 1991). They also assist the researcher in determining the cues that guide the expert's goal directed behavior and the strategies that he or she employs. It is critical that the researcher have a good understanding of the knowledge domain when this technique is used so that the participant is not stopped every few minutes to clarify simple aspects of the problem. In doing so, the participant may become frustrated and eventually simply quit the exercise (Firlej & Hellens, 1991).

Structural Knowledge Mapping

It is common knowledge in cognitive psychology circles that declarative knowledge becomes more attached to procedural knowledge as a person gains expertise within a domain (Jonassen et al., 1993). Structural knowledge is a facilitator that allows this transition to happen, and it becomes the knowledge of how concepts within a domain are interrelated (Diekhoff, 1983). Structural knowledge is at the heart of a person's mental model, and it forms the basis for knowing "why" in the relationship between procedural and declarative knowledge (Jonassen et al., 1993). Structural and conceptual knowledge encompass the knowledge *about* a particular domain; they enable the individual to form the connections they need in order to use their mental model (Jonassen et al., 1993).

The semantic networks, schema, and mental model theories mentioned in the Literature Review form the conceptual foundation upon which the elicitation of structural knowledge is based (Jonassen et al., 1993). Structure is inherent in all knowledge, and that structure in necessary for recall and comprehension, as well as problem solving. Individuals assimilate structural knowledge through interactive experiences, and experts' structural knowledge is different and much more highly developed than that of novices within a particular domain (Jonassen et al., 1993).

Knowledge mapping is an advanced level sorting task that is used in complex, abstract domains where the relationships among concepts is not immediately obvious (Jonassen et al., 1993; Firlej & Hellens, 1991; Lu, 1994). A typical knowledge mapping exercise involves presenting the expert with cards inscribed with concepts from the domain, and then the expert is asked to sort them. Modifications to this procedure have been made over the years since its inception to include leaving some cards blank to allow the expert to fill in areas that the researcher may have forgotten or did not represent appropriately (Jonassen et al., 1993). Concept sorting allows the researcher to determine the critical relationships between the fundamental concepts within a domain. When the experts are asked to sort the cards according to similarities in meaning between the terms, the researcher is able to see the relative proximity of the terms within the mental model of the expert (Jonassen et al., 1993). This task examines the priorities, dependencies, similarities, and differences as seen by the expert with respect to the domain concepts. By not supplying too many instructions, the researcher is allowing the clusters between and among the concepts to emerge. The groups or clusters can then be labeled to identify "main headings" within the conceptual structure of the domain.

Cards sorted by experts tend to reflect more elaborate and differentiated organizations structures than those created by novices within the same domain (Stein et al., 1990). The emergent knowledge structures, as defined by the expert participants, can then form the basis of instructional activities for learners or novices within a particular domain (Jonassen et al., 1993). They can also be further elaborated upon through the use of a semantic map (Jonassen et al., 1993) or cognitive map (McGraw & Harbison-Briggs, 1989). These maps graphically define the relationships between concepts within a domain and provide useful insight into the hierarchical relationships that exist. In many cases, these maps are a direct translation of the knowledge mapping task performed by the participant (Jonassen et al., 1993). Following the development of this graphical depiction of knowledge structure, the participant and the researcher engage in a dialogue concerning the particular placements and relationships of the concepts (McGraw & Harbison-Briggs, 1989).

While these methods have been chosen for their utility to the given situation, they are not without issue. It is common for all knowledge elicitation methods to have certain faults given the dynamic target they are trying to acquire. The goal is to select the methods that best represent the questions to be answered.

Potential Concerns Regarding Methods

According to Olson and Biolsi (1991), most knowledge elicitation methods have four distinct stages. They elicit behavior and information from the subject, and they summarize that data into a format that can be analyzed. Next, they analyze the data with an appropriate method, and finally, they display the information in some type of relational form. Aside from these general similarities, most knowledge elicitation techniques have a few issues with which researchers need to be concerned. When conducting any knowledge elicitation study, one must be aware of many things, especially the human factors issues surrounding the experts and the situations that affect the process. Researchers will often find that domains they intend to study are held mostly in an undefined, intuitive format. Some similar domains may have been studied, and some cases can be defined which represent typical decision-making processes. There might also be sufficient published material regarding the domain, and the chosen experts have sufficient knowledge to aid in the discovery process (Trimble, 1989). But none of these things can be taken for granted on each research project. Such is the case with constraint-based CAD, hence the reason for the chosen methods listed above. Similar domains have been explored (2D CAD, manufacturing, mold-design), but no attempts have been made towards the general domain of constraint-based CAD tools (Majchrzak, 1987; Bhavnani, 1999; Branoff & Hartman, 2001).

In addition to these concerns, the experts are in fact human with human-like personality traits and anomalies (Trimble, 1989). Researchers may encounter resistance from the expert in giving up knowledge that they have worked hard to acquire, and they may feel as if they are losing their status within the organization if that knowledge is potentially shared with everyone. Researchers may also encounter accessibility and prejudice issues on the part of the expert, given that experts are usually busy people within their organization. In an effort to maximize their research time, researchers may ask leading questions or "suggest" results that are not emerging from the data acquired. This becomes a trade-off situation usually, because the methods that are typically used to maximize time are also the ones that typically induce this type of bias. Experts are also usually better at doing things than they are at explaining them, so it is important that the researcher remain diligent in their quest for information. Finally, it is critical that the researcher establishes and maintains a rapport with the expert that will be beneficial for both parties.

Due to the dynamic nature of expertise, separate experts will not likely give the exact same answers to questions or scenarios posed during the study, and it is possible that the same expert may give contradictory information at different times during a prolonged study (Meyer & Booker, 1991). Also, observations tend to be passive in their methods, and they require a fair amount of inference on the part of the researcher to interpret what is happening. It is imperative that the researcher be familiar with the domain in order to frame those interpretations (Creswell, 1998). Researchers may find it difficult to gain access to a facility just to simply sit and watch what is going on. Due to security and sensitivity issues, it will be beneficial to enlist the help of a key informant to aid in establishing rapport and loosening the potential tension within the first few meetings (Creswell, 1998). While it is important to establish rapport with the participants being interviewed, the researcher must still be perceived as competent and worthy of the participants' time, especially if the participants tend to be involved in technical or scientific fields (Glesne, 1999).

When conducting the components of the phenomenological inquiry (observation and interviews) as described by Giorgi (1985), Colaizzi (1973), and von Eckartsberg

(1998) above, it is important to maintain a particular methodological procedure grounded in the tenets of qualitative research. Churchill et al. (1989) suggest four guidelines to abide by:

- Empathic dwelling: the researcher enters into "direct" contact with the phenomenon being studied. One must be patient and "stay with" the participant's description so as not to lose anything. This allows the researcher to become more open as to what is being communicated.
- Concentrated focusing and disciplined fascination: the researcher listens intently for all of the subtle nuances within a participant's description. The researcher also tends to "dwell" on the description of the situation so that even the smallest details become magnified.
- Thematizing meanings: This involves the participant acting or expressing themselves in such a manner as to truly believe that the way they are describing things is in fact the "way they really are". The phenomenological approach suspends this belief in favor of one that centers on a belief that experienced meanings are the correlative of particular attitudes that are assumed by the research participant. The focus now lies on "intended meanings".
- Attending to Motivational Context of Experience: This aspect of the research involves comparing the situational aspects of the participant's story to events on a greater scale that deals with the whole of their life. Usually, one looks for these related meanings throughout the rest of the data.

The expert's knowledge within a given domain is vast, and it is critical that the researcher focuses the questions for the semi-structured interviews so as not become off-task. If the participant feels that their time is being wasted, they may be reluctant to participate further, or they may provide brief answers to end the session quickly (Firlej & Hellens, 1991; Creswell, 1998). When conducting interviews or verbal protocols, it is also important not to pressure the expert. By asking a person what they have done or intend to do potentially forces them to feel compelled to give an answer. The answer may not be one that they would have chosen as much as it is one that they think that the other person wants to hear (Norman, 1983, p.11). Verbal protocols can be informative, but incomplete. It is often difficult for a person to verbalize everything they do while performing a task due to the nature of tacit knowledge (Norman, 1983, p. 11). While it may be difficult for the expert at first, a bit of gentle prompting is often required to get them going and to sustain them (Firlej & Hellens, 1991). In some cases, verbal protocols are considered contrived tasks, because the researcher often asks the participant to perform a task in a context or at a time that is unfamiliar to them. This can lead to a better understanding of the expert's reasoning process, but it can also make them initially feel uncomfortable (Hoffman et al., 1995).

Experts tend to pause to collect their thoughts, and constant interruption by the researcher will be seen as an inconvenience and can confound later analysis of the protocol (Firlej & Hellens, 1991). Asking an expert to verbalize their process also tends to alter their problem solving process slightly by forcing them to attend to a process that is not normally there. This is a slight risk, but one that cannot be practically avoided (Ericsson & Simon, 1993).

Knowledge mapping to obtain the structural knowledge of the expert's mental model is a simple technique, but the environment as well as other people present can affect it. It is an exploratory technique used primarily in the beginning stages of research in a given domain (Firlej & Hellens, 1991; Olson & Biolsi, 1991). Knowledge mapping can also be somewhat restrictive in that concepts may only be placed in one category or cluster. It is up to the relationship between clusters to overcome this (Jonassen et al., 1993). Researchers can offset this deficiency, especially in exploratory studies, by allowing participants to add concepts to the pool of cards. This keeps them from feeling restricted, and it also gives the researcher insights that they may have overlooked (Jonassen et al., 1993).

EXPERT SELECTION

Experts can be chosen in a variety of different ways. They can be nominated by peers or superiors or on the basis of performance criteria. They can be chosen based on their tenure or affiliation with a certain group, their position within a company, or their rank within a class. There is not necessarily any definitive means for choosing an expert; it depends greatly upon the knowledge domain to be examined (Sternberg et al., 2000).

Expert judgement is data given by an expert in response to a technical problem. An expert is a person who has a background in the domain area, and he or she is recognized as such by their peers or the researchers conducting the study as qualified to answer questions regarding the knowledge domain (Meyer & Booker, 1991). Expert judgement is often used to provide information on new or poorly understood phenomena, to learn an expert's problem solving process, or to determine what is known, unknown, or worth learning about a given domain. When selecting participants, anyone who is particularly knowledgeable about the domain at the level required could potentially be an expert (Meyer & Booker, 1991).

However, expertise is not a simple phenomenon. Individuals are selected for and attributed expertise all based on the norms of the domain. According to Hoffman et al (1995), expertise falls along a continuum in any given domain between complete naivete concerning a domain all the way to master. Experts for this study were selected according to their status as practicing professionals within the domain of engineering design and their use of constraint-based CAD (Hoffman et al., 1995; Ericsson, 1991; Glaser & Chi, 1988; Mieg, 2001; Meyer & Booker, 1991). Practice for these individuals included both formal education and training as well as practical experience. Similarity among the members of the group is preferred for such categories as approximate number of years of experience using constraint-based CAD tools, similarity among job tasks, and similar technical training. While similarities in technical training may differ among professionals, any person not having at least some formal technical training past high school was not selected to participate.

Based on the aforementioned issues for selecting participants, experts were selected for this study based on their background and experience, ability to communicate, availability, willingness, and attitude (McGraw & Harbison-Briggs, 1989). The goal of this study was to have seven participants, since this falls within the range suggested as most suitable to be handled by one person when using these types of knowledge elicitation techniques (Polkinghorne, 1989; Booker & Meyer, 1991). While consensus among the selected experts proved to be easier than originally thought given the similar applications of constraint-based CAD tools being used, the selection of a small number of experts in this case still provided a reasonable sense of direction for future study (Trimble, 1989) as will be discussed in chapters four and five. In addition, participants were selected only if they were a practicing professional within the mechanical CAD, industrial design, or commercial product design professions. No architectural, civil, chemical, or other non-mechanical engineering or technology professionals were selected for this study due to the relative non-existence of constraint-based CAD in those fields. Participants were ultimately selected for participation in this study based on the following criteria:

- Each participant had some form of technical training past the high school level.
- Each participant had at least three (3) years of experience in the use of constraint-based CAD tools as a practicing professional.
- Each participant used the constraint-based CAD tools for an average of fifteen (15) hours per week.
- Each participant worked in a product design environment with selection preference given to those individuals designing cast, forged, machined, or plastic parts.
- Each participant typically worked with assembly models containing more than ten (10) components.

It was anticipated that the technical background for each participant would vary, especially in regard to experience with other forms of engineering graphics, which turned out to be true in this study. The previous use of manual drafting techniques or 2D CAD techniques was not discouraged due to its potential revelation of important information regarding an individual's development of expertise in the use of constraint-based CAD tools. A description of each participant is included at the beginning of chapter four.

DATA COLLECTION PROCEDURES

The overall procedure for knowledge elicitation in this study was characterized by a combination of observations of the experts, which continued for the duration of the study, semi-structured interviews, knowledge mapping tasks, and verbal, think aloud problem solving tasks (McGraw & Harbison-Briggs, 1989). This overall theme informed a view of expertise in the use of constraint-based CAD tools that went from general to specific in the nature of its inquiry and the level of knowledge that it obtained.

The first step in conducting this study was to determine where to look for the experts. In order to determine the pool of experts to select from, members of the academic body in engineering graphics and employees at an international engineering consulting firm were asked to recommend the companies or types of companies from which to select participants. The Engineering Design Graphics Division (EDGD) of the American Society for Engineering Education (ASEE) and RAND Worldwide were asked to supply their opinion regarding which companies or types of companies should be solicited to provide experts for the study. At the end of August 2002, people in academic and professional fields of engineering graphics were sent an email describing the research study, which solicited their opinion as to the types of locations where suitable experts could be found. Over a period of two weeks, replies to the email request returned with suggestions regarding what kinds of companies or people should be studied. Upon receiving this information, it was determined that manufacturing, aerospace, heavy equipment, and mold design companies or types of companies received the most nominations. Using the recommendations made by those individuals and information obtained from the State Chamber of Commerce web site, the researcher began contacting potential companies within the state at the beginning of September 2002 using.

In an effort to minimize travel expenses, the researcher selected companies within a reasonable driving distance to his location as possible sites from which to draw the seven participants. Points of contact were made at selected companies within the human resources and engineering departments, and they were asked to nominate practicing professionals within their organizations who fit the criteria as experts for potential participation in this study. Once this was done, the researcher contacted these individuals to gauge their willingness to participate and to inform them of the reasons for conducting the research and the procedures used to gather data. Samples of the communication forms are included in Appendix A. Participants were selected in this manner to eliminate any undue bias on the selection process by the researcher (Linstone & Turoff, 1975; Meyer & Booker, 1991). The forms explained the overall process involved in the research study, the time it would require, and the impact upon the discipline of engineering graphics (McGraw & Harbison-Briggs, 1989).

The initial goal of the study was to have seven participants who matched the selection criteria as closely as possible. As the recruitment of the participants progressed, it became apparent that locating seven participants that sufficiently fit the selection criteria would be difficult. Given the economic conditions of the time period and the relatively few companies in the area from which to recruit participants, it was decided that five participants would be used as participants for the study. This number still fit the descriptions given by Polkinghorne (1989), albeit the low end of the range. Four of the five participants were committed to the study by the middle of September, while the fifth participant did not commit until the middle of October. Data collection proceeded with the first four participants, and the fifth participant was worked into the schedule when he was able. An initial meeting with each participant was then conducted to gather demographic information, review participant consent information, and establish rapport with them and others in the environment. Appendix A contains the contact letter and the informed consent letter given to each participant. The following sections provide an account of the procedures used for each specific data collection activity, followed by a description of the analysis performed on the data collected.

Observation Procedures

Once the administrative details had been completed, field observations began with each participant. Two observations per week for each participant was the initial goal, but meeting times and frequencies were heavily influenced by the availability of the participant and the flexibility of their work schedule. During some weeks, no observations took place, while in others the researcher was able to meet with some participants as much as twice during the week. Observations were conducted throughout the course of the study (from mid-September 2002 to early January 2003) based on the available access to the experts and their facilities.

Each observation session lasted approximately three hours, and during that time, the researcher observed and took notes of the participant in his working environment, based on a guide that focused on the characteristics of the environment, the participant’s use of the CAD tool, and their interactions with others in the environment (Gredler, 2001; Glaser & Chi, 1988). These questions are included in Appendix C. The field notes were later transcribed into an electronic format for analysis, at which time the researcher included reference to his own opinions and experiences in the use of constraint-based CAD tools, as well as references to various pieces of literature that might help to inform what was seen during the observation session. A copy of the observation guide is included in Appendix C.

By the end of the data collection period for this study, five field observations had been done with each participant, except for Participant1. Participant 1 was only able to complete two field observations due to his work schedule. Participant 1 and his design group were nearing the end of a particular project, and the researcher was able to observe the final stages of that project. However, as the research study progressed, Participant 1 and his design group began a new project, the initial stages of which did not include a great deal of CAD usage. Given the similarity of engineering environments and their activities (Henderson, 1994; Vincenti, 1991; Bucciarelli, 1994) with respect to the general types of activities that are conducted, missing three field observations for Participant 1 was not detrimental to the analysis of the data. A description of the observation analysis is included in the next section of this chapter.

Interview Procedures

After two observations with each participant, an interview guide was finalized based on information obtained from the observations, relevant domain literature (Gredler, 2001; Glaser & Chi, 1988; Bertoline & Wiebe, 2002; Sternberg et. al., 2000), and the past experiences of the researcher. These were completed during the period of early to late October 2002. It should be noted that only one observation was conducted prior to the interview with Participant 5 due to his late commitment to the project and a desire on the part of the researcher to remain on schedule. Interviews were conducted with each participant is a closed conference room so as not to disturb the participant’s coworkers and to minimize the potential of the audio and video equipment recording something that was confidential. These interviews focused on the participant’s past and present experiences related to engineering and design, his exhibition of certain characteristics of expertise, and his knowledge of the CAD tool. The goal of each interview was to further examine the definition and development of expertise in the use of constraint-based CAD tools *as it related to each participant* with respect to their work experiences, their conceptions of expertise, and their experiences in the use of constraint-based CAD tools. On the other hand, the observations took a more global perspective to the examination of expertise. (Moustakas, 1994; Creswell 1998).

The interviews were semi-structured in format, and the same interview guide was used with each participant. While each participant was given the opportunity to elaborate on the points raised by the researcher, each interview question was presented by the researcher to each participant in order to maintain consistency within the interview process. Interviews were audio-recorded, and the researcher also kept accompanying notes in a journal. The interviews were then transcribed and reviewed with each participant for accuracy and clarification if necessary. As a precaution, the interviews, as well as the think-aloud modeling tasks and the knowledge mapping sessions, were video-recorded, under any non-disclosure agreements that may exist between the researcher and the participants, so that any relevant non-verbal information could potentially be used in the analysis of the data as well. In an effort to maintain consistency in the treatment of each participant, all of the interviews were done before any of the think-aloud modeling tasks were completed, which were all done before any of the knowledge mapping tasks were completed. As mentioned previously, observations continued periodically throughout the course of the study. A description of the interview analysis is included in the next section of this chapter.

Think-Aloud Modeling Task Procedures

The third stage of data collection for this study involved conducting a think-aloud modeling task with each participant (Firlej & Hellens, 1991), which was conducted during the period of mid-November 2002. Each of these sessions was conducted either in a closed conference room or after normal working hours so as not to disturb the participant's coworkers and so that no confidential material was accidentally recorded. The nature of the think-aloud modeling tasks involved giving each participant a problem scenario in which they had to construct a 3D model using the CAD tool. A copy of the problem scenario as adapted from an engineering graphics textbook (Giesecke et.al., 1991) is included in Appendix E. During that exercise, they were asked to describe their process aloud. Whenever the researcher noticed extended "gaps" in their speech pattern, the participants were asked to (further) explain the action they had just performed. The goal of the think-aloud modeling task was to gather information that would give a deeper understanding of the procedural and declarative knowledge used in the operation of the CAD tool, both of which were witnessed in the observations and the interviews with each participant.

By conducting a pilot test of the solid modeling task, the researcher was able to examine the problem scenario and its potential solutions. This allowed him to better formulate questions for the follow-up interview that took place after the modeling task was finished, and it enabled him to understand some of the comments made by each of the participants. Given the nature of constraint-based CAD tools, there is usually more than one way to create a 3D model of an object and still fulfill the requirements of the design scenario. By examining these potential solutions prior to conducting the task, the researcher was able to determine potential locations of participant error or differences between the participants, as well as instances for the participants to elaborate on their procedure.

For the think-aloud modeling task, the researcher performed the pilot test in two different segments. First, the researcher developed a set of basic modeling procedures for the various solutions to the problem based on his *own* experience. These modeling procedures consisted of a descriptive list of the features, and their respective order, that could be used to create the model. Second, the researcher asked a colleague, who exhibited the requisite level of expertise in the use of constraint-based CAD tools, to perform the modeling task in an effort to gauge the level of difficulty of the task as well as to give the researcher an indication of how the data collection process will proceed.

Following minor revisions to the modeling problem suggested by the results of the pilot test, the expert participants were given the contrived modeling task for the construction of a 3D model using the constraint-based CAD tool. They were asked to verbalize their decision-making and modeling process while they worked concerning the methods they were using to create the model (Firlej & Hellens; Bainbridge & Sanderson, 1995). Following their completion of the model, a short interview session was conducted to inquire about particular choices they had made while they were creating the model.

These sessions were then transcribed, and the transcript was analyzed to discover the factors taken into account while constructing the model and the basic process used by each participant. The think-aloud modeling task was used to discover general stages of activity over the course of the modeling process and the choices that affect the activities in those stages. By examining the procedural and declarative knowledge of the expert CAD user, it was possible to gain an understanding of their strategic application of the various software commands and functions. It also attempted to expose the expert's frame of reference using the CAD tool without regard to functions that are specific to a particular brand of CAD software (Bhavnani, 1999).

Knowledge Mapping Task Procedures

The fourth phase of the data collection process was the knowledge mapping task. By completing this step after all of the other data collection methods, the conceptual structure conveyed in participant's mental model offered a potential summary of the results found in all of the other data collection procedures. In addition to the relationships between the major concepts within the knowledge domain of constraint-based CAD tools, the results of the knowledge mapping tasks served to enlighten the experiences discussed in the interviews and the strategies and techniques used in the think-aloud modeling tasks. Since this was the final stage of data collection, the knowledge mapping tasks were conducted during the period of early to mid-December 2002. Just as with the interviews and the knowledge mapping tasks, these sessions were either conducted in a closed conference room or after hours so as not to disturb the participant's coworkers and to not accidentally record anything confidential.

To develop the knowledge mapping task (McGraw & Harbison-Briggs, 1989), the researcher derived a set of cards with concepts and phrases regarding the constraint-based CAD domain taken from the interview transcripts, an engineering graphics textbook (Bertoline & Wiebe, 2002), professional trade literature, and personal experience. In total, there were eighty-nine (89) concepts and phrases that were used for this task. Each concept or phrase was hand-written on a 4” X 6” note card, and an identification number was placed in the upper right-hand corner of each card. This number was purely for identification purposes only, and it had no bearing on the final results of the task. It was simply used by the researcher to record and analyze the participants’ arrangements of the cards without being forced to repeatedly write each phrase or concept during each of the knowledge mapping sessions with the participants. A listing of the terms used in the task, as well as their reference numbers, and a description of the knowledge mapping task as given to each participant are listed in Appendix F.

In order to develop an effective and consistent presentation to be used with each participant, the researcher conducted a pilot test of this task with a colleague who is knowledgeable within the constraint-based CAD domain just as was done with the think-aloud modeling task. The pilot test insured, to the extent possible, that the list of concepts to be included on the cards has been reviewed and extended as much as possible before meeting with the first participant. It also gave the researcher some insight into potential questions to ask each participant during the debriefing session that followed each knowledge session.

When meeting with each participant, the cards were placed into the stack in numerical order based on the reference numbers in the upper-right corner of each card. Prior to beginning to arrange the cards, each participant was asked to read each one to make sure that he understood the term on the card, and if not, to clarify its meaning before proceeding. The researcher did not initially provide a definition of each term. Each participant was then asked to spread out the cards on the table and begin arranging and grouping the cards based on their own perceptions and experiences of how the terms were related (McGraw & Harbison-Briggs, 1989). The goal of this process is that the final arrangements of the cards would be reflective of the participant’s own personal perception and conceptualization of the constraint-based CAD knowledge domain and the key elements contained therein. Once the related concepts had been grouped together, the participant was then asked to arrange the cards to reflect any hierarchical, procedural, or clustered relationship that may exist between the concepts in each group. Finally, each group was labeled with a term representative of the group’s contents and its relationship to the rest of the concepts and relevant to the domain of constraint-based CAD tools (McGraw & Harbison-Briggs, 1989).

Participants were given the ability to add any terms that they noticed were missing (Jonassen et al., 1993; Olson & Biolsi, 1991). Blank cards and a pen of a different color were brought to each session as a means to record any additional cards (concepts) that the participants might add. Any cards added by the participants were recorded as being a part of the knowledge map for that specific participant, but each participant began the task with the same set of cards, in the same order, provided by the researcher. Participants were observed during this process for two reasons: to clarify any terms and to assess their relative difficulty with determining the relationships between the concepts listed on the cards. If the expert was able to organize the cards relatively easily, then the resulting arrangement is likely to be that much more realistic (Olson & Biolsi, 1991).

ANALYSIS

Due to the mixture of data collection methods that were used, this section of the chapter is divided into four sections, each one corresponding to a particular data collection method. Observations and interviews of participants are true hallmarks of qualitative research, and a staple of the phenomenological research tradition. Given that the observations and interviews yielded copious field notes and transcripts, they were analyzed in an effort to find common themes, which described the development and definition of expertise in the use of constraint-based CAD tools.

However, the think-aloud modeling task and the knowledge mapping task were adapted from the realm of cognitive psychology, which typically tends to use quantitative methods of analysis. While no quantitative analysis was done in this study, due to its scope and intent, the transcripts of the think-aloud modeling task were dissected in an effort to examine the potential courses of actions available to each participant. An effort was also made to determine if a common modeling process existed between the participants. The knowledge mapping task served to provide a great deal of summary information concerning the conceptualization of the constraint-based CAD domains by the five participants in this study. Each participant's arrangement of cards was examined for its overall layout and how that layout compared to the group as a whole. By using the information obtained from all of these measures, the researcher hoped to develop a description of the development and definition of expertise in the use of constraint-based CAD tools.

Observations

Once all of the observations had been completed and transcribed, and when the remainder of the data had been collected, the observation data was analyzed. This data was analyzed first in an attempt to describe a broad view of the definition and development of expertise within this particular knowledge domain. Since the data being collected was similar to that being collected during the interviews, except on a more global level, the researcher decided to analyze the observation filed notes using a similar procedure to the one used for analyzing the interview transcripts.

Each participant's field notes were printed, twenty-two observation sessions in all, and read by the researcher to find and correct any grammar or spelling issues. Next, the transcripts were read again, only this time, notes were made in the margins to denote key passages in the text. These notes used descriptive language common to the topic of constraint-based CAD and the engineering design domain. Using the process of horizonalization, as described by Moustakas (1994), the researcher listed all of the expressions from these text passages that were relevant to expertise in each set of observation data. Each was given equal significance and none of them were initially excluded.

The list was then examined a second time, and those horizons that were non-redundant and able to be abstracted for classification purposes were kept. These horizons became the invariant constituents of the observation data, the specific non-overlapping characteristics of expertise that emerged from the observation sessions. Upon examining this list of invariant constituents, all of those constituents that were related in some way were grouped together. These groups were then labeled according to relationships between the invariant constituents, and these groups were used as the significant themes of the phenomenal experience – in this case, expertise in the use of constraint-based CAD tools.

Each theme was then applied to the observation data in order to associate the invariant constituents back to the actual thoughts and intuitions of the researcher and the actions of the participants. Since the observations were intended to give a global view of constraint-based CAD expertise relative to this group of participants, these themes and passages derived from the observation data were used to form a composite textural description of the phenomenon of expertise.

Upon further inspection of the themes and their relationships to each other while developing the textural description, they were grouped again according to their influences on each other. It became apparent that the themes influenced each other in such a fashion as to be comprised of core, subordinate, and transitional themes. These three interrelated groups of themes were then examined by the researcher according to the imaginative variation suggested by Moustakas (1994) to arrive at the structural elements of expertise in the use of constraint-based CAD tools, which is described in chapter four. In this case, the imaginative variation used the intuition of the researcher and the observed experiences of the participants to reveal the apparent elements of the definition and development of expertise in the use of constraint-based CAD tools.

Interviews

The analysis of the interview transcripts was conducted in a similar fashion to that of the observation field notes, with one exception. While the field notes were examined at a global level and the description of expertise evolved from the information provided by the group as a whole, the interview data was used to develop a description of expertise based on the experiences of each participant. From those individual descriptions then came a composite textural and structural description of the phenomenon.

Following the interview process and during the course of the ongoing observations, the researcher provided a full account of his own experience with the phenomenon of expertise in the use of constraint-based CAD. This is the stage of the process known as epoche, as suggested by Moustakas (1994), and the full account is given following the participant descriptions in chapter four. The epoche process was an effort to examine the researcher's experiences with the phenomenon and to bring out any preconceived notions about the development of expertise in the use of constraint-based

CAD tools. In addition, the epoche process brings out the basis for the intuition used by the researcher when conducting the observations, developing the interview questions, and analyzing the various transcripts.

Upon analyzing the transcripts, the researcher initially made notes in the margins of the transcript to reflect the presence and usage of key concepts relevant to expertise in the constraint-based CAD domain, such as “training”, “communication with coworkers”, or “complex assembly”. The researcher then located statements regarding experiences that reflect the development and definition of expertise in constraint-based CAD. In doing so, the researcher denoted the “horizons” the data, similar to what was done with the observation field notes. For example, the phrases “I used to work as a drafter’s assistant” or “I used CAD a lot in school” might be examples of phrases regarding expertise development. A non-repetitive, non-overlapping list was then developed from these statements for each participant, and these statements were then grouped according to meaning.

The researcher then proceeded to develop a label for each category and assigned all of the particular horizons into one of those thematic categories. While some phenomenological studies might have had a more “emergent” list, the themes for this particular study did not deviate too much from the areas of interest in the interview guide used to interview the participant. Again, the focus of the interviews with each participant was to elaborate on their work experiences, their conceptions of expertise, and their experiences using constraint-based CAD tools in an effort to provide a description of the development and definition of the phenomenon.

Once the constituent themes from the interview transcripts were discovered a description of each category was developed and supported by verbatim examples from the transcript to provide a textural description of expertise for each participant. The textural descriptions were then examined using the emergent themes and the researcher’s epoche process to account for potential frames of reference and to construct a description of how the phenomenon was experienced. This process of developing textural and structural descriptions of expertise in the use of constraint-based CAD tools was repeated for each participant. From those descriptions, a composite structural description was developed for the group of participants as a whole. While the interview and observation data did account for a portion of the definition of expertise, they tended to provide more information regarding the development and the essence of the phenomenon of expertise in the use of constraint-based CAD tools. As described in the next section, the think-aloud modeling tasks and the knowledge mapping tasks tended to describe more about the definition of this phenomenon and less about the development.

Think-Aloud Modeling Task

The analysis of the modeling task occurred on several levels: alternatives, attributes, aspects and attractiveness (McGraw & Harbison-Briggs, 1989). Alternatives identified potential action opportunities on the part of the expert and their probable outcomes as a result of that particular selection. Attributes were the separate components or dimensions that defined each alternative. Aspects further defined each of the attributes. Attractiveness was the fourth level of analysis for the think-aloud modeling task, and it accounted for the psychological value, weight, or strength of a particular aspect. Aspects generally reflected the result of an expert's internal cost-benefit analysis. Note the following example.

The selection of one sketching plane over another, in terms of the use of symmetry in the part, while creating a feature in the model would be an example of an alternative. Each sketching plane would have its own set of consequences as a matter of the choice, which would impact the attractiveness of the particular choice. Upon choosing the sketching plane to create the feature, the expert would now have to make a decision concerning the creation direction of the feature and dimensional references for the sketch. Potential factors that would accompany this choice would be the use of an explicit dimension or the use of a geometric constraint to establish a location of an entity on the feature, which could be considered attributes in this case. Following in a similar vein, the creation of an explicit dimension or geometric constraint may have consequences later based on the potential modification that might be made to the model. The expert may perceive one aspect as being easier to accommodate than the other, so he or she may choose that one.

From the analysis of alternatives, attributes, aspects, and attractiveness, the researcher was able to discover the general nature of the modeling process used by each participant and its major stages with respect to the modeling task at hand. This was done by reviewing the transcript of each participant's modeling session to determine the various alternatives, attributes, aspects, and attractive characteristics used in the procedure. The order in which they completed the major steps of geometry creation was also noted. This process was done for each participant.

An overall characterization of the modeling process was determined by comparing the transcripts from each participant to look for common choices between alternatives, attributes, aspects, and attractiveness, as well as the use of common vocabulary and procedures. These characterizations were then compared to the interview results regarding experience to check for consistency between what each participant said they did or would do and their actual performance. Any differences were reported.

Knowledge Mapping Task

The arrangement of cards was examined to determine the various groups created by each participant and the concepts within each group (McGraw & Harbison-Briggs, 1989). Any relationships specified by the participants in regards to the concepts in each group were also noted. This arrangement was then translated to a graphical representation of the relationship structure, with the major groups, clusters, or levels of each map being the primary focus for each participant. The final knowledge map was discussed with each participant to assess why they placed each concept in such a fashion. This allowed the participant and the researcher to clarify any discrepancies the participants may have had concerning the meanings of the terms on the cards (McGraw & Harbison-Briggs, 1989) and to ensure accuracy on the part of the researcher during the transcription process.

Each participant's knowledge map was compared to his or her verbal protocol of the problem-solving task and the interview data as a means of internal consistency (McGraw & Harbison-Briggs, 1989). This comparison involved examining the participant's usage of particular terms and techniques within the problem solving task and the potential inclusion of those same terms and techniques within the knowledge map. In doing so, the researcher was able to examine whether or not each participant performed in a similar fashion to the one they had described. The knowledge map for each participant was also compared to his interview data to examine the relationship between experience and knowledge structure in an effort to gauge how previous experiences shaped the relationships that each participant made between the concepts in the knowledge map. A discussion if theses comparisons will be presented in chapter five. The semantic map of each participant was then compared and compiled to arrive at a common semantic map of the structural knowledge contained within the mental models of the participants. Some common elements did exist between the semantic maps of each participant, and any differences were duly noted as they may provide the basis for discussion concerning the effects of differences in experiences and differences in problem-solving strategies.

SUMMARY

As suggested previously, phenomenological inquiry and knowledge elicitation methods tend to be exploratory in nature (Moustakas, 1994; Olson & Biolsi, 1991), hence the selection of those types of methods for this study. In studying the development of expertise in the use of constraint-based CAD, participants were examined using a variety of techniques (Ericsson & Smith, 1991; Bainbridge & Sanderson, 1995). Observations and interviews were conducted to gain an understanding of the types of experiences that have contributed to the development of the participants' expertise within this domain. A think-aloud modeling task was used to understand how experts couple their experiences with their semantic knowledge of the software tools in order to solve a problem (Ericsson & Simon, 1993; Firlej & Hellens, 1991). Finally, a knowledge-mapping task was used to aid in the understanding the constituent elements of the participants' mental models regarding constraint-based CAD tools and their use (Jonassen et al., 1993).

CHAPTER 4: FINDINGS

The nature of expertise in the use of constraint-based CAD tools is similar to expertise in other knowledge domains in that it is complex in its origins and impacted by many factors throughout the work life of the participants. As the participants use these tools to construct the artifacts that change the physical and man-made worlds, they engage in a ritual that has its roots in several key knowledge areas. These areas are the psychology of expertise, technological knowledge as it relates to engineering graphics and the use of tools, and knowledge of the professions impacted by communities of practice and situated cognition.

This study used observations, interviews, a think-aloud-modeling task, and a knowledge mapping exercise to examine practicing professionals and their use of constraint-based CAD tools. By assuming that these practicing professionals did in fact exhibit expert characteristics in the use of these CAD tools, the researcher's goal was to expose the basic experiences and factors that comprise the definition and development of these expert characteristics. Each of these data collection methods was examined in turn as they provided information to inform the phenomenon of expertise in this area. The observations gave a global account of daily practice and the characteristics of expertise relative to the participant collectively that were witnessed by the researcher. The interviews yielded information similar to that found by the observations, but with more emphasis on participants' experiences within the knowledge domain, their conceptions of expertise, and their personal knowledge of the CAD tools. The think-aloud modeling task shed light on the participants' modeling strategies, and it gave a better look at the combinations of procedural and declarative knowledge that was used to construct a 3D model in a given situation. Finally, the knowledge-mapping task gave a summary conception of how each participant thinks about the domain of constraint-based CAD tools and its relationships to things inside and outside the realm of using the CAD tool.

The participants were selected based on their exhibition of expertise in the use of constraint-based CAD tools. They were chosen based on the criteria established in the Methodology section of this study, and all of them exhibited those criteria to varying degrees. This chapter includes a description of each participant to better understand the context and personal characteristics that led to the information uncovered in the data collection and analysis process.

In addition to understanding the characteristics of the participants, it is also important in a qualitative study to understand the characteristics of the researcher. The researcher acts as an instrument in the collection and interpretation of the data gathered. While all research studies strive to remove undue bias on the part of the researcher, the qualitative traditions tend to embrace the experiences and characteristics of the researcher more so than the quantitative tradition. In doing so, the phenomenological tradition requires that the researcher subject himself to the epoche process as described in the Literature Review (Moustakas, 1994). The epoche process allows the researcher to gain an understanding of his conception of the phenomenon in question and how it relates to the data gathered, as well as to guide him in his analysis and interpretation of the phenomenon in question.

In an effort to examine the data relevant to the definition and development of expertise in the use of constraint-based CAD tools, this chapter begins with a description of each of the research participants followed by a description of the researcher and his account of the phenomenon in question. However, the primary of focus of this chapter will be the presentation of the results gleaned from the data concerning the experiences of the participants regarding expertise using constraint-based CAD tools.

DESCRIPTIONS OF PARTICIPANTS

Five participants were eventually chosen for this research study, and all of them live and work within the state of North Carolina. Each of the participants worked within an engineering design group where they were an active member in the creation, modification, and maintenance of the products produced by the various organizations. All of the participants in this study were men, and each one had some type of technical education or training past high school. While each participant exhibited the characteristics laid out in chapter three to varying degrees, specific descriptions of each one are provided below.

Participant 1

Participant 1 is a thirty-one year old design engineer for a company that designs and manufactures pumping products for the commercial water filtration and swimming pool markets. He works in a group that consists of himself, his boss, and one coworker, however, they do interface with the tooling department and the marketing department concerning an array of issues involved in the production of their products. While this company has other facilities in the United States and abroad, this group has primary responsibility for the pumps that are designed and produced at this location. This is the only company that he has worked for in his professional career, but he does have experience working for them in the U.S. and abroad.

Participant 1 has a bachelor's degree and a master's degree from a foreign institute of technology, both of which are in mechanical engineering. While he was in school, Participant 1 did have some experience using CAD tools in the course of his duties as a research assistant, but only received instruction within one course, which basically consisted of working through the tutorials that came with the software. Currently, Participant 1 uses Pro/ENGINEER CAD software, and he is considered the resident expert within his group. In fact, he is the only one that knows how to use it. Participant 1 was sent to several training courses that were provided by the company that sold them the software. In addition to his knowledge of CAD tools, participant one is also fluent in several programming languages, including C++ and Java.

Participant 2

Participant 2 is a twenty-four year old design engineer with a bachelor's degree in mechanical engineering. He works in a large design group that has several other people in it that have access to Pro/ENGINEER and use it on a daily basis. It is a multi-national corporation that designs and manufactures heavy equipment for the construction and transportation industries. Participant 2 has five years of industry experience, all of which has involved using some type of CAD system. He had several internships while in school, where he did a great deal of 2D detailing work, as well as some design work using Pro/ENGINEER and some experience with prototyping technology. Participant 2 has worked with a variety of different manufacturing processes in his career, including sheetmetal parts, plastics, and forgings.

Participant 2 had some drafting experience in high school and during his introductory courses in college. In addition, he had two engineering graphics courses in college that used CAD software as part of the instruction. He also had professional training in the use of the CAD tools, including direct help from coworkers, access to corporate technical support, corporate in-house and off-site training, and vendor-sponsored training. Participant 2 took several professional training courses from introductory to advanced levels, and currently he is acknowledged as one of the resident experts in his company in the use of Pro/ENGINEER.

Participant 3

Participant 3 is a fifty year old design engineer for a company that designs and manufactures custom packaging and cases for consumer products. He works in a group with two other people - his boss and one coworker. Although they do interface with the tooling department and the marketing department concerning an array of issues involved in the production of their products. Participant 3 is also responsible for working closely with the manufacturing area to ensure that parts are made according to customer specifications. While this company has other facilities in the United States and abroad, this group is a stand-alone entity within the corporation, which means there is little or no support in terms of using the software. This is the only company that he has worked for in his professional career, which spans nineteen years.

Participant 3 has a bachelor’s degree and a master’s degree from a local land-grant university, both of which are in technology. While he was in school, Participant 3 had all of his instruction in engineering graphics using traditional drafting tools and techniques. In addition, a large part of his professional career used those same techniques before switching to a CAD system in the late 1980s. Currently, Participant 3 uses Pro/ENGINEER CAD software, and he is considered the resident expert within his group. In fact, he is only one of two people that know how to use it. Participant 3 was sent to several training courses that were provided by the company that sold them the software, and they range from introductory through advanced courses, including surface modeling.

Participant 4

Participant 4 is a fifty year old senior designer with an associate's degree in drafting and design. He works in a large design group with several other people who have access to Pro/ENGINEER and use it on a daily basis. It is a multi-national corporation that designs and manufactures electrical components for residential and commercial applications. During the course of his daily activities, Participant 4 often interacts with coworkers in his group, people in other company divisions, and the local tooling group to ensure that CAD data is accurate and useable. Participant 4 has twenty-eight years of industry experience with several different companies. While he has spent the last ten years using CAD tools, a large portion of his career was spent using traditional drafting techniques. He has worked with a variety of different manufacturing processes in his career, including sheetmetal parts, plastics, mechanical assemblies, welded parts, and forgings. Participant 4 has taken several professional training courses from introductory to advanced levels, and currently he is acknowledged as one of the resident experts in his group in the use of Pro/ENGINEER.

Participant 5

Participant 5 is a twenty-eight year old designer for a company that designs and manufactures inoculation equipment for the poultry industry. He works in a group that consists of himself, his boss, and four other designers; however they do interface on a regular basis with the vendors that fabricate their parts. This group has primary responsibility for the equipment that is designed and assembled at this location. He currently works with parts that are sheetmetal, machined parts, and plastic machined parts.

Participant 5 has a bachelor's degree in industrial technology and mechanical drafting and design from a university in the northern United States, and he has worked for three different companies in the course of his six years of professional experience. While he was in school, Participant 5 used CAD tools in all of his engineering graphics and design courses, primarily AutoCAD and SolidWorks. However, all of his knowledge of these CAD tools primarily came from one course and self-instruction. In his past jobs, he had professional introductory training in the use of other CAD tools, such as Pro/ENGINEER, Inventor, and CADKEY. Currently, Participant 5 uses SolidWorks CAD software, and he is considered the resident expert within his group. In addition, he also shares responsibility for the company's engineering archive with another coworker. Participant 5 spends the majority of his day using the CAD system; however, he does provide assistance to coworkers as needed.

EPOCHE: THE RESEARCHER'S CONCEPTION OF THE PHENOMENON

The epoche process is intended to give a view of the phenomenon as experienced by the researcher. It is not meant to remove any particular biases per se, but to recognize them and to account for their influence on the interpretations made by the researcher in regard to the experiences of the participants. This section of the chapter details the conception of expertise in the use of constraint-based CAD tools on the part of the researcher as written during reflective process in the field journal. It was written in three stages with each one taking a slightly different view of the topic. The first epoche session was done prior to any data collection.

> Expertise in the use of constraint-based CAD tools encompasses a wide range of actions feelings, knowledge, and experiences. Expertise, to me, often involves several years of experience within the engineering field, particularly in the use of CAD tools. Given that constraint-based CAD tools have only been used commercially for about fifteen years, they have gone through many significant functionality changes. It used to be that some constraint-based CAD tools would not create drawings, or they were not associative between assemblies and parts or between parts or drawings, all of which disrupted the engineering design process and communication channels between the people that worked in them. They have also increased a great deal in the depth and breadth of the functionality that the CAD vendors have tried to incorporate into them.
>
> CAD vendors have also tried to make their software much more multi-purpose than it was in the past to serve many types of companies within multiple engineering domains. This has met with varying degrees of success, but it has forced the average user to now account for more functions and options within the software, or to potentially disregard some of them altogether.

In addition to varying functionalities, different people within various industries will use software functions as necessary according to the typical geometry of their designs, while completely disregarding other functions. For example, it has been my experience that people who model bent and stamped parts have a good understanding of the sheetmetal functionality within the CAD tools that offer such functionality. That is one of the reasons that they decided to use that particular software in the first place. Also, those people that design cast metal, forged, or plastic parts usually have a thorough knowledge of the various solid geometry creation techniques, fillets, rounds, and the various modification functions associated with those particular features. Those people also typically have some basic knowledge of the surface modeling functions within the CAD tool.

Experts in the use of constraint-based CAD tools also have an extensive understanding of parent/child references and the conditions under which they are modified or created. This is usually the case regardless of the types of parts they create. Most people that I would consider to be experts in using these CAD tools also have a good understanding of datum geometry, how it is created, and when to use it. This last point can vary considerably, so it may be the case to say that they know when not to use datum geometry. Most expert constraint-based CAD users also have at least a basic understanding of how to create assemblies within the CAD system. They not only know how to put parts together, but they know how to edit those relationships when necessary. Experts will also know how to create a basic 2D drawing using the model as a reference. They may not know how to use every command, but they can at least use it well enough to be approved under corporate standards.

This last point – the ability to create a basic drawing or assembly – speaks to a higher issue, which are the differing requirements of various people within the organizations. This often happens due to the division of labor at some companies. Some engineering departments will have somewhat different requirements and uses depending on the job duties of the people involved. In large companies with multiple divisions, it is not uncommon to have engineers do preliminary layout work and have the designers use the CAD tool for the remaining stages of the design process. In smaller companies, engineers and designers (or just designers) have to fulfill a variety of roles that may require their knowledge of the CAD tool to be much deeper due to fewer human resources.

It has been my experience that expert constraint-based CAD users tend to always be very good modelers. They are extremely proficient at creating valid and robust geometry. Being proficient also allows them to use more

> of the CAD tool's functionality, which increases their likelihood of success, due to their knowledge of the various means to create particular geometry.
>
> Experts also have the ability to foresee potential changes that may happen in the design process that will have an impact on their models. They also have a good understanding of the internal and external customer requirements that could also force a change in their models. To address this, they will anticipate certain potential changes and build their model in such a fashion as to make the changes easier in the future, particularly in terms of their modeling strategy regarding feature type, feature order, parent/child references, and design intent.

The second epoche session was done as a reflective exercise about half-way through the data collection process. The researcher began to see expertise in some ways as a state of mind or an attitude that is not wholly-contained within tangible actions.

> I am at a point in the process where all major data has been collected and the analysis process is about to begin. As I look back, expertise has not lost any of it's characteristics from the first epoche session, but I think I see it in a different light than I did before.
>
> Expertise can also be thought of as an essence or state of being, possibly even a state of mind or an attitude. Experts in all areas have a confidence about them, which they often use to aid in tackling tough or unfamiliar problems. They are recognized as experts by the people around them and possibly by themselves. In light of this, they are often given (or they assume) positions of authority or higher standing within a design group or department.
>
> Expertise also appears to have some degree of self-efficacy or self-examination built into it. Many people do not think of themselves as experts; other people simply bestow that characteristic upon them through their need for information. While an expert's attitude usually has a fair amount of confidence in it, it also contains a bit of guarded optimism. They typically know when they can or cannot do something. However, I have seen expertise become fickle, enabled or disabled by the consequences of a particular design choice. In making those choices, an expert will consider many factors, not the least of which is whether or not they believe the methods they are using will be successful. I have seen many designers not use constraint-based CAD tools to their full potential for fear of what may happen if they make a mistake.

The third epoche session was done as a reflective exercise after data collection was finished in an effort to re-visit where the process began. This segment looks back to the original questions that the researcher had about conducting this study. It exposes some of the researcher's own experiences with constraint-based CAD tools, and how those experiences came to shape the original conception of this particular study.

> The quest towards a meaning or definition of expertise in the use of constraint-based CAD tools comes in part from my own curiosity and amazement of those who are better at using those tools than I am. In many ways, I would consider myself an expert in using those tools according to the criteria set forth in this study. I have six years of professional usage of the tools, including teaching those tools to others. I have performed a variety of modeling tasks, and I have used them extensively within industrial environments.
>
> But I know that my experience is different from others, and I know that there are people who are better at using these tools than I am. How a person develops expertise in the use of these tools is often based on those differences in experience, and in some cases, those experiences can be quite extensive.
>
> So, how do we give people similar experiences as they learn to use these tools? I ask this from the point of view of a teacher. I have had students "get it" and those who "don't get it", so how do we reach those who "don't get it?" How do we give them adequate experiences to learn the tool? What are the critical, common elements and processes of the knowledge base that they should know? I argue that this is done by mimicking those who use the tool on a professional basis. Those people have gleaned information and knowledge from their lived and working experiences, which could be transferred to a learning environment in so far as possible.
>
> The amazement that I referred to earlier, regarding those that know more than I do, stems from an issue of confidence. Technical people like to be sure of their knowledge, and when they are not sure, their comfort level for their current situation changes. In an effort to maintain some degree of comfort, they are continually seeking answers to their questions. Whether it comes through personal contacts, experiments, or training, they need to find it. I often think of myself in this fashion as well.
>
> I also see those experts as being able to address almost any problem or issue within the software. Some of my former colleagues had a great deal of knowledge about the software, but not much professional practice to go with it. On the other hand, others have had a great deal of professional practice coupled with a great deal of knowledge about the software. I think it is this past experience and knowledge of the software, as well as the mechanisms with which to put it all together, that gives them the ability to

> tackle almost any problem. The study of this topic then should follow fairly closely then with the literature concerning expertise, experience within the professions, and technological knowledge.

These excerpts from the researcher's field notes paint a picture of his intended direction for this study and the factors that lead him to it. Throughout these three passages, several elements were obvious. The importance of authentic experiences, extensive domain knowledge, and thorough understanding of the core software processes are essential in the mind of the researcher. While this epoche process was not to discount the findings presented in this chapter, it does serve as a barometer with which these findings can be interpreted in conjunction with the relevant literature available. The next several sections of this report present those findings with respect to the various data collection methods, with a particular eye towards a description of the thematic elements of the participants' experiences with the phenomenon and the configurations of their internal mental models of the knowledge base.

OBSERVATIONS: AN OUTSIDER LOOKING IN

The following description of expertise in the use of constraint-based CAD tools is a portrayal of the participants' knowledge based on periodic observations by the researcher within their working environment. It combines their procedural, declarative, and tacit knowledge into strategic use of the tools at their disposal, CAD and otherwise. This knowledge of their tools is impacted by the semantic and syntactic nature of those tools, by tacit knowledge of past experiences contributing to their mental models, and by the influence of the engineering design profession and communities of practice.

A Global Thematic Portrayal of Expertise

As constituent themes of expertise in the use of constraint-based CAD tools began to emerge, it became apparent that they could be classified in a global fashion. These themes consisted of either things directly related to the use of the CAD tool or things not directly related to the use of the CAD tool. Themes related to the CAD tool emerged from the researcher's observation of the participants while they were actually engaged in the use of the CAD software, such as cognitive strategies, command usage, and downstream uses of the model. During the observations, the participants performed other actions besides using the CAD tool, such as communicating with colleagues, considering design factors, and problem solving activities, which are common in nearly all working environments. In addition, each one of them exhibited a particular way of working. While this seems like a simple description at first, it became readily apparent that all of these factors are intertwined in the definition and development of expertise in this study.

All of the participants exhibited the following themes of expertise throughout the course of this study. However, the frequency of their exhibition depended on the project they were working on during the researcher's observation. It is through the completion of these various projects that the researcher and the participants came to know that the social and cognitive factors that surround the use of constraint-based CAD tools are interrelated at various levels. They form a global view of the development and definition of expertise in the use of constraint-based CAD tools. Following is a description of the general themes that emerged from the observation data, which is then followed by a description of the phenomenon of expertise in the use of constraint-based CAD tools as *observed* by the researcher examining the participants' ways of practice.

Strategies for using the tool – The data revealed that the participants exhibited their own personal strategies to use in the creation or modification of a 3D model when designing their products. These strategies were eventually coupled with knowledge of the inherent workings of the software to complete the task at hand. In order to do that, the participants often needed to consider the extent to which their actions might influence other things, such as related CAD files and manufacturing timelines. The results of the particular strategy employed were typically manifested within the resulting behavior of the 3D CAD files, and they had some determination on the participants' progression through their work.

Eventual uses for the CAD model – After creating the CAD model, or during the creation process, the participants would often use the CAD model for various things: machining tool operation, finished inspection, or data sharing to name a few. In doing so, they were required to use techniques within the CAD software that would create geometry that was easily modified and manipulated to support its use in other areas of the enterprise. CAD model usage is tied directly to another emergent theme, Design Considerations, and the relationship will be described later in more detail.

Software usage – Software usage is just that: a description of how each participant used the software. Each participant had his own choices for creating and modifying geometry within the particular design environment. As they struggled with this creation and manipulation of geometry, it became evident that each person had his own particular techniques for creating and editing geometry, including those areas of the model that caused problems or errors with the methods that the participant had initially chosen.

Technical Communications – At various times, each participant would use the model as a vehicle for communication with coworkers, superiors, or individuals outside the group. It was done by highlighting various surfaces or whole parts, modifying dimensions to show a “before and after” scenario, or by simulating movement within the assembly files. Often times, the model became a centerpiece around which people gathered to discuss pertinent information related to the task at hand. This is different from the Social Communications listed below in that Technical Communications is directly related to the use of the 3D model, particularly, to relay engineering and design information between various people and groups, and it is not related to simple dialogue using written notes, sketches, or verbal conversations.

Support Structure – In most working environments, there is some type of support structure that exists to help people accomplish their tasks and goals. In the case of the participants in this study, support structures typically took the form of internal help desks, written reference materials, training guides, secure access to software vendors’ web sites, or help from a coworker. However, three out of the five participants had no substantial support structure to speak of, and in many cases, they had to develop a solution to a problem with little or no assistance from anyone or anywhere else. In light of this fact, their level of expertise was supplemented in a slightly different manner than their counterparts who did have a more elaborate support structure.

Artifacts – A result of the engineering design process is the production of artifacts to address a given design problem. Some of these artifacts represent the goal of the finished process, while others represent an intermediate step on the way to the end. In addition, some of the artifacts are tangible, and some are not. The participants in this study typically had access to many artifacts, such as model or drawing archives, sample parts and prototypes from vendors, or tooling that was generated as a result of using the solid model as a reference. These artifacts contributed often in their ability to diagnose a problem, and they enabled them to more quickly and easily solve those problems by using these artifacts as references.

The Design Environment – Engineering environments are dynamic and complex places full of many factors that affect the successful design and production of a product. The participants' design environments contributed in a unique fashion to their development of expertise in the use of constraint-based CAD tools. For four out of the five participants, this meant being able to walk directly to the shop to examine the characteristics and behavior of production parts and tooling that were being created. They could then incorporate that information into the 3D model, as well as diagnose potential errors that are not always easily noticed when reviewing the CAD model. In addition, all of the environments that were part of this study allowed for collaboration between coworkers as they designed an object.

Social Communication – As in any work environment, coworkers communicate with each other. In this particular study, it was no different, but a critical level of communication did emerge, which was the solicitation of information from each participant by his coworkers. Each of these participants played a role within their particular group, and people sought their opinions and technical knowledge regarding the use of the CAD tool and what to do with the models that were produced. Communication also encompassed the flow of information through the engineering environment and how much each participant either directly or indirectly impacted that flow. Finally, this social communication of knowledge also included the use of the model by each participant as a vehicle for communication with his coworkers, specifically how the model was created and the model's ability to serve as a "warehouse" of engineering knowledge.

Past Experiences – Each participant's past experiences contributed heavily to the development and definition of their expertise in the use of constraint-based CAD tools. Two of the participants each had over twenty years of experience in the engineering design field. The other three participants each had at least four years of experience in the field. All of them had been using constraint-based CAD tools for at least three years, and they had encountered a variety of modeling and design scenarios. They all had traditional drafting experience, as well as knowledge of materials and manufacturing processes. All of these prior experiences contributed to the way they used the CAD tools, particularly in the ways they created geometry, specified references, evaluated their potential options and choices within the software, and what they expected as a result of their finished modeling processes. These past experiences, coupled with articulated modeling strategies and knowledge of the fundamental characteristics of the CAD tool, paint a good picture of these five participants' expertise in the use of these tools.

Design considerations – For each of these participants, the factors that they considered during the creation of a 3D model were directly impacted by their knowledge of the CAD system and its processes, the local engineering environment, and their past experiences in dealing with similar situations. Factors such as anticipated design requirements and potential changes to them over time, the interaction between parts in the product assembly, and external influences (e.g., customer requirements and manufacturing processes) all directly influenced how the participants created geometry in the CAD system.

The Way He Works – Each participant exhibited unique ways in which they worked, although they did have some common characteristics. Each participant tended to work with a given set of design circumstances and use that information until it ran out. They would then begin to search for and apply information relevant to their problem that could be found in his past experiences, reference materials, and other coworkers. It also seemed as if each participant had his own routine: the way he liked to work, which determined the manner in which he searched for the aforementioned sources of information. Company-specific processes and practices also affected not only the manner in which each participant worked, but it also impacted the way they would use the CAD system and the ways that they would apply past experiences and strategies.

Problem Definition and Solution – During the course of the observations for this study, each participant encountered a variety of problems that required a solution, especially in regard to the creation of geometry with the CAD system. In each case, the participants spent a great deal of time gathering information, such as dimensional values between two components, parent/child references, or simply testing a command to evaluate its results. Each time, they would then compare this information to past experiences and their knowledge and expectation of how the software operates to determine an accurate definition and scope of the problem.

Participant Characteristics – All of the participants had some type of engineering- or technology-related education and training in a formal sense. While this aided them in the definition of the problem and gathering information to solve it, practical experience was often the only guide in solving problems directly related to the operation of the CAD tool. Three out of the five participants had CAD instruction as part of their formal education, but it was typically simple model creation that did not resemble the complexity they encountered in their job performance. Due to this level of complexity, all of the participants were well aware of the CAD system functions that they knew well and those that they did not know or that they had problems with. Some of them did not consider themselves "experts", but simply "more experienced" based on the elements of their job duties.

Domain Knowledge – All professions have a core knowledge base and accepted practices for the way work is done that are bounded by the cultural norms and practices of the profession, and engineering and technology are no different. All of the participants had extensive knowledge of the products that they designed, in addition to the materials and processes that were used to make those products. In the use of the CAD tool, each one of them was guided by the "best practices" recognized within their engineering environment. This was often coupled with their past experiences and the design considerations at the moment to produce a particular strategy for using the CAD tool to create a model that embodied the design intent required for that particular project.

A Global Composite Textural Description of Expertise

The composite textural description of the development and definition of expertise in this study reflects the significant relationships between the various thematic elements of the phenomenon as they relate to the participants as a group. The presentation of results in this section of the chapter reflects the global nature of these themes, and it cites specific examples from the researcher's field notes to illustrate these relationships.

The development and definition of expertise in the use of constraint-based CAD tools is enlightened by information that is related to the CAD tools themselves and to information specific to the engineering design domain. Both of these include procedural knowledge, for example, in terms of how to use the CAD tools and how to utilize problem-solving techniques. Declarative knowledge is also included in things like knowledge of the various types of geometry the CAD system will create or the standard values for the thickness of sheetmetal and the accompanying bend radii that goes with them.

Strategic knowledge also plays a role in the development and definition of expertise. Things like understanding the various methods to create geometry in the CAD system and the selection of the most appropriate method for the current design scenario, or the selection of references to create geometry based on what has worked in past modeling exercises. And winding a thread through all of these types of knowledge is the tacit knowledge of the expert; things that he knows or does, but cannot say why he knows or does them. The knowledge of the engineering design environment, the same geometry creation technique used repeatedly, and the particular ways that people work are all examples of tacit knowledge that play a part in the development and definition of expertise in the use of constraint-based CAD tools. While the themes listed above are directly related to the CAD tool and some are not, it is evident by their description that they are interrelated, and that they embody strategic, declarative, and procedural knowledge related to the use of these tools. The elements that contribute to the development of expertise are informed by those that contribute to the definition of expertise in the use of constraint-based CAD tools and vice versa.

According to the data collected for these five participants, the definition of expertise in the use of constraint-based CAD tools is comprised of five core themes: (1) strategy for using the tool, (2) problem definition and solution, (3) design considerations, (4) domain knowledge, and (5) past experience. These five core themes were used in combination by the participants in their performance of the necessary tasks within the design environment. In many instances, these tasks greatly influenced the subordinate level of themes that were also derived from the collective participant observations: (1) software usage techniques, (2) downstream uses of the CAD model, (3) social communication, and (4) technical communication. The design environment, the way the participants work, support structures, artifacts, and their personal characteristics are transitional themes that continuously impact or are impacted by all of the other themes. A listing of the themes in each category is shown in Table 1.

Table 4.1

Global Composite Themes of Expertise Based on Observation Data

Core Themes	Subordinate Themes	Transitional Themes
• Strategy for Tool Use • Problem Definition and Solution • Design Considerations • Domain Knowledge • Past Experiences	• Software Usage Techniques • Downstream Uses of CAD Model • Technical Communication • Social Communication	• Design Environment • The Way the Participants Work • Support Structures • Artifacts • Personal Characteristics

All five of the core themes are interrelated with each other, and they contribute in both a direct and indirect way to the subordinate level of themes. Typically, each observation involved the participant addressing some sort of design problem, which may have originated from one of several different sources: corporate marketing, product problems in the field, direct customer request, or maintenance on the current design. Regardless of where it came from, the participants had to begin formulating the scope and definition of the problem, and they had to begin acquiring the requisite information to develop a solution. Their decisions about including or excluding information were often based on the design considerations pertinent to the particular situation. The following excerpt from the researcher's field notes is an example of one of the participants taking into account Design Considerations as he is developing a strategy for geometry creation and implementing a solution to the problem.

> Today, participant 5 is working on a redesign to the frame of the machine. Currently the machine has an angled support gusset in each corner of the

> frame. It is welded into the corner of the frame, but the vendor is having difficulty creating this weld.
>
> Participant 5 is going to replace the angled gusset with a two-piece, 90-degree gusset which will be butt-welded to the upper horizontal frame member on one and to the vertical side frame member on the other end. This will happen in a total of three places on the frame. The gusset will be made from two pieces that are the same part. It is square channel steel to match the rest of the frame, and it is 3.5 inches long. It is square at one end, and it has a miter cut at the other to form a 90-degree bend when mated with the other piece.
>
> The first thing that Participant 5 did was to search the PDM database to see if a piece like that existed already so as not to duplicate effort and part numbers. He found that there was none, so he created it. It did not take long at all: an extruded square base, a shell to hollow it out, and an extruded cut to miter one end of it.

To address this design problem, Participant 5 used his knowledge of materials and fabrication processes to design a series of parts that would enable faster production and easier maintenance. Materials and processes are two of the invariant constituents of the Design Considerations theme. In doing so, he had to gather information and examine the potential impact of the creation of a new part number within the system by using the PDM tool to query the model archive.

As stated above, information gathering is one of the invariant constituents of the Problem Definition and Solution theme, and his examination of the potential impact of new part creation fits into the theme of Design Considerations. Another example of the development of a problem scope based on design considerations can be seen with participant 2. In this case, not only did he have a variety of design considerations, but the development of a solution was also affected by his communication with a design group outside the country.

> When I arrived today, Participant 2 was in the process of revising an attachment group on the machine that forms a cage around the cab and canopy to prevent the glass or the operator from being hit by debris on the job site. Just as with my last visit. Participant 2 is working on the redesign of the object to enable a material and cost reduction. This is one of Participant 2's ongoing tasks for the year – to examine existing component

> groups on the machine to determine if a competitor is filling the market with lower-cost attachment with the same function and if so, to design a component group to compete with the market. Participant 2 was able to acquire some photos of a competitor's product in the field, so he is currently evaluating his company's current offering compared to that of their competitor. However, the primary concern he has is to reduce costs and assembly time on the current standard components as well.
>
> The original design was experiencing a crack on the overhead portion due to the vibration of the machine. As it turns out, the natural frequency of the support rails in this component group falls within the natural frequency of the larger machine. When this happens, the attachment groups tend to shake and vibrate in an exaggerated manner. The original designer added a plate to the top of the assembly to stiffen the body of the component group, but that has become rather expensive over time. The component group is also soft-mounted to the frame of the machine, which means that it uses rubber grommets in the mounting hardware assembly to reduce vibration. In addition, it has a series of slots in the flange on the top of each rail to take up the assembly allowance between parts. Participant 2 is considering moving these slots to the flange on the bottom of the rail, but he has stated that he has some checking to do. The primary factor in the decision to move the slots is a communication that must take place with the facility in Japan. That is where the majority of the machines are assembled, and participant 2 must first ask them if they are having trouble with the assembly, because he does not want to fix something if it is not broken.
>
> In order to perform the aforementioned change, Participant 2 must interrogate the assembly model of the component group extensively in order to determine the extent of his proposed changes. In order to do this, he must consider the P/C references that exist between the components that he is modifying and the components that come afterwards. If not, he could potentially destroy the entire assembly in terms of the design intent required reflecting the movement, or lacking thereof, in the support rails. He uses the majority of the Info tools in Pro/ENGINEER to do this, because he has commented several times about having problems later on if he does not thoroughly interrogate the model to begin with.

Another example of the extent that some of the participants would research a problem scenario can also be seen in another excerpt regarding Participant 2.

> Again, as before, he made a conscious effort to incorporate many factors into his decision making process, which is one of the general indicators of expertise. This "scoping" of the problem was also evident in his creation

> of a Cut feature at the bottom of the main windshield housing. In doing so, he had to make sure that the sheetmetal housing part followed the contour of the hood. If not, there would be too large of a gap for the welding procedure and the adhesive that held the window in place would not seal properly. He spent nearly thirty minutes on this procedure in an effort to determine the ramifications of his actions. Once he had the information that he needed, he performed the actual Cut operation in less than a two minutes, but it appeared as if it was the time spent gathering information that made this possible.

As can be seen in this example, Participant 2 spent a great deal of time and effort assessing the situation before proceeding towards a solution. He gathered a great deal of information, and he accounted for several design criteria, some of which he may have no control over. Participant 2 also used a good deal of Domain Knowledge, in regards to the physical properties of materials in a high-vibration environment, in his decision to move the mounting slots on the rails. As can be seen in these two examples, a myriad of design considerations confronts the constraint-based CAD user during most design scenarios. In addition, the articulation of those considerations often takes the form of Social and Technical Communications within the design environments, which was shown here in the conversation that Participant 2 had with the group in Japan and their control of the majority of the assembly processes.

As mentioned previously, the five core themes provide the backbone for the subordinate level of themes, which are software usage techniques, downstream uses for the CAD model, social communication, and technical communication. In most cases, these subordinate themes are the embodiment of a combination of the core themes, such as the software command choices for creating or editing model geometry are based in large part on the participants' strategy for using the CAD tool and the design considerations in the design scenario. The conversations between coworkers while discussing the creation of a CAD model in a particular fashion is supported by each participant's past experiences and their domain knowledge.

Once the problem definition and scope had been reasonably set, the participants then began to employ their strategies through particular sequences of commands or geometry creation and modification techniques. In addition, they were able to contemplate downstream uses of the model, as well as to enable communication via the solid model database. In the following example, Participant 3 had to create a plastic case that would hold the products designed by one of his customers. He had to create the case using only the information given to him by the customer in the form of an IGES file. He used the surfaces in the IGES file as a reference for creating the geometry necessary for the model, as well as a communication vehicle between him, the tool designer and the customer. However, Participant 3 had concerns that the customer may come back at a later time and ask for modifications, so he built the model in such a fashion to accommodate those changes if they were to occur.

> As I began to watch him create the geometry that he needs, I have again noticed him using Datum Curves as the driving element behind his geometry. Due to the complex nature of the surfaces of his part, he finds that using Datum Curves is advantageous from the stability perspective. They tend not to fail as easily when modifying and redefining the part. In addition, Participant 3 uses Datum Curves as a means to create the outline of a feature, and then use the Duplicate Entities functions in Sketcher to drive the shape of the feature. He also uses Datum Curves to drive the creation of Variable Section Sweeps that he often uses in place of complex Rounds or Draft. His reasoning is that those Solid features are often more stable and less likely to fail than are the normal Round and Draft commands. Rounds and Draft often fail when subsequent features are added to the model, or when their references are manipulated.
>
> Participant 3 also stated that the customer for whom he was constructing this model would not accept a model that had External References. This means that he must break all ties to the reference geometry that he copied from the IGES surfaces that he was given. He had created his Datum Curves based on their coincidence with particular spatial locations in the assembly by copying edges and other references. In order to break those ties, he had to re-dimension the curves inside their sketches so that they were located to the default datum planes of the part instead of being referenced to the assembly.

The Communication themes that emerged in this study focus on technical and social communications as they relate to the CAD model. In the following excerpts of the field notes, Participants 2 and 3 show different forms of communication, one using the model to communicate, and one using the model as the focal point of the communication.

> However, depending on the level of work to be done and the end customer, Participant 3 will not always make a drawing. For example, when making the tool cases, he does not necessarily make many drawings, because he passes the solid model to the tooling people, and they generate the tool paths from the models.

The next example surrounds a conversation between Participant 2 and one of his coworkers about the redesign of the machine made in Japan.

> Participant 2 also asked his coworker to help him in evaluating his design, because the exhaust stack is in the way. I am not sure what the coworker does, but it may be something in product planning or assembly planning due to his continued use of a spreadsheet program. His coworker has suggested that participant 2 may not need the cross members at all, and just use the x-shaped cross members to make the assembly rigid. The coworker has also suggested that participant 2 evaluate the cost of the channel steel at this point so as not a great deal of time and effort is wasted on a solution that will not be feasible.

This next example of social communication also exhibits the flow of information within a design group and gives an example of how Participant 4 often interacted with his colleagues. In addition, it exhibits the nature of the engineering domain and its associated language.

> Consistent with the idea of professions having their own knowledge base and enforcing boundaries around it, Participant 4 uses his own jargon when he talks about his work to me and with others in the organization. While I have difficulty at times understanding what he is talking about, all of his coworkers are perfectly clear as to what he is saying. Participant 4 also interacts with others in such a way as to be the provider as well as the beneficiary of information. There was a particular person from tool design who asked Participant 4 about a very specific component within the product and wanted to know his opinions regarding a potential course of action related to the ongoing changes to this component.

Participant 1 and his design environment also exhibited a good example of communication in terms of its directional flow within the organization, and how this impacted the way he applied his level of expertise to the situation.

> At this point, Participant 1 was working on a model of an Impeller for one of the company's current pumps. The reason for this is that the pump has been made with that Impeller for several years, but the documentation drawings have never matched the production parts in terms of finished

> geometry. This series of pump is the leading seller for the company, but their drawings do not actually correspond to the geometry in the finished part, so Participant 1 is creating accurate models of the part in order to create accurate documentation drawings. The information to do that was passed along to him via one of his coworkers; she had marked up a set of drawings according to the information the company had received when a finished Impeller was inspected with a CMM machine. Having accurate solid model data is important, because the company intends to communicate with their vendors more and more through the used of the 3D database. In addition, the parent company has a quality initiative that they have enforced on all of their constituent companies in an effort to lower production costs. One of the key ingredients to that plan is an increasing use of the engineering design database as a vehicle for communication with suppliers and as a means of inspection.

As the core and subordinate themes interact with and inform each other, remaining themes tend to pervade the definition of expertise by acting as a blanket that surrounds the phenomenon. The design environment and the support structure contribute directly to the development of expertise or provide evidence for the existence of expert characteristics. Most of the participants had access to their respective production facilities, which was of great benefit if there were any shop problems that needed to be addressed. It also gave them the opportunity to test portions of their design and receive virtually immediate feedback regarding success or failure. An example of this comes from the initial description of Participant 1's and Participant 5's respective work environments.

> I arrived at the facility at about 9:00 am. After meeting with the participant briefly in the lobby, he gave me a tour of the facility. Similar to other engineering design environments, they are located adjacent to and on the same property with their manufacturing facility. Although, in this case, the majority of the production operation consists of assembly operations rather than part fabrication, but they do have some injection-molding equipment for their plastic parts.
>
> I met with Participant 5 today… finally. He gave me a tour of the "shop", but it looks like they don't do a whole lot of manufacturing here. It's mostly a custom assembly operation and prototyping center. Most of their "parts" come in already put together, and all they have to so it put it in its final position on the machine. Although that stands to reason I guess, considering they have only sold about 150 of their machines. The office area and the shop are not separated by too far of a distance, so participant

> 5 does not have too far to go if there is an immediate problem. However, they do extensive field trials for which there is some travel involved for each member of the design team. At this time, they have the overwhelming majority of the patents on the technology and processes used by their equipment, so they are setting the pace in terms of the design of the product.

While the previous examples have presented context-specific insight into the definition of expertise in the use of constraint-based CAD tools and some of its contributing factors, the development of expertise is a bit more difficult to describe. Through his own experiences and intuition, the researcher was able to interpret the actions, discussions, and people in the organizations that participated in this study to examine the development of expertise in the use of these tools. While expertise in most fields is developed over extended periods of time, it is also impacted by the level of immersion of the participant into the environment and the types of experiences had by the participant.

In this particular study, the definition of expertise was described by core and subordinate themes, as well as themes that permeated both levels. The development of expertise can be described by some of those same themes, but only through a more intuitive process. The primary focus of the development of expertise appears to center on the themes of past experience, support structure, the design environment, and personal characteristics. In the researcher’s interaction with the five participants, he was able to observe them in their design environment performing their normal job functions. It was through these functions that their levels of expertise manifested itself in their actions. The researcher was then able to intuit from those actions the apparent nature of participant’s past experiences, the level of help and support they had access to, personal characteristics that might have attributed to their success, and the effects of their design environment.

As mentioned previously, one of the most influential factors on the development of a person’s expertise is the kind and duration of experiences that they have had within a particular knowledge domain. While observations of extended duration were not possible in this study, it became apparent that the participants in this study were impacted by their past experiences as well, and it was not just from a CAD-tool perspective. One of the more striking examples of this was the manner in which Participants 3 and 4 used the Sketcher tool within the software and the reasons that they did so. The following examples are excerpts from the researcher's field notes to illustrate this point.

> As he is creating geometry in his initial feature, Participant 3 selects all of the dimensions at one time to be modified. In doing so, this keeps him from having to select each one individually, which is enabled by the software's dialog box functionality. When selecting multiple dims for modification, if they are selected all at once, the software will display a dialog box with the dimension name and its associated value, and the user will be able to modify it from one common location while maintaining the scale of the sketch. Once he is finished, Participant 3 moves all of his dimensions to the outside of his sketched geometry before proceeding with his next operation. When I asked him why he did this, he stated that is helps him to view the sketches quickly and accurately when modifying the geometry, and that it follows the conventional practices for making a drawing. Participant 3 likes the functionality, because it saves him time. But he also said that he "has orthographic projection stuck in his mind, and this functionality seems to match what is in my head."

Participant 4 is a lot like Participant 3 in that both of them arrange the dimensions in Sketcher as they work. They both say that it makes the dimensions easier to read when they enter into a Modify or Redefine situation. He also said that he would like to have the Move or Move Text capabilities in the Modify command in order to make the dimensions "look better." Again, I see the drafting mentality coming out in the older participants.

By spending a significant portion of their careers using a drafting board in their design work, Participants 3 and 4 have developed certain ways of working within the CAD tool that reflect that experience. In their respective cases, it appeared that those techniques served them well. But all of the participants' past experiences were not related to the use of a drawing board. Some of those experiences were specific to techniques they had used in the past with varying degrees of success, as can be seen in this section of field notes describing Participant 2's mentor and some of the techniques that he espoused.

> However, upon discussion with Participant 2, it was interesting to note that while he agreed with most of the design standards, there were a few that he thought were unnecessary. He commented several times about his

> mentor and that particular person’s work habits. His mentor would often advise Participant 2 about particular ways to do things, which seemed to contradict many of the things that he had learned about the tools. For example, his mentor often times suggested that he should simply add a text dimension to the drawing as opposed to updating the geometry of the model. That particular technique defeats the purpose of the using a parametric design tool in the first place.

Another example can be seen here in regard to a discussion that the researcher had with Participant 2 regarding the choice of material to be used in a particular design and its impact on the shape of the part. The resulting shape of the part consequently had an effect on the methods he chose when inserting that component into a higher-level assembly model.

> I also asked him if the channel steel would be rigid enough to resist the vibration of the machine, and he commented that it should be (or at least it has been from his past experience). As he moved the square block that would comprise part of his new design into position, he commented that he was not able to use a simple Mate in order to position them due to the curvature of the rail components. Instead, he chose to use the Point on Surface constraint, which he said that he does not like to use very often because of its instability during major changes to the assembly.

As seen in this last example, past experience with the use of particular software commands certainly has an effect on future choices based on the success or failure of previous commands in a similar scenario. This can be illustrated in an example related to Participant 1 and his use of a particular geometry duplication technique. He had chosen to use that technique and was discussing it with the researcher when his coworker overheard the conversation. The following excerpt illustrates his reasoning for choosing the commands that he did, and it includes the commentary of his coworker.

> After about twenty minutes or so, he was finished with the first vein, and he began to duplicate them in a circular fashion around the circumference of the Impeller. I asked him why he was using the Copy and Group techniques as opposed to using a Pattern to duplicate them. His response was basically one of acknowledgement. He knew that he could have used this technique, but chose his current technique when he realized that he had not created the requisite geometry for the Pattern and did not want to go back and recreate the vein just to add in the missing geometry. A similar discussion between Participant 1 and I also occurred in relation to the series of holes he made in the hub of the Impeller. He chose to create

> three separate Extruded Cut features in the hub as opposed to one Revolved Cut feature. The resulting geometry is a multi-diameter hole that contains a brass Insert that is drilled and tapped to mount the Impeller to the shaft. Since the Insert is a separate part, Participant 1 thought it would be a good idea to make the hole that accommodated the Insert as a separate feature, even though he knew he could have made the multi-diameter hole as one feature if he had used a Revolved Cut. As we discussed the Pattern function, his coworker overheard us as she walked out the door, and she commented that the Pattern feature "never works. It is just too hard". After she had left, Participant 1 looked at me and stated that it really was not that hard "if you know what you are doing". By his mannerisms and tone of voice, I got the impression that he has these types of conversations with his coworker often.

The choice of techniques used by Participant 1 to make the desired geometry were influenced by the fact that he knew that he did not have the requisite reference geometry in place to use the duplication functions that the researcher was inquiring about. It appeared however that his coworker had experienced problems with that particular geometry function in the past and had simply chosen to no longer use it, even if there was a simple error that could be corrected.

It also appeared that the participants' design environments contributed to their levels of expertise as well. All but one of them had convenient access to the facility where their products were made and assembled. The timely feedback they received when there was a problem with the object allowed them to more quickly and accurately incorporate that into the 3D CAD models that they were creating. In addition, each of the participants had an area where they were able to collaborate with coworkers. Even though all of them worked in some type of cubicle, they had the freedom to ask questions to their coworkers and contribute their expertise when necessary.

> As I sat with participant 5, I noticed that his work area was similar to that of the other participants in the study. He had his own cubicle, which was part of the columns-and-rows layout of the office. It seemed like people were able to collaborate if they chose to do so, but at the time, I only saw people working at their own station.
>
> Participant 1 has a fairly large area, but it also includes the engineering drawing archive as well as bookshelves that contain various engineering documents and reference books. Participant 1's work area is neat and clean with his office supplies in order on top of his desk and in his drawers.

> Participant 1 also keeps several samples on is desk of the current parts he is working with. He uses them for reference as he creates the 3D models, and he also stated that it helps him visualize what exactly he is working on if he has a question. When I entered his office, it was arranged in a second-story portion of the factory area, along with the desk of his boss and his coworker.
>
> The workplace environment that Participant 2 had was similar to other facilities that I had been in with this company. They have cubicles arranged in a pattern of four, with a table in the middle for collaborative work. In fact, as I set my bag on the table, I noticed that there were several marked up drawings there from a previous meeting.

A closely related theme to the design environment is the support structure that existed within each engineering organization. Depending on the size of the company, some participants had a fairly elaborate support structure, such as a corporate help desk or employer-provided training programs. In the cases of other participants, they had no support structure at all, other than their own means of acquiring knowledge. Participant 3 worked in a small division of a larger company where he was the only designer on staff. While observations of him have been used several times in this discussion as examples to illustrate various aspects of expertise, he has developed many of his techniques on his own.

> This group seems to be rather self-sufficient. A larger company owns the company where I did the observation, but each division operates independently to some degree. Participant 3 mentioned that they do not have a PDM system due to the size of their group and because they do not make similar products to the other companies within the organization. In addition, when they switched to Pro/ENGINEER from CADKEY, they did it mostly on their own. They had some initial training, but they tended to develop their own work habits. When their product line began to grow in size, they found that some of their methods and techniques were ineffective and inefficient, so they brought in the help of an external consultant. He helped them develop custom color palettes, start parts, map keys, and modeling techniques. The consultant also developed custom scripts and configuration files specific to the modeling of plastic, blow-molded parts. Participant 3 also stated that he participates in professional conferences, user groups, and networking, in many cases, because of the small size of his company. Since they do not have a technical support group per se, he has to find out a great deal of information for himself. Participant 3 and his coworkers also rely on each other to address a lot of

> their modeling problems and to develop solutions that work specifically for them.

A similar scenario exists for Participant 5, although he has other responsibilities besides that of designing products.

> I have also noticed that they have no corporate standards, at least for modeling anyway. They do things like Mirroring and Patterning in kind of a random fashion, sometimes even both in the same part. However, in watching participant 5 create models, he is quite conscious of the functions he uses and the relationships that he establishes. Currently, besides being a designer, participant 5 is also a system administrator. He installs software, manages network issues, and acts as a form of an internal Help Desk. I am looking forward to seeing him perform these various roles, especially the Help desk function. Participant 5 also refers to reference materials quite a bit. Since most of the geometry they build is comprised of standard parts, he has a variety of catalogs and books in his workspace.

Conversely, Participant 2 works for a multi-national corporation that has hundreds of designers, many of whom use the CAD tool extensively. He has access to a corporate library of 3D models for common parts, as well as very elaborate (though sometimes constricting) design and modeling standards. Participant 2 is often sent to training courses a couple of times each year to refresh his skills in the use of the CAD tool.

> In creating this plate, he used the same Form feature used on the brake pedal, which he pulled from the library. It appears that they have a ton of user-defined features already created that can simply be placed on a model without a lot of geometry creation being required.
>
> In addition, Participant 2's company has an engineering specification that mandates that this type of form geometry on a sheetmetal part be at least 28 millimeters apart on center…

It appears that smaller companies with few designers on staff tend to have very little in the line of best practices or standards on how to model their products. This forces their CAD users to develop their skills primarily on their own. They tend to use a very limited portion of the CAD system due the lack of exposure from other users and company developed techniques. Larger companies with more designers will learn more of their techniques through other users within the company, which in many cases is enabled by the structure of the environment. Many larger companies with this number of CAD users will also develop a set of standards and best practice for modeling their products with the CAD system. Users will combine information from these standards with their own knowledge and observed techniques of other users to formulate their own modeling techniques. There are also companies with hundreds of CAD users across several divisions. A company this size will usually have an extensive library of CAD tools available to their users. These tools may include such things as libraries of models, internal support system, databases of questions/problems/solutions, custom help files, consultants. In this case, one may find that many CAD users develop very few CAD skills from their own knowledge or experimentation and more from these tools.

The previous examples provide an overall textural view of the development and definition of expertise in the use of constraint-based CAD tools. By examining information relevant to the participants in this study, one is able to gain insight into the phenomenon of expertise through the thoughts and actions of the participants as interpreted by the researcher. The excerpts pulled from the researcher’s field notes are intended to provide a glimpse of the participants’ working environments through language and descriptions common to the field of engineering design. The observations conducted in this study were meant to provide a global view of expertise in the use of constraint-based CAD tools as it related to the five participants. Using the results of interviews, think-aloud modeling sessions, and knowledge mapping tasks with each participant, later sections of this chapter will provide information related to more specific elements presented in this global view of expert CAD use. However the following section of this report builds on the textural, thematic description given here in an attempt to provide a more specific description of the phenomenon of expertise in the use of constraint-based CAD tools based on the interviews of the five research participants, particularly in the areas of past experiences and the participants’ own conceptions of expertise.

INTERVIEWS: THE EXPERIENCES OF EACH PARTICIPANT

Due to the nature of the interview questions, the resulting themes from the data clustered into seven categories that further expanded several of those that were discovered during the observations. The interview guide was divided into three groups of questions that examined work experience (professional and academic), expertise in general, and CAD tool usage. All of these categories, however, focused on the experiences of the participant in general, the purpose of which was to further examine the relevant experiences that lead to the development of expertise and the participants experiences using the CAD tools that lead to their own conceptions of expertise.

There is some overlap between the themes from the observation data and the themes from the interview data. It should be noted, however, that the observational themes focused on the interrelationship between the invariant constituents in each category to gain a global view of expertise in this domain. In contrast, the themes from the interview data focused on the experiences of each participant as they relate to everyday use of the tools. Upon examination of the transcripts, it was determined that all of the invariant constituents for each participant could be grouped into the themes listed in Table 2.

Table 4.2

Thematic Elements of Expertise Based on Interview Data with Each Participant

- Professional and Academic Experiences
- Support Structures
- Typical Domain Activities
- Conceptions of Expertise
- Problem Solving
- Factors Affecting CAD Usage
- Elements of CAD usage

After the invariant constituents were grouped to provide the structure for the themes listed in Table 2, each of these categories were then applied to the participants' interview transcripts, and the following descriptions of each theme were developed. Following the description of each theme are individual descriptions for each participant of the experiences involved in the daily exhibition of expertise, as well as composite textural and structural descriptions of the phenomenon similar to those given after the examination of the field observation data.

Professional and Academic Experiences – The data revealed that all five participants had an extensive array of previous work and software usage experience. Each of them had been working professionally for at least five years, and one of them had twenty-eight years of experience in the engineering design field. Several of them have also worked for more than one company, so they have seen many different environments from which to gather methods and strategies. Each one has used a variety of CAD tools, which have helped to shape their problem solving strategies and the techniques that they employ. In addition, two of the participants spent significant portions of their careers using traditional drafting tools and techniques, and that has helped to shape their problem solving strategies and the techniques that they employ in using the CAD tool.

Support Structures – Two of the participants currently work in an environment where their support structure is quite extensive. They have access to training courses, knowledgeable colleagues, and on-line databases of lessons learned, all of which contribute to their ability to use the software. The other three participants work in small groups and must develop solutions to their problems individually or with limited options in terms of help from coworkers. In spite of the lack of an extensive support structure, these three participants did find collaboration in the coworkers they did have as well as customers and other areas of their organization.

Typical Domain Activities – Authentic practice in an environment conducive to the use of CAD tools has helped each participant develop their own unique set of skills and abilities. On a daily basis, each of them communicates with other people who need their skills and knowledge to accomplish their job functions. Typically, this communication takes the form of using marked-up drawings or sketches to create or modify geometry that will be used throughout several stages of the design and production process. Each one of them also spends a significant amount of time using the CAD tool on a variety of engineering and design projects. Each of the participants also performs several roles within their group or organization in addition to their use of the CAD tool, such as liaison with the production facilities, a mentor to other coworkers, and the technical support guru.

Conceptions of Expertise – The data concerning the participants' conceptions of expertise were somewhat varied in how they arrived at the core characteristics of their personal definitions, but each person stressed the ideas of extensive knowledge and varied experiences. The data also revealed that timeliness of the information is also critical; it does no good to the solicitor if the expert takes too long to give an answer. By that time, they have already arrived at a solution by some other means. These conceptions of expertise appeared to impact their daily activities as well as their view of the support structure within their organization. Their decisions on who to collaborate with to develop a solution to a problem and their ability to implement a problem solution were impacted by these views of expertise.

Problem Solving – It appears that problem solving is made up of different factors: a learning style with which to gather information and a mind set for what to do when all of the information is gathered. The data point to hands-on and visual learning styles as being useful to gather information. But it is the mindset of the user that is potentially the most important factor. Being able to couple past experience with knowledge of the CAD tool's inherent processes appears to be one of the keys to developing a successful solution to the modeling task. In addition, the data revealed that a certain confidence level seems to be required in order to implement that solution given one's knowledge of the software and how it operates.

Factors Related to CAD Usage – The data revealed here are similar to those revealed in the section on design considerations that evolved from the observation data, but these factors align more closely with the use of the tool on a personal level. These data include downstream uses of the model driving modeling decisions made by the user, communication and cultural issues within the design group, the effects of time constraints on the decisions made with regard to modeling geometry, and the stature of the CAD model in the overall design process.

Elements of CAD Usage – It appears that the five participants use a variety of techniques within the CAD tool to allow them to work faster, which coincide with their problem solving strategy and their past experiences of what works and what does not work. The implications of their current modeling decisions and how that affects the design intent of the model also appears to be at the forefront of their mind. Not all of them had a wide array of commands that they used. A couple of them tended to use the same set of commands most of the time. Each participant also stated, in their own way, the definitions of what was acceptable for “good” and “bad” geometry creation and use.

The range of ideas that these constituent themes express is broad and highly personal to each participant. They encompass the relationships between past experience, software knowledge, and the factors that enable and disable effective use of constraint-based CAD tools. The following textural and structural descriptions of expertise are specific to each participant, elaborating from a personal perspective on the topics related to each theme. Following the individual accounts, is a composite structural description of the development of expertise according to the five participants.

Textural Description of Expertise for Participant 1

Participant 1 has worked for various divisions of his current employer, both in the United States and in India. During his time in India, he managed a design team that was responsible for the re-engineering of one of the product lines. It was an interdisciplinary team that included engineers, as well as four people who were responsible solely for the creation of the CAD data. They were given marked-up drawings to work with, as well as physical parts from the existing product. As they created the models, they would communicate with various other groups in the company via email and via the CAD model files.

> (N): To get started, describe your past work experiences, whatever those have been? Also, how has CAD been involved in those experiences?
>
> (P1): Well, uh… Prior to my joining this company in the U.S., it was the same company that I worked for in India… the re-engineering of one of our most popular cleaning and sanitizing equipment products. We bought a company that doesn’t have any drawings for those parts, and the VP of engineering asked the Indian team… we have a center for design and research in India. He asked them to re-engineer those products. What they want is solid models and drawings for those products. They sent the original parts to India and asked us to make computer models and drawings and then send those back so they could release them for tooling.

> N: OK. The company that you worked for in India… Is it the same company that you work for now, or is it a division of that company?
>
> P1: It is the same company, but they have a division in India. And that division is a small… about 12 engineers and one project manager. We also had one person who was a doctorate, but he was a technical liaison. Together, we made up an interdisciplinary group. Some of us were electrical engineers, some chemical engineers, some mechanical engineering, some polymers… So we all worked as a team. The CAD team was three other engineers and I.

In addition to several of these types of projects, his group in India also assisted a related company in the United States by creating models and drawings of their product lines. On this project, Participant 1 took a leadership role in which he spent nearly as much time communicating with the stakeholders in the project as he did with his design team.

In light of these experiences, it appears that using constraint-based CAD tools increased his productivity, precision, and the overall quality of his work. According to Participant 1, "mistakes on drawings and other communications were minimized due to the associative nature of the tools." It also appears that the use of these tools also increases effective communications between people in a design group due to the visual nature of the people in the group and the manner in which the model graphically communicates information.

> N: You made an interesting statement that I have not personally heard a lot of people make although I believe it's true. "If you model well, the drawing is pretty easy." Talk a little but more about that if you can. Why do you think the drawing becomes easy if you model well?
>
> P1: I think it is. This is an interesting question. If you are creating a drawing which is going to be checked by another engineer who is familiar with Pro/E, then it is very easy to make the other engineer satisfied with the drawing. In the current environment…
>
> It is easy because when you create a drawing actually you get drawing views very easily. When you add dimensions, you get them feature by feature that follows how you created the model. If you created the model well, then you get the dimensions that you added to the model to show up in the drawing. You can always erase the ones that you don't like. If you really create a drawing as per the dimensions of the model, then you can

> easily modify the model from the drawing also. That is a complicated kind of associativity. Whatever the features you created in the model with certain dimensions, those are the dimensions that are going to appear in the drawing. You're not going to create any other dimensions.
>
> You're going to see the dimensions that you used to create the feature are the same dimensions you're going to see on the drawing. And, the modification of the model and the drawing will be easy at a later time, which is the biggest reason. Adding or removing dimensions is not a big task; it takes just a few minutes. The drawing is dimensionally driven if that's how you model it.

Participant 1 also had an academic background that involved the use of CAD tools. He received his degrees in mechanical engineering from a technological institute that fostered collaboration between students and industry. He was involved in several research projects as a graduate student where he assisted in the creation and analysis of geometric model data.

> N: Did you… Before you did you master's degree did you work for a company before that?
>
> P1: I worked in a research institute in the university, but as a project research associate. In the university, they get research projects from different companies and they execute it at the univeristy level. So I was a project research associate. I also assisted a professor in geometric modeling and finite element modeling, thermal analysis, for the brake wheel hub of a combat aircraft.

He started using 2D CAD tools, and then he progressed to a machine design course where 3D CAD tools were used. However, he and his classmates were not given much instruction in the use of the tool, so they had to learn it on their own. Participant 1 stated that by not having much help, that he "had to develop [his] modeling methods by [himself], and figure out the tools."

During the course of these experiences within industry and academia, Participant 1 has worked with a variety of different communications and design modes that appear to have helped him develop expertise in the use of constraint-based CAD tools. These various ways of creating and designing have also appear to have helped him become familiar with the specific daily activities that happen in a design environment and the ways that those impact one's use of CAD tools. Working with part, assembly, and drawing files is common to most engineering and design projects, because each one documents the design in some way. In doing so, this provides the user with an awareness of the extent and scope of their actions with the CAD tool, as well as an appreciation for the scope of the design problems by seeing all of the interrelated pieces. According to Participant 1, designing in this manner allows one to make decisions about the relationships between parts and how they will or will not fit together.

> N: Why is it that you worked with a combination of parts, assemblies, and drawings, as opposed to one or the other?
>
> P1: Well, the project is like that. They didn't send us one part and ask us to model it, although one time I did model just one part and send it back. But they sent the whole assembly to India, and we had to make sure how many parts it had and how they fit together. And once we understand the assembling of different parts, we start modeling each part and creating the drawing. After that was done, we would send them back here. Those drawings and models would then be sent to the toolmaker.
>
> So why we did that… I don't know. Probably because my supervisor asked us to do that, and we did it.
>
> N: Do you think it's beneficial to have all three of those kinds of files present in the course of a project? The reason why I ask it that way is that several of my participants have said that they work back and forth between the part and the assembly to get the information they need?
>
> P1: I think it would be better to work in that fashion rather than working with the part alone.
>
> N: Why is that in your opinion?
>
> P1: Well, just because you design the part that doesn't mean that it's going to fit into the assembly. You have to make sure that the clearance and interference are acceptable. So, the design of the part has to meet the dimensional constraints in the assembly. You have to make sure everything is OK with the assembly.

Throughout his use of CAD tools, Participant 1 has commented that he had to consistently rely on his own problem solving and learning capabilities to make sense of the technology he was using. In doing so, he seemed to have developed particular ways of learning and working that center on investigation and hands-on experience. It appears that his lack of a formal support structure within his group requires him to send time gathering information from a variety of sources. He works in an environment where information is readily available from the production group, the customers, and from his superiors. All he has to do is find it.

> N: Do you have any kind of support structure?
>
> P1: In Pro/ENGINEER?
>
> N: Yeah… in terms of like a help desk or a help line or any sort of resource materials in the companies that you have worked in, past and present. Can you describe any kind of support structure that you have to help you use the tool?
>
> P1: What we do here is hard-core engineering. Our ultimate goal is to get the pump in the box. So we do a lot of other tasks besides Pro/E, so we discuss things with manufacturing and quality engineers, customers, engineering managers, etc. Right now, I would say that I don't have any support structure within our organization, but if I have any questions, I can call PTC's technical support. I have access to their database.
>
> N: Is there anything else besides that?
>
> P1: Well, within the team right now, I am the only one on the team who knows Pro/E. We are only two; me and my co-worker. She has not been given formal training, so she is learning it on her own as she goes along. Since I have been here, she has gotten better, but she has worked for the last 20 years so she has good experience within the industry. So I would say that we do not have any other support structure. But… I'm not sure what else you mean.
>
> N: What about books, training materials, etc.…?
>
> P1: Yes. We have the training guides, but those are the ones that I got from the courses. If I need any help, I will call the PTC help line. I can find the answer from the Help function, but sometimes it is inconvenient. Sometimes, I use the Help function in the software, but I usually don't find a solution.

He has one other coworker in his group that is responsible for design work, but that person is not proficient in the use of the CAD tool. Therefore, Participant 1 not only completes his own tasks, but seems to serve as a mentor for this person as well. In doing so, he seems likely to be much more self-reliant and aware of his knowledge of the tool. He has developed his own methods for gathering information and verifying its content and accuracy. While his current company has paid for him to attend training, initially, he had to learn the CAD tool without any formal instruction, including the complex vocabulary and semantics of the software. By having some background in the use of other CAD tools and knowledge of the design process, he seems to be able to put the information about the software tool together effectively for his own uses.

> N: In general, how do you best learn something?
>
> P1: That's a really good question. My style in learning is… I think there are different ways to learning – reading, listening, watching, and involving… and also presenting. You can learn… Among these, the best way to learn more is close observation. Also, it depends on what you're interested in. If you're interested, you can observe more closely and involve it with more enthusiasm as well. If you're really interested in what you're doing, you really learn more and experience more.
>
> So if I'm really interested in something, I'll observe and I'll collect some information regarding that topic, and I'll read about it. Then, I'll raise questions of the people who are aware of that topic. And that's all I do. The best way is if you're really interested in it, just observe that topic and involve it. Involving is really useful and a good experience.
>
> N: So, doing something hands-on… that works well for you?
>
> P1: Yes. Hands-on. I think so; that's a real experience. You can always watch and listen to come to a decision. But, that's awareness again.
>
> N: Let's say that you want to learn something so that you are at least reasonably proficient at that task, whatever it is. It sounds like what you're saying is that you tend to observe a lot, you tend to read a little bit, you collect information about it and do a little bit of research, but you also like to practice that task and be hands-on at it. Is that right?
>
> P1: Yes. Actually, reading might inculcate some awareness, but is doesn't give you experience. You only get experience when you involve; that's real experience.

While the access to a limited support structure and the influences of past experiences seem to have contributed to the development of expertise in Participant 1, he has also cited that his daily activities contribute to the store of background knowledge that he uses while making decisions using the CAD tool.

> N: Can you characterize a typical day, or an average day, at your job?
>
> P1: Well, a typical day at our job varies. But with the last three or four years with this company, most of my day is often spent with Pro/ENGINEER and the different designs. So I would say that…
>
> N: When you say “different designs”, do you mean different design projects or different designs within the same project?
>
> P1: Both ways. Since I want to explain about my experience, my typical day is most of the time spent in designing with Pro/ENGINEER, and understanding concepts from the senior engineer, and discussing any problems I may have concerning feasibility. My typical day is that.
>
> N: You’ve described a typical day at your job, but is there a typical project that you might work on?
>
> P1: I’ll give an example of my current project as a typical project. My boss is the primary engineer for the design of the project, and he started this project a couple of years back. There was another engineer that designed a pump that was roto-molded that was not successful in the market. The VP of Engineering and the engineering department came to us to design the same pump as an injection- molded part as a technical process.
>
> My boss took the lead on it to design the injection-molded pump. We designed the parts, and submitted it to the financial department to approve the capital on that pump. That took like five to six months I think. Recently, we were approved for the project, so we are making sure of our design. I am making sure that the parts he designed originally in AutoCAD will fit together properly and be correct by modeling them in Pro/ENGINEER.
>
> All in all, I would say that we are just making sure that what he designed is OK so we can release it for tooling, because the tooling will be very expensive. So, that’s a typical project. Once we’ve got the tools built, we will make sure the prototypes are what we want. Once we test the prototypes in our lab, on site, and in the agency, and everything comes out OK, we start production.
>
> N: So it sounds like CAD fits into that project in a number of ways.

> P1: Oh, definitely. Yes. The power of solid modeling is enormous, and you can probably extend that power to any corner of the engineering process. If the solid model is made correctly and accurately, you can do analysis, you can make drawings, generate tooling, whatever we want. That's from the computer model… and it also allows you to discuss the project in a collaborative fashion. People think that CAD is only 3D modeling, but it is so much more. It can increase quality, decrease time to market, speed up product development…

While his particular group is small, they do have a noticeable division of labor. He and his coworker take direction from their boss. This direction comes in the form of marked-up drawings or preliminary layout sketches, which they then use to make the models of the parts. The significance of this is not so much the mode of communication, but how it is done and from whom it comes. Participant 1 appears to use a problem solving style based on experimentation and hands-on learning, and he has indicated that too much direction can stifle that process.

> N: You mentioned about your coworker and her 20 years of experience. Let's make a little bit of a comparison between you and her.
>
> In general, a person with that many years of experience…if a person has that many years of experience, what do you think has led to their experience?
>
> P1: It's experience, you know. They just follow what the engineer is saying. So just perception and using that to grasp what the engineer is saying. She has to do whatever the engineer's say; they are guiding her.
>
> N: Do you think all of those years of experience help a person solve a problem?
>
> P1: No. I don't think so. Because… You can have some kind of experience, but you will not realize much working in that fashion. You have to do what other people say, and you don't get a chance to work anything out on your own. You might find out something, but it is probably not the best way, but that is the way that you have to work in some organizations.
>
> Most of the time, the designer is not given enough freedom to think on their own. They will raise a question and discuss it with the engineer, but they might not be in a position to convince the engineer. Normally, the engineer will lead, and they will follow.

The experimentation in the use of the CAD tool seems to provide him an idea of which techniques work and which ones do not. He appears to reason through his changes by using the tools within the software to make sense of the present design problem and to determine a solution. While experimentation with a particular command or technique often leads to new knowledge, Participant 1 is also keenly aware of the time constraints within a typical design environment. It is often then that he might settle for a technique he knows will work in the given situation, based on past experience, rather than spend time exploring other potential options.

> N: If you must use a function in Pro/ENGINEER that you have never used before, or it's been a while since you used it, how do you proceed? How do you go about doing that?
>
> P1: Well, I'll try first by making that feature by remembering. If I don't get it then, then I will use their manual. I should be able to get it from that. If I still can't get it, then I will contact PTC technical support.
>
> N: What has your experience been in using that strategy? Has it worked?
>
> P1: Within the U.S., it has been better.
>
> N: What about that particular sequence – trying it out, then looking to the manual, then looking to the Help file, then looking to the PTC tech support – has that sequence worked?
>
> P1: Yes, I think so…
>
> N: How do you know that you have modeled something "correctly" (i.e., according to your intentions or the requirements of the project)? What let's you know when you are finished?
>
> P1: I will know myself if something is correct or wrong, and if someone really wants to know whether a model is right or wrong, I have to think about the requirements. If it meets the requirements, I may say it is right, but if they go deeper, I might have to say it is not.
>
> The answer for your question is whether you know about the fundamental principles of the software. If you do, you will know if what you are modeling is correct or not. But unknowingly, if you do a mistake, you may not know. But your design intent should give you a clear indication if what you are doing is wrong or right.

Having all of these background experiences seems to have allowed Participant 1 to develop a conception of expertise in the use of constraint-based CAD tools. According to Participant 1, experts need to provide information in a timely fashion, and their background or credentials seem to not necessarily be as important as having the right answer at the right time. People who have an interest in the topical area of expertise and who place a value on that information are the ones who appear to solicit the expert's opinion. Participant 1 also considers extensive experience in the field and high levels of motivation to be expert qualities. Although, he is quick to point out that many people do not consider themselves as experts when they are asked for their opinion or to provide information.

> N: Let's shift direction a little bit. This is a general statement. How would you characterize an expert in any particular field?
>
> P1: In my opinion, the expert is the one who can provide a solution or answer in a timely fashion, instantaneously… whenever you want. If I want to do something, and I get information from you on the related topic, then you are the expert. If somebody can provide information at that point in time, then they are the expert.
>
> But that is different than being a scientific expert. A scientific expert in solid modeling might be doing research, writing papers, collecting data… becoming a professional in solid modeling. But in my opinion, getting what I want in a timely manner, that is an expert. The other stuff doesn't matter. The person that provides me with a timely information is an expert.

In the case of Participant 1 though, he appears to be the resident expert in his design group. It seems like he is the only one that has a high proficiency level, which enables him to accomplish productive work, using the software. He has stated that a variety of problem experiences have contributed to his level of expertise, and that activities "representative of the engineering design field are important to get involved in" to develop expertise in using these CAD tools. Participant 1 considers an expert CAD user able to capture in the model the design intent of the situation through efficient modeling techniques and applicable strategies. In doing so, it appears that there are many factors to be considered in the creation of a "good" CAD model, especially downstream use of the model, because some people do not seem to understand the subtleties involved in the creation of geometry with these kinds of CAD tools.

> N: How would *you* characterize the difference between an expert (experienced) constraint-based CAD user and a non-expert (less-experienced) constraint-based CAD user?
>
> P1: Again, as per my opinion, the expert is the one who gives what somebody wants… meeting his boss' requirements by following Pro/E's rules and regulations.
>
> You have to keep in mind the functions of Pro/E, such as parametrics and associativity. Also do not sketch a feature with irrelevant dimensions. So if he is sketching a part around a centerline, there are numerous ways you can create it.
>
> [P1 sketched an example] My way can be done by creating three diameter dimensions and the length dimensions. But if somebody does it by dimensioning each entity in the sketch, they will not get the dimensions somebody wants on the drawing. So he would be an expert if he is able to give the dimensions in the model that somebody wants on the drawing.
>
> N: So it sounds like efficiency has something to do with it?
>
> P1: I would say so. I don't feel he is an expert if he does not give the dimensions at the Sketcher level that he wants in the Drawing. He has to get the dimensions that he wants on the drawing.
>
> N: So capturing those critical dimensions in the model…
>
> P1: I think so, yes. Capturing the critical dimensions in the model is important. You can also give tolerances in the model if you want. So somebody should keep those in mind, so they should create the model in such a fashion that it follows the Pro/E rules and regulation. The rest of that can be done a later time.
>
> N: What are some of those rules and regulations you are talking about?
>
> P1: Parent/child relationships are one of them. When you create a feature, references are important. You have to keep those in mind in order to minimize mistakes. But you can always meet the requirements of somebody who does not know Pro/E by doing whatever you want.

> N: So it sounds like that expertise, or the difference between the expert and the non-expert, is that the expert is more efficient and he is able to better able to capture the design requirements.
>
> P1: Yes, I agree with that. The expertise in Pro/E comes from the more you use it.
>
> N: The example that you sketched right there is a great example of something an expert would do. Can you think of anything else in the CAD tool, besides differences in sketching and dimensioning, that an expert would do and a non-expert would not do?
>
> P1: Actually when you design anything in Pro/E, the design intent plays a major role. You have to think about how you are going to achieve the design of that particular part. You can always design in different ways. Users have to ask some questions about that part and how you are going to design it. Maybe you are wrong, but it is always important to ask yourself what you are going to do and how you are going to do it. That is time well spent before you start a design.
>
> I would say an expert will consider all of the factors that are involved and a non-expert will not.
>
> N: So an expert tends to develop a fairly elaborate plan and a non-expert will not?
>
> P1: Definitely. Yes.

While he recognizes his level of proficiency in the use of the tool, Participant 1 is quick to acknowledge that using the CAD tool effectively is not the overall goal of the design process; the goal is to produce a product. So it appears that having extensive tool knowledge must also be combined with having extensive engineering domain knowledge.

In meeting the proper specification and creation of geometry using constraint-based CAD tools, Participant 1 has stated that there are certain elements of using the CAD tool that are important. Constraint-based CAD tools have reduced the amount of mistakes that have occurred in his environment, due in large part to the ability to use the 3D model as an input for downstream processes and the ability to account for the design intent of the user within the CAD model.

> N: So all of those things that people have to consider as they are building geometry… for example manufacturing processes – you mentioned

> manufacturability. Also software command choices – should I make a hole or a cut? Also interaction with mating parts – how do the objects fit together in the assembly? And design intent – how do I want this model to behave? So all of these are example, and we can start there. But how do you describe the influence of all of the different factors that are involved in using the CAD tools to make a model?
>
> P1: Well, if you always design to account for the proper design intent that is always better. But how many other people are doing the same; that is always a question mark. But definitely, I think they are beneficial for some reasons, because when you make use of that model in finite element analysis, the surfaces that you use will matter. When you create a drawing, you have to dimension a drawing. So design intent will always affect what you do.
>
> N: Do you think that all of the factors that I mentioned here have equal influence, or does one of them have more influence than the others?
>
> P1: Yes and no. it depends on how complex the model is.
>
> N: Which one might have more of an influence than design intent?
>
> P1: All are going to play a role, but manufacturing process will play a big role as well. Being aware of manufacturing process is better, but how it's going to affect what you do in Pro/E might be minimal.
>
> N: Will it influence how you make the model?
>
> P1: Yes, definitely. There is a difference between casting and molding. Surface finishes, roughness… all of that is important.

While design intent and other considerations are important, not all users are careful in incorporating them correctly, so it seems to be necessary to have firm grasp of the basic processes of the CAD tool in order to create and edit geometry in an effective manner. If not, many of the benefits of constraint-based CAD tools could potentially disappear.

Expertise in the use of constraint-based CAD tools seems to be a complex phenomenon in the eyes of Participant 1, and it appears to include many factors, some of which are beyond his control. He has a variety of past experiences, which contribute to his problem solving abilities. Couple this with a small design group and a non-existent support structure, and it appears that Participant 1 is often left to his own devices to solve a problem in using the CAD tool. However, this has given him an enlightened conception of what expertise is in terms of using the CAD tool, which also seems to have enabled him to understand the myriad of design considerations given to the effective use of these tools.

Structural Description of Expertise for Participant 1

Participant 1 has had a variety of past experiences that have contributed to the development of his level of expertise in the use of constraint-based CAD tools. He has worked in design teams, as well as been responsible for their activities. Projects that he has worked on have focused on the redesign and reverse engineering of many existing products. In doing so, he has had to become an active and productive member of a design team, create models according to standards, and share information between other local and remote groups within and outside the organization. The educational experiences that Participant 1 has had have prepared him for participating on these teams through his participation on various research and project teams. These teams received information and direction from industrial partners, which meant that in his case, the activities were authentic in nature and viewed as goal-oriented. These experiences have provided Participant 2 with a background of the engineering design domain and the basic knowledge contained therein.

In his current environment, Participant 1 follows the directions of his supervisor, which influences their channels and methods of communication. In this case, it appears that they often use the 3D CAD model and the drawings that are produced from it. However, due to his boss' lack of knowledge of the software, Participant 1 must spend a great deal of time preparing the model or the drawing to be viewed by his boss and others, due to the subtle nuances of the software's display effects. This requires that he take into account his knowledge of the design process, standards, and the company's products. In addition, he splits time between using the CAD system and researching various issues associated with the current project. He must take that knowledge and implement that using the CAD tool in the form of design intent in the model. In a typical design, the model will be used to extract 2D drawings, which will become the vehicle for communications between Participant 1 and his coworkers. Any changes made will have to be incorporated into the model, and the drawing will be easily updated. Participant 1 has stressed that due to this associativity, it is imperative to have a critical understanding of the fundamental operating procedures of the software, including various geometry creation techniques and editing functions.

Within any environment there exists some support structure that aids in the pursuit of the primary objectives. In the case of Participant 1, his support structures have been limited in availability and resources. Because of this, he has been forced to develop a problem solving strategy that relies heavily on observation, experimentation, and research. He currently has access to a coworker with limited knowledge of the tool, his training guides from software training courses, and access to the software vendor's web site. When these sources do not provide an answer to his questions, he must experiment with different solution contrived of his own devices. Due to time constraint and the complexity of the design situation, it is likely that when he finds a method or technique that works, Participant 1 will continue to use that in as many situations as possible.

Expertise is a phenomenon that is generally context-specific, and for Participant 1 it is no different. His characterization of expertise is one of timeliness and value. To him, experts will have the answers when they are needed and present them in a fashion that is relevant to the person asking the question. While he does not necessarily consider himself and expert, he does consider his abilities "a nine out of ten." All of the problem scenarios that Participant 1 has been involved in have given him the ability to examine the issue critically to determine its scope and its consequences, particularly in the use of the CAD model. Considerations such as parent/child references, feature order, associativity, feature type, critical dimensions, and design intent are all part of the scope of any modeling task that he takes on. Through his past experiences inside and outside the software and the structure of his current environment, Participant 1 is able to account for these factors and more in his development of a 3D CAD model. However, he is quick to point out that not all users are capable of doing that, so it is critical that one has a good understanding of how to interrogate and edit a model as well while still maintaining the design intent.

Textural Description of Expertise for Participant 2

Participant 2 has had a variety of professional and educational experiences to reach his current level of expertise. However, given his age, it appears that they are likely not as varied as those of the other participants. He began using CAD tools in high schools, but it was all 2D drafting.

> P2: Well, I started out on AutoCAD… like most people did back in Drafting in high school. And, uh, worked with a few companies in college that did AutoCAD. We did some custom modeling for people… just updating custom floor plans and stuff like that.

After high school, he studied mechanical engineering in college, where he received a background in both 2D and 3D CAD tools. His experiences in using CAD software during that time were mixed.

> P2: I did not experience 3D CAD until I was in college in mechanical engineering where we had Pro/ENGINEER on our systems at school. I just got involved and trying to use it for projects and things like that…
>
> I did take the advanced graphics communications course where we went through AutoCAD 2000, I believe, and that has limited 3D modeling ability. And then some Pro/E work, I mean nothing to amount to anything, but I did have some Pro/ENGINEER in there.

While it seems to have been beneficial to have the background of 3D modeling, it was mainly just an overview of the major concepts. Participant 2 appears to have mainly learned to use CAD tools on his own without any formal instruction. While in college, Participant 2 worked in many internship positions where he learned firsthand about he engineering design environment. Based on the interview data, he seems to have been able to combine this knowledge of the daily practice of engineering design with the theoretical knowledge that he was learning in school.

Participant 2 worked for several different companies while in college, but all of them focused mainly on custom modeling and prototyping. Although these early experiences were not extensive, they appear to have given him good foundational knowledge in how products are made and how to account for that process in the use of the CAD tool.

> N: Was using CAD a large portion of those past experiences, or were you doing other things as well?
>
> P2: Oh, I was doing other things. We were doing mostly… with all of those jobs mostly doing mostly prototyping. And, so, I was a machinist for one company, and we did a lot of prototyping. We did all of the prototyping for the engineering ideas and things like that. So I would be… I would say probably at least a third, if not half, was CAD work and then the other balance would be working with your hands trying to get things to work or put things together.
>
> N: Do you think that helped you use the CAD system?
>
> P2: Oh most definitely. Yeah. If you know how things go together, and if you know how things are going to be machined or built, you go on and start with those surfaces or that's the basis of your geometry.

At one of those jobs, he was assigned a mentor who taught him many of the fundamental processes behind the use of constraint-based CAD tools.

> P2: During my junior year in college I got an internship with Walt Disney World, and my mentor there was a big fan of Pro/ENGINEER. So he taught me 3D modeling… 3D constraints. You know... how to build geometry and how the whole idea works. When he did that, he pretty much just let me loose. He gave me a few tutorials, and said, "Have at it", and I learned it on my own. When I really had a question, he would sit down and explain the theory of what I was doing. Not necessarily the mouse picks of how you do it, but more like "Here's what you're trying to do, and here's the area of the program you need to be in. Try again."

Given the size of the design environments in which he has worked, all of Participant 2's professional experiences appear to be similar in that he works with parts, assemblies, and drawings in the design of the companies' products.

Participant 2 currently works in a large company, with many designers and engineers who work concurrently on various projects, where he works to support the design and maintenance of the current product. As an engineer with his current company, he devotes about half of his time to the use of the CAD tool, and the other half is devoted to things like communicating with customers, design review meetings, and analysis.

N: What team would you work with?

P2: I am on a structures team, so we'd be dealing with all of the structures of the machine, the weldments, the frame, any linkages, things like that.

We would coordinate all of the testing, and I would be responsible for the model and the drawings, and then we would be responsible for figuring out how to implement this in the company. I would have to figure out how to take care of… I would make a decision on how to scrap material or on whether or not these parts can be re-worked, what type of machining they can take and what they can't. I would have to issue a letter for warranty purposes, or do we need to have a PIR.

N: How does… you mentioned this a bit earlier. How does CAD allow you to make those kinds of decisions?

P2: Um… it's more of a visualization tool. You're not gonna be able to… uh… you can come up with… it makes things easier to visualize. You can communicate better with the models, or pictures of the models, or some type of print. You can do a top view of the model without having to make a drawing. You know… you can use these things to communicate your ideas with your superiors or your teammates to sell your design and to convince or prove that your fix, or your decisions, will be better than what we have.

So, I would say… CAD doesn't… If you know how to use CAD, that's great, but that's not going to make you a good engineer. We still have to use the same principles, the same basic calculations, and the same basic theories. It just allows you now to communicate better with yourself and other people.

N: Have you had experiences in the past that have shown you that using CAD in that fashion is necessary or is helpful?

P2: You mean like specific examples?

N: Yeah… or you can generalize the examples.

P2: Yeah… It's nice to be able to see something in 3D. So we designed a [component] package. We wanted to see the machine with these components on there. We had the [the support group] on the top, what we call the guards that keep brush off the hood and glass of the machine. We have a guard on the front of the blade to keep brush from spilling over the blade so that you can push more loose brush and dirt. We had screens on the windows to protect the glass.

We could take that model and take that to our marketing group, and say this is what it is going to look like. This is how I am going to sell it to you from

> an aesthetics point of view. So… there's uh… it's definitely a good visualization tool. Most definitely

Most projects in this environment result from a desire by management to increase the market value or the production cost of the product, which means coming up with a way to make it cheaper and with fewer parts. With this being the case, Participant 2 must spend a great deal of time investigating the product, which usually requires examining the individual parts and assemblies.

> N: So even during those times when you are not necessarily creating something, how do those times affect your usage of the CAD software?
>
> P2: You just get an overall view of how things are put together. I mean, you'll… especially… mostly when you are investigating parts, most of the time we're looking at specific features. In assemblies, we're looking at how things work together, clearances and tolerances, and things like that. And some of that's a little tough to discern in the software and a lot of times, the problem is in the inability to manufacture the part due to what the software has. So, you kinda have to go through some of the weaknesses of the software at that point and learn what those are.
>
> N: So, when you say how things fit together, when you say "things", are you talking about the components of the machine or are you talking about how commands in the software work together?
>
> P2: How the components in the machine fit together. You get some interesting… especially with sheetmetal, well, parts in general, you'll have a great… you can use a surface, and you can copy this surface to another part, and you can build it all up, and you can hide the surface. And then when you build it, you're off, and you can measure it, and measure it, and measure it and you're within tolerance of what you specify on the drawing, but… So you have a great looking hood and our CAD part is perfect, but you can't make it perfectly. So we have to build features into CAD which allows more tolerance. You can't put things on top of each other because of interference. So, in real life, the situation is a lot different than it is in the CAD tool.

By combining that information with his background engineering knowledge, it seems likely that he can use the CAD system to develop a solution to address the problem. In fact, he seems to spend more time gathering information about the problem than he does in actually making the changes in the CAD system. Part of this is due to the structure of his environment, but it also appears that his extensive knowledge of the editing tools within the software and his command of the fundamental processes embodied in the software also influence it.

> N: I guess, when you are creating or editing using the CAD, how do you go about getting the information you need? This can be…
>
> P2: Is this knowing what feature I'm trying to create, I mean am I just trying to model this thing right here, or am I trying to solve an engineering problem?
>
> N: I would say solving a problem.
>
> P2: I would look at what the problem is. Is it an interference problem? Is it a failure problem? What is the root cause of the problem? So we can determine that, and nine times out of ten, that's not gonna be determined through CAD software. It's going to be determined through testing, analyzing, something other than CAD stuff.
>
> Now, then what you'll do is you can go in there and edit the model after you come up with your fix. CAD doesn't come up with your fix; you have to come up with the fix. Then you can go in and model it. Then after you do that, at your feature level, you figure out what feature the CAD tool is going to produce. Then you go through a list bank in your head, and figure out if this feature will be the best in this case… probably for a variety of reasons.
>
> N: Such as…?
>
> P2: Such as… I will choose a certain feature because it will be less menu picks. It will be less time consuming. It will be more robust when I attach other features to it.
>
> N: When you say "robust", do you mean like its not going to fail?
>
> P2: Right. [pause] Trying to keep things simple, will help to keep them robust. The more robust something is, then the less likely it is to fail.
>
> N: What about in terms of… investigating at the model level or at the tool level. Is there anything that you can use to investigate the model itself?
>
> P2: Um… we have some functions in Pro/E that will do that for you. You've got your… we use a lot of other people's models, so I use a lot of Regen Info, things like that. You can use Surface Gaussian Curves to figure

> out of your bend is going to work. You can use graph… you can measure, all that good stuff. We do a lot of Mass Properties analysis and all kinds of things like that. We take… we reduce prototoyping time.

This knowledge becomes invaluable to him when trying to solve a problem due to his current support structure. Participant 2 has an extensive support structure within his company, including on-line help, colleagues who are knowledgeable in using the software to collaborate with, and corporate technical support; however, these sources often lack relevance to the problems that Participant 2 must handle.

> N: How would you describe the one that currently exists?
>
> P2: Currently, as far as support, again… the people around you offer support, the company offers training. With very little hassle, you can take about any training class in CAD you want. We have on-site support staff, our IS group. We have several people that work with PTC support when we have various problems. And as a corporation, we have thousands of people that are competent in the use of the software. By sheer numbers, sooner or later, you'll run across the person that can answer what you need.
>
> N: Given that elaborate support structure, have you … do you think that has helped you in your use of the tool?
>
> P2: I think… little in general as far as how to create a part and a drawing. That has changed very little from the very first experience I had with the software. The modules and the more advanced features, yes… it has helped me. My understanding of those things is a lot greater. When I started, I was fairly competent. So, I don't feel, like after the training classes and all of that, I don't feel like I am a vast-amount better modeler. I think I have learned more menu picks, but I don't think I have more ability to use the software.
>
> N: Why do you think you do not have any more ability after having gone through those particular training classes?
>
> P2: Um… because everything is broken down as to the way that the software is created, everything is simple. You're gonna make very simple geometry to come up with complex parts. As long as you conceptually… you can make the same features in a cut as you can in a protrusion. You can have your variable section sweeps, your swept blends, and all of that stuff, your surfaces… you can use those, but the basic building blocks, the ideas, the principles are all the same. It's just using a different command. A mate is still a mate, a line is still a line, and Insert is still an Insert, and the

> variable section sweep doesn’t do anything to change that; it’s just more complex.
>
> N: It seems like what you’re saying then is that, in those training classes, often times the context in which you would use something is missing?
>
> P2: Right.
>
> N: And that most of the exercises that you do in those courses are simply self-contained. There is no other external factor there to help you see where you would use these things or how you would put them into place.
>
> P2: Yeah. Sort of. But I think more along the lines of the ability of the software is taking features… and there is a whole array of features that you can use, and these features can be put together to build something. So, once you have your basics… a protrusion or a revolve or whatever… you can use those in a variety of ways to get what you need. So the process of “Oh, this is how you make a variable section sweep”, well that’s great. I can reference that; I can pull my manual out, and I can say that, while I forget how to do it now, I can do that. I don’t use it everyday, but I can find the information. The classes don’t necessarily teach you how to apply the function that you want.
>
> N: How do you figure out how to apply it?
>
> P2: You… you, um… you’ve got to be put into a situation when you need the geometry. When you have tried various approaches using the basic features to create your geometry, and those have not worked. You are then forced to use the advanced functions, but you have to go through the iterations in order for it to be a meaningful exercise. This adds a great deal to your “toolbox”, because you have seen several different situations when geometry will and will not work.

In trying to develop a solution to these problems, he uses many of the model interrogation tools within the software to gather information and to define the problem scope. He also uses the software to experiment with various geometry combinations and arrangements due to his confidence in his abilities with the tool. In light of this fact, Participant 2 is quick to point out that the CAD system is only a tool, and that it cannot develop a solution to the problem alone.

> N: You mentioned three very broad categories right there: new products, cost reduction, and field problems. How is CAD involved in those three areas?

> P2: First of all, you're going to have your research. You're gonna open up geometry you already have, or geometry that similar, and you're going to take a look and see what's going on. You can pull drawings, models, whatever, and you can find out what's really going on. You can take measurements if there is interference, you can find out a lot about what is going on with the design. Then you will go through, and after you've determined the engineering fix, which CAD is not going to hand that to you most of the time, then you go and change your model to reflect that engineering change.

Participant 2 also did not necessarily consider himself an expert, just "a good problem solver." He appears to be able to solve his problems though through an extensive knowledge of the software and its functions coupled with knowledge of the product he is designing. According to Participant 2, "command knowledge is not as important as the end result." Participant 2 seems to be considered one of the resident experts in his group, but he has problems using the software just like other users do, and it seems as if his awareness of these difficulties leads him to choose particular solutions that have worked in the past.

> N: Is it always an iterative process like that, or are there times when you know that you need feature X right here?
>
> P2: Oh yeah. Definitely. I mean… it just depends on what you're doing. Where you are in your thought process; where you are in your design process; what other features you are required to put in later. Also what features did you fail to anticipate in the beginning? All of that comes into play. But, yes, you can definitely say, "Well, I need a hole here." But I very rarely use the Hole feature, because when you need to make a slot now, it's tough. Things like that.
>
> N: It almost sounds like you're saying that there are certain types of problems or certain… template types of problems – that in certain situations, you will always, or almost always, tend to do this.
>
> P2: Right. That's exactly it.
>
> N: Can you give me an example? You kind of alluded to one with the hole and the slot.
>
> P2: Yeah. Definitely. Well, you have the tendency… or I have the tendency that if I have a symmetrical part, I use a lot of Mirror Geometry. I do that

> because you will… you'll have a hard time… If you can build half of it and mirror it over, number one, you cut your work in half. But number two; you can change the part dramatically by only altering half of it.
>
> So I would say I typically use Mirror Geometry on symmetrical parts. A lot of your Copy commands, if you're not sure where things are going to go, the Copy command is not a good thing. You end up failing when you try to delete something or break references, or you have half of your model wiped out.

His conception of expertise seems to focus on the ability of the expert to be able to account for all of the various factors that impact a problem situation in order to develop an effective solution.

> N: How would you… just in general…and this can be in any particular field, if you could generalize this. How would you characterize and expert?
>
> P2: An expert would be somebody that has a… not a complete… a knowledge of a particular field. You can have experts in all types of things… he knows what he doesn't know. But he knows that he does know a lot, but he knows, "I don't know why this works, but it works, and we're trying to figure that out."
>
> N: So there is a certain level of acceptance… that certain things are just a given…
>
> P2: Right.
>
> N: … or that I don't know something, but here is all of the stuff I do know, and so provided that I can keep things within this boundary…
>
> P2: Then we can control it. Once we get out of this boundary, then we may not be able to do it, and we may need to learn more. Also, the expert also knows how to research [a problem], how to find out… he knows if it's worth wasting your time to do that.
>
> N: The things that you just said coincides with a lot of the research literature about experts – that they have a very extensive knowledge base. But there is also literature that talks about their problem-solving strategies, or their ability to integrate information, sort of holistically. And also, their time in terms of how much experience they have in a particular area. How would you say that those things impact expertise?

> P2: Oh, yeah. Definitely. Being able to apply one kind concept in this situation to a similar situation to apply to a gap there, I would consider one of the main ideas of an expert.
>
> N: So that's like a template...?
>
> P2: Being able to look at a problem and say, "We've seen this before. Not these particular parts, not these particular situations, but we've seen this type of problem before. We've experienced this phenomenon before." And being able to bridge those gaps, and say, "Well, why is that?" You can reason your way around and find the root cause; that would be how an expert would work.
>
> N: OK. What about expert's strategies?
>
> P2: Strategies?
>
> N: Yeah, for solving problems or processing information. How would you characterize that?
>
> P2: Maybe it's because I am not such an expert, but I would tend to think that it would take on… again, a very simple example, they break things down into pieces, they break complex drawings down. They have a bigger understanding, I would think, of how to communicate a design.
>
> Maybe I need to have things given to me in smaller details, I don't know.
>
> N: Experts do what is called "chunking" of their problems. They'll chunk information together and process it as a whole. Have you… would you say that that is representative of an expert… that you would think about a lot of information and put that to use?
>
> P2: Oh yeah, most definitely. Being able to take a variety of situations and come up with a solution, to determine the root cause… I guess I'm talking about an engineering expert. You've got to be able to do that, to evaluate all of the factors. Now… you know, sometimes not all experts have *all correct* or *all feasible* ideas. They may have several solutions, but they may not all be feasible. There's a difference there too. Um… but, yeah, in general, I think that would probably be true.

He also sees experts as "having lots of experience within the field and being able to answer questions in a short time. Experts use experience to produce meaningful results." In accounting for all of the various factors in a design situation, Participant 2 sees experts as having the knowledge to incorporate variability into their model through their geometry creation techniques. Given that the model seems to be a vehicle for communication and design visualization, this is critical. But Participant 2 also stresses that it is important to consider the cost of putting too much work into a model when it is not necessary. When using the CAD tool, a balance must be reached between adding "robustness" to the model versus the time it would take to do so. That is why having a firm grasp of the basic geometry creation functions and when to use them appears to be essential to the expert constraint-based CAD user.

> N: OK. How would you characterize the difference between an expert constraint-based CAD user and a non-expert constraint-based CAD user?
>
> P2: Expert is going to have foresight. A non-expert is not going to have foresight.
>
> N: All right. Is that all?
>
> P2: Um… I mean… there will be some… The expert I would assume to be faster using the tools.
>
> N: Why do you think the expert would be faster?
>
> P2: Well, he takes the shorter distance between two points, number one. And that he's faster because he can make complex geometry, swept features, stuff like that.
>
> N: When you say " shorter distance between two points"…
>
> P2: Well, if you're trying to get… uh… I don't know. If you're trying to get this soda can, you know, you could… You could extrude it up, and then cut features away, or you could just revolve it.
>
> N: OK. So… command choice?
>
> P2: Command choice. Yeah. Feature choice… being able to see what the most applicable feature would be. I'm sure there is somebody out there in the world that would try to build this soda can without any joints, you know... that would revolve a cross-section that was .08 millimeters which or whatever, without using the Shell function. Things like that.
>
> N: What is it that you think makes those people faster? What makes them choose specific commands over another?

P2: A general… simple understanding, a fundamental understanding of what those commands are and what they do… and where they can be applied.

N: You mentioned the speed of the expert as opposed to the non-expert, the fundamental understanding of commands… Anything else that could differentiate between an expert and a non-expert constraint-based CAD tool user?

P2: Well, the end result will be more stable, and you… Given a set of constraints… that whatever they are: height, width, length… those will be a lot more variable in the expert's model than they will in the non-expert's model. The features will not be as… They'll be tied together… They will be either tied together or not tied together in a way to allow variability in a model. That's the advantage of 3D, parametric modeling is the ability to make changes, because change is going to happen.

N: it sounds like the expert has the ability to anticipate potential change?

P2: Yes, most definitely.

N: OK. So, the ability to anticipate that change, the ability to "scope the problem", and speed… Anything else that would contribute to expertise in the use of constraint-based CAD tools?

P2: [long pause] Um… I mean… having a broad knowledge of the advanced features and stuff like that.

N: OK. Let's talk about those. Can you give me an example?

P2: Variable section sweeps, swept blends, or being able to make a… you know… understanding Drafts or Advanced Rounds.

N: What is there to understanding Rounds and Draft and Advanced features? What goes into understanding those?

P2: Well, number one, understanding where they are going to be applied, and why. What advantage do they give you when you do apply them, because sometimes it is easier not to apply them than it is to apply them. And, uh… But if you've got something that the geometry is easier to build without it, then this just allows an easier way to produce the geometry that you need.

> If it makes your model complicated and hard to change, then it would not be a good idea to use it.

Constraint-based CAD tools automate many of the rudimentary geometry creation activities in the design process, which seems to allow the expert to concentrate on the "bigger picture."

Participant 2 appears to view expertise in the use of constraint-based CAD tools as a complex phenomenon controlled by the expert's ability to recognize the conditions of his situation and create or edit geometry accordingly. To do that, they must have a fundamental knowledge of software processes and their design intent. Appropriate geometry creation and editing techniques seem to be important factors for Participant 2, and it appears that they should be selected for the object in question based on the information collected to develop a problem solution.

Structural Description of Expertise for Participant 2

Participant 2 has had a variety of past experiences that have contributed to the development of his level of expertise in the use of constraint-based CAD tools. He has worked in several internships while in school to supplement is theoretical knowledge with practical experience. These experiences have provided Participant 2 with a background of the engineering design domain and the basic knowledge contained therein. Projects that he has worked on have focused on the redesign and reverse engineering of many existing products, as well as the creation of new products. In doing so, he has had work with models and assemblies that have been created by other people, which can lead to many unexpected problems in terms of using the CAD tool. Being able to investigate those problems and implement a solution has given Participant 2 a great deal of confidence in his abilities in using constraint-based CAD tools.

In his current environment, Participant 2 spends the majority of his time updating and maintaining the current product in the field. Most of his time is not spent designing things from scratch. He builds geometry that is to be used at "the next higher levels of the assembly." This causes him to interact on a daily basis with many design considerations, both internal and external to the CAD software. Things such as customer requirements, cost reductions, and how changes to address those issues will propagate through the various CAD models after the changes have been made are all potential considerations. In fact, he spends more time investigating the problem than he does actually making the changes. He would not be able to do this without a thorough scope of the problem and the fundamental understanding of the relationships upon which the software is based. According to Participant 2, immersion into the design environment on a daily basis enables proficiency in the use of the tool. However, proficient skills do not replace the need for strong theoretical knowledge within the engineering design domain.

Within any environment there exists some support structure that aids in the pursuit of the primary objectives. In the case of Participant 2, his support structure is quite extensive. He has been able to collaborate with others in his group, take several CAD training courses, and have access to a database of lessons learned. In light of all of this, he finds his support structure lacking due to its generic nature. The elements therein have no appreciation for the context in which he operates. When these sources do not provide an answer to his questions, he must experiment with different solutions contrived of his own devices. Due to time constraints and the complexity of the design situation, it is likely that when he finds a method or technique that works, Participant 2 often will make a compromise between models that are highly robust and those that simply suffice due to limited resources.

Expertise is a phenomenon that is generally context-specific, and for Participant 2 it is no different. His characterization of expertise is one of timeliness and value. It is about having depth of experience within a particular field. To him, experts will have the answers when they are needed and present them in a fashion that is relevant to the person asking the question. Participant 2 also stresses that the ability to generate a sound modeling strategy based on design intent is crucial. Constraint-based CAD software is able to incorporate many of the rudimentary geometry creation activities by default, thereby freeing mental resources on the part of the user to think about higher-order issues. Through his past experiences inside and outside the software and the structure of his current environment, Participant 2 is able to account for these factors and more in his development of a 3D CAD model. However, he is quick to point out that using the CAD tool is simply a means to an end. Capturing the design requirements *through* effective geometry creation is still the main goal. Considerations such as parent/child references, feature order, associativity, feature type, critical dimensions, and design intent are all part of the scope of any modeling task that he takes on, and they directly impact his choices for geometry creation and editing actions.

Textural Description of Expertise for Participant 3

Participant 3 works in a small engineering department of a company that makes custom, blow-molded packaging for consumer products and various other plastic articles for the consumer product industry, and he has worked for this company since his graduation from college with a master's degree in technology. In fact, this location is only one of many divisions within the parent company. Within his design department, there are only two other people including his boss who does no design work but handles all of the administration of the facility. Due to the small size of his group, it appears that he and his coworker "wear many hats."

> N: In your past experiences, everything prior to now being past experiences, how much was CAD involved in your day-to-day activities in the past jobs you've had? Was it the only thing you did or were you doing other things besides creating drawings and models with the CAD system?
>
> P3: Um, my industrial experience has been totally with my current employer. We've been through several ownership changes, but we are a custom plastic molder with a small engineering department. Therefore, we have to wear a lot of hats. I manage a project from the time it is a gleam in a customer's eye until we deliver the product to the door. So, my day is not totally spent in front of the CAD screen, but there are some stages during the project where I could spend, and sometimes it has been, twenty-four hours straight in front of the CAD screen in order to make a deadline.
>
> We don't have draftsmen, so we do our own drafting. We do our own designs. We do the bill of material work on a mainframe system that is completely a dinosaur, and so that does not interface with the CAD system at all. So, there are a lot of things in creating a product that is not directly related to CAD modeling, but it is an integral part of my responsibilities.
>
> N: OK. Having had to wear all of those different hats, do you think the other things you have to do that are non-CAD related have impacted the way you choose to use the CAD tool, or the decisions you make while you use it?

> P3: It really um… Other than keeping… In this environment, design for manufacturability is key from the very beginning of the design, so you're always keeping that in mind. You're always very cost-conscious of how you design the product, trying to minimize whatever costs are involved.
>
> We want to utilize whatever best practices have been established through the history of this type of processing. Industrial practices we also try to keep in mind.

He is in charge of the product design from start to finish, and because of this, he is required to use most of the functions within the CAD tool to accomplish his daily activities. Many things are included in those daily activities, such as interfacing with the customer, resolving production issues in the shop, and creating his own detail drawings when necessary. The data suggest that all of these activities have given him working knowledge of the software command structure, as well as its applicability to various design situations. It has also contributed to the strategies that he creates to solve his design problems.

At the time when Participant 3 graduated from college and began his professional career, CAD tools were not wide spread within industry. His primary tool for creating engineering graphics was the drafting machine. By using these tools for a large portion of his career, and due to the nature of his educational background, Participant 3 seems to be well versed in the art of making drawings, and he possessed all of the requisite skills. In his transition from using the drawing board to using a CAD system, it appears that he was able to overcome the limited functionality of early CAD systems with a thorough understanding of engineering graphics and its related concepts, which helped him in planning his designs.

> N: OK. You mentioned that you had used a drawing board, I guess a drafting machine or triangle and T-square, or some combination thereof…
>
> P3: Yes, combinations thereof.
>
> N: Do you know if that's affected the way you use your CAD tools, whether they be 2D CAD tools or 3D CAD tools?
>
> P3: I think that it has had a profound effect, because… For one thing, I understood orthographic projections. Particularly in the early days of

> CADKEY when it did not have anything but a simple screen capture as a form of generating drawings, understanding projections and basic view theory to describe an object, I think it completely affected how I attacked the CAD system and how I used it.
>
> I think that it has had a greater effect when I was using a 3D wireframe system than with a solid modeling system.
>
> N: OK. Other than a good understanding of projection theory and the particulars that go with that, was there anything else about using the traditional tools that helped you in your use of CAD tools?
>
> P3: I think because we are taking our design largely from a clean-sheet-of-paper approach, you have to have a fairly good idea of where you're going with your CAD model when you start off. I'm not just doing formal drawings from somebody else's concept or design, I'm creating a design from scratch in most cases. So, having had the drawing board experience and also quite a bit of sketching… being able to quickly sketch something out and plan out where you're going with your CAD model has helped tremendously.

As suggested by the previous interview passage, those experiences of planning, sketching, and drawing his designs have largely impacted his use of the CAD tools in terms of planning a design. It appears to also have enabled him to overcome elements of the software that do not match his background in engineering graphics and its standards for communication.

As his company progressed from the use of a drawing board to 2D CAD tools, and from 2D CAD tools to 3D wireframe and eventually constraint-based CAD tools, Participant 3 was able to adapt his skill set and knowledge base to effectively use the new tools. In a typical day, he spends the majority of his time using the CAD system, even though he is responsible for other things. During the design of his products, he often works with parts and assemblies to develop a new design.

> N: OK. When you have done all of the things that you have done, and probably in the present, do you work exclusively with parts, or assemblies, or drawings, or a combination?
>
> P3: We use it all.
>
> N: Why is it that you tend to use it all, as opposed to focusing on one thing?

> P3: Well, because we are dealing with a combination of parts. It's not… I'm not just drawing a gear. I'm doing a case which is, as its very essence, an assembly of parts. And sometimes I also get involved with the tooling that makes that part and designing that as well. So just by the nature of our activities, and because we have to wear a lot of hats, we're not just… I'm not just drawing half the case, or the interior the case, I'm drawing the whole case and the whole part. I also use Assembly functions as tools to help me develop the design going from the parts that are contained within the case, designing from the inside out so to speak. Making sure that I can capture those parts adequately and accurately, I make those parts first, assemble them in space, and then I draw the case around them.
>
> So… and then to communicate that design using a variety of functions from the CAD system, the first of which would be a traditional drawing. Very often our customers cannot read those drawings, so we have to give them a pretty picture. That's one thing that Pro/E has a very superior capability in doing screen captures of a shaded model, and that is a very effective way of communicating with our customers that various features of their case designs. So we use that quite a bit.
>
> But then, each assembly is only as good as the parts that it's made of. So we use them all.
>
> N: OK. Do you think having used the primary functions of the CAD tool, and because you have to wear so many hats in the company, do you think the way you use the CAD system, and the level at which you use it… How do you think that is different from a person who simply does modeling or simply does drawing, which is a case of a lot of large companies?
>
> P3: I think I have to push the boundaries of the system a lot more. I want to consider it as a tool to help me get my job done, and I want to find the best and most efficient way to achieve the objectives, and to use this tool and everything that it can do. So… we're doing a lot of things, from the perspective of some of the Customer Assistance Engineers from PTC, we're pushing the envelope as far as complexity of models and doing the types of things we're doing. A lot of companies our size don't get into that whole realm of the functionality of the CAD system. We're asking questions that a lot of the technical support people have never have asked to them before.

In addition, he makes it a point to use the "best practices" as established by those in his industry. In the past, the design process allowed many more people to look at his work than they do today, to impart their knowledge base into his design. Today, he is much more reliant on his own knowledge base and the ability of the CAD tool to capture that tacit information into a useful model. As discussed in the passage below, in part by his increased awareness of the tool and its processes, but also because design environment conditions dictate as such.

> N: In your development of expertise in the use of these particular tools, do you think the level of collaboration you have with other people, or the lack thereof, has that affected your development of expertise in the use of constraint-based CAD tools?
>
> P3: I think it's kind of provincial. Again, I'm going to use what I know works, and what I feel comfortable in using. And whether it has helped… Sometimes when we're exchanging models with our customers, to see other peoples styles of modeling and styles of handling various things in Pro/E, one thing that I have found there is that there is almost an infinite number of styles in creating a Pro/E model. And, so you're going to see a lot of different approaches.
>
> I guess the measure of whether or not it's working is if you're able to deliver your design on time to meet the customer's expectations, to make it manufacturable, and also for the model to be robust enough to where you can put a tool path on it, drill the mold around it, and not have a lot of geometry issues or any geometry issues.
>
> N: When you say "robust", what exactly do you mean?
>
> P3: To me, a robust model is one that can withstand some pretty drastic changes and not blow up.
>
> N: OK. That's what I thought it was; I just wanted to make sure.
>
> P3: And in our environment, a robust model is one that can go to the tooling phase without any refinement by the tool designer. It should be transparent to him, whether he is adding shrink to it or putting a surface on it, there shouldn't be any geometry problems with what you've done. There shouldn't be any "holes" in the model.
>
> N: How do the CAD tools fit into the design process here at your company?
>
> P3: That's the way parts are done. We are effectively a paperless environment internally. The only time we generate a formal drawing is at the customer's specific request or if we need some very basic internal documentation. Even then, it's not a full working drawing; it's just a picture with a number that defines the appearance of the product.

> N: So from concept to refinement to documentation to production, the majority of that is electronic using the CAD tool?
>
> P3: Exactly. We can't make anything at this point. Our expertise was… the best way to understand that is to understand how we did things with paper and pencil. I would make a drawing, and the tool designer would then make a drawing of my part, a tool drawing, where he would reverse it and draw the mold and dimension it. Then, it would be turned over to a pattern maker who would make it in wood, and then the wooden model would be traced with a hydraulic-tracing milling machine into the material that the mold would be made from. That would be aluminum out there.
>
> One of the advantages of that system is that you've got so many pairs of eyes making input and looking at your work during the phases of the design. You have a lot of different skill levels. The tool designer at that point had to be able to look at your product design and be able to draw it in reverse, at a different scale, which took an incredible amount of skill. Consequently, he picked up a lot of the problems with your design, if there were any, as far as manufacturability or machinability. And then if he did not catch them, then the pattern maker would catch them. So you had a lot of checks and balances, but it was largely because of the level of skill and expertise by the individuals involved downstream between the actual design and production tooling.
>
> The way it works now… We do the design… the tool designer then uses the tool to extract that shape from a mold base. He turns the geometry over to the programmer who uses another software package to generate the tool path, and the mold is cut, sometimes before anybody has really looked at it. So it makes the… I have to be a whole lot more careful with what I am designing in this current system, because there are not the human checks and balances in place. There are certain software checks and balances present, but the human checks and balances with the skill level built in is missing.
>
> N: OK. How does that… Does the CAD tool help you make any of those decisions or account for any of those factors?
>
> P3: It is essential. For one thing, being able to look at a shaded model, and then being able to do things like interference checks or draft checks. Those are critical to the way the product is developed.

Given the size of his company, Participant 3 has no internal support structure. As he has stated frequently, "I am on my own." If he does receive any help with using the software, it typically comes in the form of a consultant or technical support group at the software vendor. The training classes he has attended have been beneficial in learning the basic vocabulary of the software, but often time the semantics of the software do not match the thought process of the user.

> N: OK. In the past, and I think I know the answer to some of this already, I know you said you had taken some of the “official” or vendor-sponsored training classes. For what you have done in the past, although it is similar to what you’re doing in the present, have those courses been beneficial?
>
> P3: Extremely. There’s… When we were first evaluating Pro/E, we evaluated several different solid modeling systems, and one of the things that we were evaluating… we asked them to loan us the system for a couple of months and play with it with no training. Let’s see how intuitive it is, because we didn’t have anybody in the company that had any Pro/E experience. We don’t have any help desk or any inside resources… just us.
>
> So it had to be intuitive to a certain degree. At that time, we found that Pro/E was not intuitive at all. From the tutorials you could go through, they were very basic and in some ways very counter-productive to really using the tool. So it was essential to have the basic Pro/E training to be able to sit down and do anything useful with the software in any sort of useful timeframe.
>
> We had the Basic modeling. We had Advanced modeling. We had Advanced Assemblies… and Drawing. About a year and a half later, we took the Surfaces class. All of those have been helpful to a point as far as making sure, if nothing else, that you understand the vocabulary. Every modeling system has a slightly different vocabulary of terms and capabilities. And it is essential to go through the training, particularly in later versions where there is no printed material that accompanies the software upgrade.

Because of this, he has had to develop his own methods and strategies for solving problems. In many ways, using CAD tools, particularly constraint-based CAD tools, has forced him to change the way he thinks about creating geometry. Participant 3 has had to overcome this dilemma by being able to recognize the inherent characteristics of the geometry in the design situation, while remaining aware of the background software processes that affect the geometry creation task at hand.

N: Have you had any experiences in the past, or prior to using constraint-based CAD tools, that have affected now the way that you do use constraint-based CAD tools?

P3: I think in a large way, having first used paper and pencil with a drafting machine, and then gone to a 3D wireframe system, I've had to unlearn and completely change the way I approach a design to be efficient and effective using a constraint-based or solid modeling CAD system.

N: What kinds of things have you had to unlearn or change?

P3: Um… [long pause] The way that you approach a design has to be completely different, and you have to be a whole lot more organized with how you do things. In a 3D wireframe mode, the order that you create things is not really important. In constraint-based CAD systems, the order that you create things in is everything. You can very quickly and easily paint yourself into a corner, and then have to start all over again if you don't allow for an amount of robustness in the design. You have to be a whole lot more disciplined, and in some ways, more cautious about the ways that you do things. But I think what you end up with is far superior than with the other systems.

The biggest challenge that we have is still simple geometry issues, because the vast majority of what we do has draft and rounds, sometimes in very strange combinations, or at least what Pro/E thinks is a really strage combination. And it simply says "No, I'm not doing do that." So, sometimes you have to do work-arounds, and you have to change the way you want to create a model, simply because it doesn't work the way you want it to the first time.

N: It's interesting that you said it makes you be a lot more disciplined and that potentially, if you're not disciplined or you're not thorough in your planning process, you could have to start over. Doing things like Modify, Redefine, Reorder, Reroute, those kinds of functions… do those not give you enough flexibility to save yourself so to speak?

P3: I think every time you're faced with that, you have to ask yourself is it going to take less time to do it right, starting from scratch, or go in and fix what I've got. And that has to just be a judgment call on a case-to-case basis.

N: I guess, provided that you recognize that you've done something wrong and that you recognize enough to know how to go back and in fact, do it right.

> P3: In some cases, it's… When you say "do it right", you talk about doing it in such a way that allows you to achieve your desired result. Technically, both models would be equally sound, but one would not let you modify a dimension that is necessary to modify to get where the customer wants to go.
>
> Sometimes, no matter how well you plan, the customer is going to want to change the one dimension that causes the whole model to blow up, and you have to start from scratch. And that's just part of it. When I was… The other thing is that I used to get very upset when the model failed, when you had to go back in and Redefine something. Now, you know that it's just part of designing in Pro/E, and it's no big deal anymore. You just fix it and go on. It's one of those things that you learn to live with.

In developing a means to overcome problems in using the software, Participant 3 uses a hands-on approach to problem solving with a goal of understanding the processes behind the step. It is based on practice that is relevant to the context in which the skills will be used.

> N: OK… speaking of expertise. Let's shift gears a little bit here and move into the third section of the guide and that is the section of expertise.
>
> When you learn something or are in a learning environment, how would you describe yourself, your own personal learning style?
>
> P3: [long pause] One of the terms that we learned way back when was "organic", meaning that the more senses you could have involved in the learning experience, the more effective and efficient it is. I think I tend to learn that way. I am the type of person who reads and follows instruction manuals when available.
>
> I also like to experience things. I learn quicker when I have a hands-on component in the learning…
>
> I also think there needs to be the logic behind, or the reasoning behind, why you do something in a certain way in a certain order. I think it is sometimes more important to learn that than the actual tool itself…

If he is faced with a task that is unfamiliar to him, he uses a variety of sources to gather information: his domain knowledge base, a knowledgeable counterpart, and experimentation to find a solution.

> N: OK. If you had to learn something new, or if it's been a while since you've done something, how do you go about doing that, just in general?
>
> P3: I try to find something to read about it. I look for the instruction book or the manual. [long pause]
>
> That's the first step; I try to find out as much as I can about it through whatever ways I can that are practical. And then, particularly if it's something that's brand new… other times there are… I think it's perfectly valid just to play and experiment and see what works and what does not. It takes more time to do it that way, and you have to be comfortable with the outcome. If you want to do something right the first time, you better read the manual.
>
> N: How do you address any particular challenges in that kind of a process, or that you face in using these kinds of CAD tools, particularly constraint-based CAD tools? And in doing your job, how do you address any challenges or problems that you have?
>
> P3: I think the first thing you do, obviously, is you use you existing knowledge base. You bring to the table whatever you can, and then you seek out people that know more than you do. If you can't find something to read about it that enlightens you any more than you already are, then you seek out somebody that can help you. If all else fails, you play with it until you finds something that works.
>
> N: In seeking out somebody that you think can help you, what do you base that decision on or that selection of the person on? How do you pick them?
>
> P3: [long pause]
>
> You try to find somebody that knows more than you do about that particular subject. It's like any sort of consultation process. Unless they're bringing more to the table than you've already got, it's kind of a futile effort.

However, Participant 3 also has a high degree of confidence in his abilities and knowledge base, honed by working on his own through the various software tools, which he uses to give him "some measure of comfort" in performing in an unknown situation.

> N: If you encounter a function inside the CAD system that you have never used before, or it's been a while since you've used it and now you have to use it again, how do you handle that scenario?

> P3: Right now, I try it and see if it will come to me. You become familiar enough… I've been using Pro/E now for over six years, and ten years of CADKEY experience prior to that. So, at this point, I'm not afraid to try it. I save what I'm working on, and I try something brand new in a model I've created just to try that particular feature so that I'm not going to risk messing up something that I've been working on for two weeks.
>
> I'm going to experiment, but it's not going to be in such a way that I'm going to lose anything by doing it.
>
> N: So if you're just going to experiment, or you feel comfortable enough just to try it and see what happens, how do you get from a point where you don't have that comfort level to where you do have it? What can we do to get people to a level where they feel comfortable enough to try it?
>
> P3: There's no substitute for doing it. Part of that is helping them understand some of the "whys" in what their doing and not just giving them a cookbook approach when they are learning the system. To me, that was the biggest shortcoming in the formal instruction I had. It was all very much a recipe-based approach to solid modeling. If you wanted to go to do something differently, or if you did the steps out of order and it did not work, you didn't know why it didn't work. You just knew that it didn't work. So it was very… you were somewhat increasing your knowledge base, but you didn't have anymore wisdom on how to use those tools than when you started. That is the biggest drawback to these systems and the way they are taught right now.

In addition, investigation is based on clearly defined design parameters that are discovered only through knowing where to look or who to ask. Participant 3 solves problems with the software by simultaneously searching for answers and experimenting with different techniques for creating geometry. That search however, is tempered by time constraints as discussed below. "It is not always necessary to have the perfect model."

> N: OK. Having more than one project going at a time I would say is probably a typical way that a lot of people work. Having that scenario here, and given the fact that you do wear so many hats, has that affected or does it affect currently, the way that you use the CAD tool or your ability to use the CAD tool?
>
> P3: I think the way that it impacts… to a certain extent, it is more related to a sense of urgency from each project that I'm facing and whether or not you're willing to try something new and different or go with the tried and

> true and just hack it out. Instead of trying to do something new and elegant, you know it's going to work and so you'll do it that way simply because you don't have the luxury of the time to devote to a learning curve for something new. You also want to be as efficient with your time as you can, and that kind of impacts what you do. You learn… For instance, with Pro/E, normally if you can do a model by minimizing the number of features, the better off you're going to be in the long run.

In determining all of the relevant characteristics of the design situation, Participant 3 must communicate closely with the customer, often times sharing CAD data back and forth. It requires that he perform a great deal of reverse engineering activities and create a variety of geometry types. It appears that this has helped to strengthen his level of expertise in the use of constraint-based CAD tools. Just as the other participants have stated, Participant 3 does not necessarily consider himself to be an expert, although he does consider expertise to be heavily based on a person's experiences.

> N: What kinds of things, or what types of experiences, have gotten you to that point, that medium to high level of expertise?
>
> P3: The idea of having to do a lot of reverse engineering of fairly complex parts. You learn a lot doing that… also being faced with dealing with plastic parts totally in your experience. You're not just drawing screw-machined parts or sheetmetal parts where you're dealing with right angles and planar surfaces. You're dealing with weird things on a daily basis, and you have to kind of step up to the plate or it's not functional for you.
>
> N: You mentioned dealing with plastic parts and things that are not only right angles or simple bent geometry. Can you elaborate on that a little bit more? What kind of actions have you taken, besides reverse engineering, in the creation of that kind of geometry that's contributed to that level of expertise?
>
> P3: Um… I think you learn quickly when you start measuring things and trying to re-create them in the CAD system and make it as accurately as you possibly can, because you're going to use that model for other things. You're not just using it to make a pretty picture.
>
> Again having progressed from the drawing board, to a 3D wireframe environment, to a solid modeling environment, you learn to deal with things in a certain way and to look at things in a certain way. When you start to having to reverse engineer objects, the success in your final product is dependent on your accuracy in reverse engineering those products. And when they become more organic in shape using wildly curved surfaces, and

> you have to figure out, first of all, how to quantify those things before you can then reproduce them, it really helps you understand how that you then can create things from a clean sheet paper, using those same skills and tools.

People make a transition from using the software in a very linear fashion to using it holistically to account for the existing conditions. "It is not necessarily about knowing more, but knowing different." According to Participant 3, expertise is confined to a particular area, and an expert is "comfortable explaining even the most basic concepts of the knowledge base." Different backgrounds and specialized knowledge aid in collaboration, because knowledge in all areas is unnecessary – "you just have to know how to get it."

Participant 3 also describes experts in any field as having an extensive knowledge base, and that they know the limits of that knowledge. Experts in the use of constraint-based CAD tools are no different. They are solicited based on their level of software use and their years of experience, which is a direct reflection of what they know.

> P3: An expert is someone who is comfortable enough with his knowledge base that he can explain, whatever subject he is regarded as an expert in, that to a complete novice effectively.
>
> N: How do you think he is able to effectively explain that?
>
> P3: He is comfortable enough with what he knows so he can escape the jargon and the… he knows his subject well enough that he is comfortable in using it and explaining it at its very basic levels.
>
> N: Does he also know what he doesn't know?
>
> P3: Yes, he does. That's part of the comfort level, and what he does know, he knows very well. He also knows his limitations, and is ready to admit that he doesn't know and usually finds someone who does.
>
> N: How do you think an expert learns something? And kind of building on this… he knows what he knows, and he knows what he doesn't know, is he able to track himself and monitor himself as he is learning to know when he has reached that point between knowing and not knowing something?
>
> P3: I'm not sure if that's a characteristic of an expert or just of an intelligent, well-educated person. I think it is probably one characteristic of an expert, but I don't know if it's the defining characteristic or not.

> N: Can you describe any situation in which you were an expert? It doesn't necessarily have to be related to CAD.
>
> P3: I think an expert is relative. If you know more than the person asking you for help or advice, then you're an expert in their eyes.
>
> In certain ways, true expertise is having knowledge beyond what is essential to do the job at hand so that you can deal with the unknown or the unexpected. You're comfortable enough with the tool that you're given. You can go beyond the realm of the current experience and effectively use those tools to do something new.
>
> N: OK. If you characterize an expert simply as a person who knows more than the person asking for help, then I'm assuming that at some point, you've been in a situation like that.
>
> P3: Oh, yeah. It happens quite often. It's a combination of education and experience and being able to use the knowledge gained from that to solve problems.

Experts must also account for costs, customer requirements, and manufacturing processes as they compare the current situation to those that they have experienced in the past. Based on those comparisons, the development of an effective modeling strategy is crucial to success. Participant 3 intends for his models to be robust, although the software characteristics sometimes affect his exact procedures.

> N: How would you characterize the difference between an expert, or more experienced, constraint-based CAD user and a non-expert, or less experienced, constraint-based CAD user?
>
> P3: I think the first thing is going to be the efficiency, how well do they use the tool. There will be less trial and error and a more direct approach to achieving the desired result. They end up with a more robust model with fewer steps and fewer features the first time around.
>
> N: What about in terms of confidence level, or a willingness to try something new or novel in the solution to a problem?
>
> P3: I think they will be willing and open to try something new, because they're comfortable with… they know something that works. So that gives them a good foundation to build on and apply new skills. Whereas, if

> you're not confident with the little knowledge you have, you're not going to go out and try to build on a shaky foundation.
>
> N: What about in terms of those certain core or fundamental concepts that we talked about earlier, such as references, use of datum planes, feature order, things like that?
>
> P3: In what?
>
> N: The differences between experts and non-experts.
>
> P3: I think in the case of the expert, it's going to be second nature. He's not going to have to think about the steps he goes through, and it's going to be more efficient and effective use of his time. Whereas the novice might go through the same steps, but they have to go through a cognitive process to rate, or go through a formal checklist, before they are able to go through and do that problem.
>
> N: How do you think experts are able to… or is there a general process or characterization that we can make about experts and how they are able to capture their design intent in a model?
>
> P3: I think they will make less compromises with their design intent for ease of feature construction; whereas someone less skilled will choose the easier and quicker way simply because it is an easier and quicker way to model it, rather than their initial reason. They will let the CAD system drive their design intent down rather than using the tool to facilitate the original design intent.
>
> Does that make sense?
> If you really wanted a convex surface, but you couldn't model it, you probably model as close as you could and let the modeler take over.
>
> N: Having said all of those things, can you give some type of summary characterization of expertise in the use of constraint-based CAD tools means to you?
>
> P3: To me, it's being able to efficiently and effectively create a model that reflects your original design intent. It is not compromised due to your inability to use the CAD tool. In other words, you're not changing the design intent just because you cannot figure out how to model it.

He intends for his models to "hold up under changes", by incorporating basic modeling fundamentals into his design work. He uses a variety of techniques to control the extent of his changes given the associative nature of the software. He also employs techniques to save time and to organize his geometry. While it seems that expert CAD usage is complex and depends heavily on the environment, Participant 3 emphasizes that the true test of a good model is that it “can be manufactured and it does not blow up when somebody goes to change it.”

> N: Kind of building on this theme… there is various criteria, and often times specific to the person and situation, in terms of whether or not someone has modeled something “correctly” or according to your intentions. How do you know if *you* have modeled “correctly”?
>
> P3: The answer is very simple. Does the part that comes off of the machine on the manufacturing floor function the way it was designed to function? That’s where the rubber meets the road. It doesn’t really have anything to do with the CAD model, the degree of “correctness” or not when you get right down to it.
>
> N: Think about it in terms of design intent, or if a person can make changes to the model without it failing, or if you pass the model to somebody else and they can make changes without it failing. Are those important?
>
> P3: It’s very important because if… In my situation, if I can pass my model to the tool designer and he can make a tool without any geometry problems (geom check issues, accuracy issues, sometimes when you add shrink to a model, features that used to work blow up; there’s no way to work around it). There are some things that Pro/E does, that no matter what you do, it will not perform that function. So, to a certain degree that’s a measure of the robustness of the model. But really when you get right down to it, is the end product what you wanted it to be?
>
> N: OK. If you were to encounter a model that was not necessarily modeled in an optimal fashion, or it wasn’t very “robust”, how do you overcome that?
>
> P3: I think you do it on a case-by-case basis. From a practical standpoint, you do as little work as you have to in order to make it functional for your purposes. You don’t care about an infinite level of “robustness”. You only want it to be robust to a point where it is useful to you.

Participant 3 emphasizes that CAD knowledge breaks down into two parts: software-specific knowledge and general concepts. A user’s past experiences and context in which they currently work impacts both of these. Not only does it seem that experiences have to be extensive and relevant, but it also seems that the extent of one's support structure has a bearing on the problem solving strategies that are developed. In addition, a firm understanding of the design objectives and a desire to reach them appears to lead to an effective set of strategies and techniques.

Structural Description of Expertise for Participant 3

Given his age, Participant 3 has made the transition from using traditional tools and techniques to using 3D constraint-based CAD tools. Within that time, he has also used 2D CAD tools for drafting purposes and 3D wireframe CAD tools. All of these tools, and their associated techniques and processes, have given him a unique perspective from which to attack his daily design problems. Participant 3 is able to effectively plan his designs and account for potential changes, which is a requirement for any constraint-based CAD user, through his knowledge of sketching and layout drafting that he learned when "creating designs from scratch."

Participant 3 has no internal support structure to assist him in his use of CAD tools. He has taken formal training courses for using the CAD tools, but they have only been useful in developing is basic vocabulary for the tool. Since that is the case, he has had to develop a repertoire of methods for solving his problems individually, which rely heavily on experimentation and the ability to research and scope the problem effectively. In addition, Participant 3 is the only designer on staff at his company, which means that he must incorporate input and direction from a variety of sources, including customers and the manufacturing area. At times, these two entities can be at odds with each other in terms of requirements for the design, so he must make his choices based on a thorough understanding of the accepted practices within his profession, which include choices about materials, manufacturing processes, design standards, and common modeling techniques.

Participant 3 considers expertise in any field to be heavily based on a person's experiences and their background knowledge of the subject. He also sees experts as those people who have the ability to overcome unexpected challenges that arise by combining knowledge with the confidence to experiment with various solutions. Participant 3 will solicit help and advice from these types of people outside his organization when necessary or available, in addition to his own experimentation and information-gathering techniques for solving problems.

As they accumulate time spent using the software, CAD users progress towards a state of being where their use of the basic functionality of the tool becomes automatic in favor of devoting mental resources to the more challenging parts of the task. In this way, Participant 3 is not different. “You’re thinking more about the end result of modeling than what I’m going to have to do to get there.” He has become much more efficient with regard to geometry creation and his ability to recognize the correct geometry for the given modeling situation. He has been successful in this endeavor due in part to his “organic” learning style, and his ability to unlearn previous techniques and methods by adapting his thought process and his conceptions of the tool to a new way of modeling. Participant 3 has learned not to compromise his design intent for ease of geometry construction.

While design intent is heavily impacted by customer requirements, manufacturing processes, and the function of the part itself, time constraints often do not allow a model to be created to an infinite level of perfection. The factors must be weighed in their level of importance and given due consideration. Participant 3 is also quick to point out that perfection in a model is often not necessary, but being able to manipulate the model to fit your given needs is invaluable. It is in the robust creation of the model in the first place that this ability to edit it lies. Planning in the use of parent/child references, using features of adequate complexity, and understanding the fundamental processes which underlie the software are critical in building reusable geometry. He also stresses that his own strong working knowledge of these functions has allowed him to attempt almost any modeling scenario with a high degree of confidence.

Textural Description of Expertise for Participant 4

Participant 4 has had nearly thirty years of experience in the engineering and design profession, and during that time he has made the transition from using traditional drafting methods and tools to using constraint-based CAD tools with a stop at the various stages in between. It appears that these experiences have had an effect on Participant 4 in terms of his ability to capture critical dimensions within his CAD models and his techniques for geometry construction.

P4: Um… in terms of CAD. I was introduced to CAD at my previous employer, and I the CAD system of choice for that company was Computervision. And I went and had a two-week course in Computervision. And it wasn't long after that things turned south, and that entailed my entire work experience with CAD with that first company.

With the training I had gotten in Computervision, I was able to land the job I have now with my current company. The CAD experience I have had prior to my current employer was relatively short, but I have used CAD at this current company for quite a few years.

N: What other kinds of things did you do, or have you done, that prepared you to use CAD in those prior work experiences?

P4: Well, if I'm understanding that question correctly, I have been working in the engineering field since 1973. The first companies that I worked for were strictly manual drafting, pencil on paper. So I have had the experience of starting out as a draftsman making detail drawings when I got out of college. But I then moved on to doing some design, but all of it was in the paper world.

This might be getting a little bit away from the design criteria, but you have the everyday process you have to do in order to release parts in the process of getting parts out the door, but I don't know if you want to go that route. Writing change notices, making the changes to the drawings based on the change notices. Releasing parts into production. Sometimes dealing with vendors, trying to get the specifics and getting it documented properly on our drawings. That's pretty much my routine through the years.

Of course, over the years, things have changed in procedures and in the tools that are being used.

N: You mentioned drafting and that you had done a fair amount of drafting through your career. How do you think that has impacted the way you work now using Pro/E?

P4: Well, view creation has definitely gotten a lot faster. Once you've got your model designed, you can go in and create multiple views in very quick order. Getting the view displayed exactly like you want, like you know… It seems like it never quite works right. Typically, what we do here, is that on our plastic parts, we don't show hidden lines, so hidden line removal is great. But sometimes, we need to show hidden lines. So sometimes, it seems like you can't have both. My experience has been can I actually

> show some hidden lines and not others? This also happens with tangent lines and their visibility in drawings.
>
> I think you can, but getting it to do that sometimes is difficult. So, I think that has sometimes been a problem in the software. Also, trying to get the dimension that you want to show up in the view where you want it to show up is also difficult. But I may be speaking now more about my knowledge, or lack thereof, in the control of trying to get specific information to show where you want it to.
>
> So from a drafting standpoint, view creation has been great. Trying to get the views exactly like you want them is tedious. Sometimes though, doing such things as editing a section view is rather simple. What used to be rather tedious in a pencil and paper world, where you had to do all of the erasing and redrawing, has become rather simple on the CAD system. So, it's got its pros and cons, just like everything else.
>
> N: What about in terms of modeling? Is there anything from the world of drafting that you carry over into the world of modeling… things like geometric construction, or your thought process concerning references and datums, critical features and geometry? How has spending a significant portion of your career in a drafting situation affected the way you do your modeling?
>
> P4: I don't know exactly what you might be prodding for?
>
> N: Do you think having had to create things like a layout of parallel lines and tangency conditions… has it impacted the ways and strategies that you use to create models?
>
> P4: Well… let me take a shot at this. I believe that my prior drafting in the pencil and paper world has been a benefit to me in going into the CAD world. Now if I try to expand on that…What is really buried in that statement is that if you're using feature-based or constraint-based CAD modeling, and if you think about the model from the standpoint of how it's going to be detailed on the drawing, then you can relate how you put the feature based on how it's going to be detailed.

During his past and current job duties, Participant 4 has worked with the elements of the entire design process, including a great deal of work in documenting the design of products using parts, assemblies, and drawings.

> N: In your past experiences, you mentioned making the transition from drafting to Computervision, and then on to Pro/ENGINEER. Have you ever

> worked with parts, assemblies, and drawings, or have you spent most of the time working with just one of those, or has it been a combination of the three of those?
>
> P4: My experience has always been… In the design stage of course, you're working with the parts. I've been a designer here at [current company], so I've done more than just detailing. The situation we have here is that we have designers who do the layout work, design the parts, and do their own drafting, and personally I think that is the most efficient way to do it. So therefore, as far as my experience has been, I have always done the parts, assemblies, and the drawings.
>
> Now, if you're asking as far as what I've done mostly and you're talking about in time, I think that parts take the most time. Of course, assemblies take a little bit less time than that, and it takes less time to make the drawing of the part.
>
> P4: First of all, I think it is a matter of manpower. We don't have a large pool of designers, detailers, engineers, that kind of thing. We do have a pool of engineers and a pool of designers. Designers do all of this work. So to me the reason why I've always done all of it, is that we did not have the manpower. And number two, I mentioned a while ago is that the most efficient way to do drawing is for the person who designed it that knows which features are related to what and how it needs to be dimensioned. But I can back that up and say that if the dimension is in the model, does it really need to be in the drawing. For example, if you had the luxury of being able to define all of those features so that all of your dimensions actually represent the way that the drawing should be set up, then it may be easier for a detailer to take your model and make a drawing of it.

While CAD tools have allowed him to work faster in some cases, he notes that these tools "have changed the engineering design process, and sometimes not necessarily for the better." While drawings were made in the past for communicating the design of the object and for inspection and legal purposes, Participant 4 now uses CAD models to perform similar functions.

> N: Throughout the last several minutes that we've been talking, you've described modeling and also creating drawings. The majority of the time in your experiences… Everything I'm hearing you say always comes back to the creation of the drawing. Is that really the main goal, modeling for the sake of making a drawing?

> P4: Well… I come from 25 years of experience in the field, and things change over time. Years ago, the only way you had of producing a part was from a drawing. So you had to have to drawing to send to the model shop, the foundries, whatever… They had to make the tooling from the drawing they were given. So drafting was the primary means of communicating what you wanted.
>
> On top of that, in order to accept the part from the vendor, you had to have it inspected. And the only way to inspect it was to compare the actual parts you got from the vendor to the drawing, because that was what the part was supposed to be made from and you have to inspect it according to the original contract which was drawing.
>
> So, as time has gone on, there are more and more companies trying to get away from drawing creation, especially what we call "100%-dimensioned" drawings. You used to have to dimension every nook and cranny on a part, because that was the only means of communicating this information to the vendor who was making the part. Now over time, they can get CAD databases. And the fact that more and more companies having access to being able to use these databases… As we do today, and the parts that I have worked with here is that, once we get what used to be Computervisions wireframe models and right on up to what we use to day which are Pro/E solid models, as soon as we get a completed model we go straight to the vendor to get quotes, and they start cutting the tool.
>
> Now they are able to do that without a drawing. The problem comes though that once they create the mold or whatever the tool is, they can create this from the database. The current state that we're at right now is that when they send it to us, we've got to accept it based on something. The only way to do that right now, first-article inspection, is to use a drawing. So basically, you've got to have a drawing for inspection. So that's kind of a long way around the question. From 25 years ago, when the drawing was the only thing you had, to today, when the drawing isn't as important initially to get tooling started, but it is important for inspection and for something to release.

It is in the performance of these functions that use of traditional drafting methods and techniques appear to have most impacted the ways in which he works and his level of ability with the CAD tool.

A typical day for Participant 4 consists of many different activities, some of which are related to using the CAD tool while others are not. He works within a division of a large company, and there are many engineers and designers in his group, with all of whom he has some type of contact even though they may not be at the same physical facility. Participant 4 communicates with counterparts in a foreign country concerning the development of interfacing components to the components with which he is working. This form of communication appears to involve passing models and drawings back and forth between the two locations.

> N: Talk a little bit about your current project, as much as you can, and describe how you use CAD in terms of this project.
>
> P4: The current project I'm working on is a project I'm working on with another designer. We have an engineer and a tool designer working on it also. But basically it is a device that mounts to another device that comes from France.
>
> So what CAD… The way CAD has been involved with this is that we are able to get the French database of their entire device so that we have direct access to mounting features. There is some interfacing of moveable parts from their device that we have to pick up on. So being able to utilize the assembly drawings, we're able to pull in the French database, and pull in our database and our device, and assemble them together properly. Check and make sure that we are interfacing with their device in different modes of operation. Of course, all of this is based on nominal models and placements.
>
> Have I covered enough of what you're looking for?
>
> N: Yeah. That's a lot. You mentioned that you share information, particularly in the form of CAD databases, back and forth between here and France. Describe that process.
>
> P4: Painful.
>
> N: Why? I know you mentioned language, but apart from that, what else makes it difficult?
>
> P4: [long pause]
>
> Language isn't the problem, so much as… I assume we're speaking about CAD databases right now?
>
> N: Yeah.

> P4: The French device is the primary device. We are doing peripheral devices here. They have control not only of their device, but they also control, to some extent, our devices because of the interface we have to use with their device and trying to get them to change some of those interfaces is rather difficult.
>
> Now, on the other side of that, with the sharing of databases… We are in the design stage right now in our device, and they are in the design stage of their device. Ours is constantly changing, and they are constantly changing. We do not have direct access to their "original" database. What we have to do… and this is another one of those things about all of the capabilities of CAD and knowing a little bit of something about it but not all.
>
> What we have been doing in the past is that at some point in time we would ask France to take their device and make a backup of it and put it in an FTP site. Then we would go and grab the FTP site, and put it into out database here. We can't make any changes to it, but we can use it as reference.
>
> The problem is how often we get this updated database because they have to prepare it for us. Now, on top of that, their device has several options, and the file that they send us has all of the options in it. So when we get it, we're not quite sure which part do we actually pull out or include to really give us the base units we want to look at. So we've got that problem.
>
> They typically don't, since we're doing the peripheral stuff… We need their databases; they don't particularly need ours. Occasionally, they will take some of our databases, but the majority of it is we need their databases since they own the base units.

He also consistently communicates with the manufacturing group concerning the tooling being made to produce the part. In doing so, he uses a particular method of creating geometry that he refers to as "cobbled up parts." These methods reflect the design iterations that a part goes through, particularly due to changes in the design process, but it also appears that these are the reasons for a large amount of rework when the design process is finished. However, this method is not solely his own. He has commented that many people within his design group work this way, because it is difficult to foresee all possible design situations when you first begin to model a design using the CAD tool.

Information appears to flow to Participant 4 from his boss as well as engineers on staff, which appears to contribute to his methods to some degree. It seems like the critical design parameters for his projects are usually dictated and controlled by other people, sometimes from a remote location.

> N: What is your level of involvement typically on a new design?
>
> P4: [long pause]
>
> Our structure is… We have an engineer who is ultimately responsible for the entire design, and he may have an idea. He would provide me with any specifications I may need to know about footprint size, what the constraints are regarding overall dimensions and orientation, interfaces with other devices, travel specifications… Whatever the specifications are that the new device has to fit within and manipulate; that is what they generally give us. From that point on, I pretty much am the type of person who likes to start down the road with the design where I would jump on the CAD system and start putting a concept together. If it takes four pieces, eight pieces, whatever it is… trying to rough out the parts to make this device. And as I go down this road, I stay in close contact with the engineer, sometimes to the point of too much information. But the reason I do that is because I want to make sure that I have not strayed too far from his idea and that we are going down this road together. I'm not out on a tangent doing what I want to do and he thinks I am going down some other road.
>
> N: Let me ask it this way. How would you describe a typical day at your job, and how does CAD become involved in those typical projects or experiences?
>
> P4: Um, My job is to design parts of devices to do a specific function. And in order to do that… In order to do my job, I've got to be able to design the parts using CAD. I've got to be able to of course have the assembly in CAD. I've got to detail the parts using CAD.
>
> And then the other things I have to do that are not CAD related is I have to release the parts. I have to do file management, and file management is kind of loose. I have to release the parts, and make sure the files are done correctly.
>
> There is also the communication of working with other groups inside of the company, like tooling and manufacturing. In that case, you're using the CAD system again, because you're using it as a visualization tool.
>
> So… this is my job. I have to create design of components, and I eventually have to release these components. That's what my job is. Now that… If you look at that in time, that cycle could be years. On a day-to-day basis, CAD is probably 80% of my day. For example, hacking a part in two so that I can

> see the internal workings of how it may snap to another part but I can't see it otherwise, or discussing the options of how to solve these problems with the engineers in charge or the tooling guy that is in charge of tooling or the advanced manufacturing guy who is involved with how the part is going to be assembled on the shop floor. That is so everybody is on the same page before we make this change. And that is a typical day for me, constantly pulling and tugging on these files to make changes to get the end result so that this entire device is functional and able to be assembled.

In addition to a seemingly one-way information flow, he must also incorporate company design standards into his models, which are dictated by people at another site. By coupling the external design and communication considerations, it appears that Participant 4 is forced to deal with many factors in his use of the CAD tool.

To help him in accomplishing this feat, it appears that Participant 4 has a rather large internal support structure. He has attended several training classes for the various CAD tools that he has used, and he has commented that some are better than others are. Participant 4 has also stated that the training classes he has attended only teach the basic concepts, but without those, you would have no frame of reference from which to work. It also appears that Participant 4 uses the manuals that he received in the training course as a reference when he encounters a problem. In addition to training received, Participant 4 also appears to rely on collaboration with his colleagues to help him solve problems.

> N: I don't mean personnel challenges, but if you have difficulty doing something that is work related, how do you overcome that?
>
> P4: The software shouldn't dictate the direction you take. And I say software, but it could be software limitations or knowledge limitations. And that gets to be frustrating.
>
> You don't know… Several times… not just myself, but we all… everybody who uses Pro/E here basically sits in the same area, and we talk about this kind of stuff. If we have a problem, we try to resolve it ourselves. If we can't, then we start asking the other users to see if they can help.
>
> N: When you want someone to demonstrate it to you, how do you make your determination on whom to go and ask?
>
> P4: The biggest thing is who I think has the experience. It goes a little bit further as well into people I also have had personal contact with and how we interact in a normal situation.

It appears that he is reluctant to use the on-line corporate help system due to its speed and complexity; it just takes too much time to hunt for the answer.

> N: Have you had any kind of support structure inside that company that helped you use the CAD tools?
>
> P4: My experience here is that we had people on-site that were our IT people, and they were here as well as at other companies. So when you had a question on how to do something, first of all, we had the training manuals which are good for going back to review how to do something.
>
> Second, we have our own group members who have different levels of experience, as well as experience with various modules of the software. Third, we also have the IS group you can go to in order to pose a question and you have a couple of choices of there. Sometimes when I go to the IS people, I am surprised at what they can do. I don't know if they sit in their cubes all day and just play with the software. It surprises me sometimes what they know and what they don't know.
>
> When you go to the IS person you have a couple of things that can happen. He may be able to sit down and show you what to do if he has experienced that same problem before. You also have online help from all of the people in the company: FAQs, chat rooms, training modules, training courses. It is also possible for the IS people to tap directly into the PTC Help database.
>
> My problem with all of our online help is that I need to know how to do something *right now*. And with all of that information out there, if you do not use the right set of keywords or concepts to narrow the search, then it is potentially useless. I haven't tried that a lot, but… It's like a lot of the things… When we learned these things, if we can be exposed to it, we may not use it all the time, but you can go back and retrieve it when you need it. I know that this online stuff might be useful, but timing is always an issue.

It appears that just as with other participants in the study, Participant 4 is typically under some time constraints, which ultimately have an effect on his ability and methods for gathering information to solve his problems. He tends to rely on the people in his group for a great deal of information and help. If that is not possible, he will experiment to develop a solution, but only if time allows.

> N: Have you ever tried possibly just experimenting? I've heard some of my other participants say that if they are stuck on things sometimes, they will just experiment.

> P4: With CV, I had about 10 years of experience with CV, and I felt very comfortable with it. With Pro/E, I am now to a level of comfort where I might do that. Given that your job is to make parts and do this and that, I think there is a learning curve. When you start out on a new software, your learning curve is steep and you are somewhat uncomfortable with everything that you do. Over a period of time as you got to be more and more comfortable with the software, and you go over here and you pick a relation, all of a sudden… [you are] at the point on the curve of being comfortable enough and have enough time, to just go out and experiment. I have to have the time to do that in order to get work done.

Participant 4 has stated that he is a visual and hands-on learner, which appears to have some effect on the methods he chooses to gather information and to attempt a solution. But it seems like this also causes him some degree of difficulty when the operation of the CAD tool does not match his expectations. He might decide to "work around the problem rather than fight with the system."

> N: You mentioned the Round command and getting it to work sometimes is a matter of changing the Radius to a smaller size. What made you arrive at that particular solution?
>
> P4: Well, what happens a lot of times, you have surfaces that come together that you want to put a radius on. Well, if the size of the radius that you want to put on this edge happens to be… at some point in time, if the radius makes a surface disappear, it will fail.
>
> Now, there's ways around that; I know there's ways around it. I know you can go in and do some advanced round stuff, make it a variable radius that goes from one size to nothing, you can put some blending in there… But, to be honest with you, I haven't been taught that. I've seen it; I know it exists. But I haven't been taught that, and I don't have the experience with it. So rather than struggle with it for hours trying to figure out how make it work, the best thing to do is to make the radius smaller, trying to do something else that will make it work. Sometimes it winds up you don't put the radius on it. There are situations when you run out of time and have to go on.

He usually makes an attempt to decipher the cause of a problem, even though time constraints may dictate a less than optimal solution. His ability to collaborate with coworkers and to account for the tooling requirements of the part appeared to affect the choices he makes when creating geometry within the CAD tool.

While he is similar to the other participants in his view of himself as an expert, Participant 4 seems to have a good idea of what embodies an expert. Participants 4 perceives an expert to be able to "recognize the signs" and the "presence of critical factors that indicate a particular situation". He says, "they have an awareness and understanding" that goes deeper than the average person does.

> N: What does expertise in the use of constraint-based CAD tools mean to you?
>
> P4: It means having the awareness that the constraint is there, the understanding of what it does, the knowledge of how it may impact or react with other constraints, and which one to use at the time.
>
> I guess, really… it goes back to the things I just said a while ago. You've got to be aware of the constraints in the software. You've got to know what they mean and how to use them. If you don't… if you're not aware of them, then you're not an expert.
>
> N: Like what kinds of constraints?
>
> P4: Well, in Pro/E, you've got the constraints of tangency, point on entity, alignment, collinear, vertical, horizontal, symmetrical… You've got to know that the names of these constraints exist.
>
> N: What about references, like parent/child references?
>
> P4: Oh sure. If you're going to try to model what would be considered a "proper modeling technique", he needs to be aware of constraints, how to use them properly. He needs to be aware of parent/child references. He needs to have knowledge of Relations if he is going to use those. He's got to be aware of all of the command options that make a constraint in a model, and he's got to be aware of those options. And he also has the knowledge of what they do, what they control, and how they interact with each other.
>
> N: Are there any external constraints, anything that is *not* CAD-related? Customer requirements, maybe…
>
> P4: Well, you mentioned "customer-related", and the only thing I can think of there is if the customer is giving you a specification. It has to meet this footprint, or these weather conditions, or whatever the specification might be.

N: What about cost?

P4: Sure.

N: What about manufacturability?

P4: I'm not aware that… I know for a fact that I can put negative draft on it to a point that I can't pull it out of the mold. Now my tooling guy will come back to me and say that it is not manufacturable. So in the context of the word you used, I know I can make a part that is not manufacturable…

N: But you have to consider whether or not somebody can make that part or not.

P4: The software will not come back and tell me that it is not manufacturable, but I have to have some expertise in mold design to know, to shape which direction I put that draft on. From that standpoint, that is a reference that is established outside of the CAD system that will affect modeling techniques.

N: How would you characterize the difference between an expert, or an experienced constraint-based CAD user, and a person who is a non-expert, or a less experienced constraint-based CAD user?

P4: Well… if the expert… I guess I have to assume that since he is considered an expert, he will always, or most of the time, build in constraints that will allow him to make adjustments to his design without failure. Where… and it would give him the predicted results he wanted.

So I guess the difference is, again, between understanding what it means and properly applying that in the modeler.

N: What about… is there anything else, other than an understanding of geometry and its behavior, that would differentiate between an expert and a non-expert? What about in terms of strategy or modeling procedures or techniques?

P4: I'm sure. Based on everything that has been taught to me, they really stress design intent. And the sales pitch is "Don't start modeling anything until you know the design intent." Well, I'm sorry. If you wait for the design intent before you get started, you'll never get started. You've got to start somewhere. I may be totally wrong there, but I believe that.

> So if an expert was to sit down here and you gave him his design intent, he would use that to create constraints and relationships to build that model and never have a feature failure during changes.
>
> N: What about parent/child references?
>
> P4: You have to understand those relationships too. It's interesting… When I went back and started doing this remodeling project that I've spoken to you about several times, one of the things that I kept in mind when I started that process was parent/child references. You don't want to have each [feature] a child of the one just prior to it. Because if you ever come back and delete this one here (above it), then it's gone. So, I'm aware of that; that's what I was talking about earlier when I was talking about awareness. So I found myself trying to be very particular about that and trying to tie as much of the features as possible to the basic three datums as possible to try to eliminate using faces. If the face lies on the datum, then use the datum.
>
> N: Other than geometry behavior, relations, references, are there any other difference between an expert and a non-expert?
>
> You mentioned awareness, experience, knowledge, and constraints, whether they be specific to the CAD system or outside the CAD system, they are still constraints. So, you would say that the general characterization of an expert carries over to an expert constraint-based CAD user?
>
> P4: Yeah. You can't be an expert in anything if you're not aware of what is available to you, how to use it properly, and the proper way to apply it.

However, he also points out that expertise is relative to the situation, and that it is sometimes "accidental" based on another person's perception of the situation. He also believes that expertise has boundaries, and that the expert's awareness increases with exposure to various types of situations and their levels of complexity.

According to the data examined, expertise has economic qualities for Participant 4. While it appears that expert CAD users can account for customer requirements, manufacturing requirements, and the processes of the software, a balance between complexity and editability must be found. It appears that the compromise between elegant modeling practices and the further functional use of the model must be made to minimize the impact on monetary and cognitive resources at a later date.

> N: When you create or edit a model using a CAD tool, how do you go about analyzing the situation in order to get the information that you need to do that particular job?
>
> P4: Well, if I designed the part initially, then I have a pretty good… I have an intimate knowledge of how it was constructed. So, approaching that situation is totally different than approaching one that *you* may have designed, because I know nothing about it.
>
> What has to be considered…If I designed it, I pretty much know how it's built. I know instinctively pretty much what the parent/child references are. If you designed it, I have no idea. So the first thing I might do is go back through the regeneration process and just kind of see how it was built. I may… there might be one particular feature that I'm going to modify, so I might query the parent relationships and child relationships for this particular feature. I may get brave and go out there and make the change and see what happens. If it falls into a failure mode, I may just suppress everything that's affected, and look and see what caused the failure. Go back and look to see if I can adjust or exploit any remaining parent/child relationships.
>
> Depending on how the part was modeled, depending on how the relationships were built, depending on the constraints that were used, depending on how any Relations were used… Depending on all of that stuff, if it was done "expertly", this change that you want to make may be as simple as modifying a dimension and regenerating. Or, it could be a nightmare. And I've seen both.

To help in overcoming this potential problem, Participant 4 emphasizes that knowledge of fundamental software processes is more important than knowing all of the commands. It seems that only a few of the commands are used for a majority of the modeling tasks that he performs. It appears that Participant 4 has a preference for using "simpler" features, and that this allows him to work faster towards the creation of a robust model.

> P4: The software is so powerful and so sophisticated that my typical commands when creating a part is to use Protrusions and Cuts to build it. On top of that I use Draft, Chamfers, and Rounds, and from that I form the geometry I need. Those are the commands I use. You can create a lot of stuff with it, but is that the most efficient way to do it, I don't know. There may be more efficient ways to do it in the software that I don't know about.
>
> N: Do you agree with the statement that sketching your intent… and what I mean is do you think it is a good thing to take advantage of your ability to

sketch contoured profiles as opposed to just simply extruding a block and whittling away at it? Do you think it is advantageous to sketch profiles?

P4: Yes. The problem I see… Depending on the complexity of the profile, you have the problem in the Sketching environment… You have some ability to move the dimension around and stuff like that. It cleans it up a little bit. You don't have the ability to throw the arrow to the outside like you do in the drafting world or move the text. The sketch, in my opinion, you should be able to position those dimensions so that they are pretty well laid out so that you can follow that sketch as you are viewing it or studying it or whatever. The lack of the ability to be able to manipulate and control those dimensions visually is limited. So that is one problem I see with doing a complicated profile as opposed to hacking and whittling and that kind of stuff. The reason that I say that is bad is because if you have to go back in that sketch, the dimensions get all thrown around again and it takes some time to figure out.

Sometimes, rather than have one elaborate sketch, I have heard that Pro/E likes to have simple sketches because they remain more stable. So in some cases… You have to make a decision. Do I make an elaborate sketch and extrude it, or do I make a block and put a chamfer here and put a radius here? It also depends on what features are behind or below this and how they may be related to the feature you are creating. If you've got… If you need straight edges to reference in a feature that is below this particular one, then you may want to keep it a block as long as you can, and then come back in and start shaving and shaping the surfaces. So it depends on what may be related to it. It depends on how intricate the sketch is, because when you're looking at the sketch in the sketch environment, the more minute and numerous the pieces are, it gets to be very cluttered very quickly.

N: Having said all that, many people would say, I think, that simply sketching a rectangle, extruding that to make a block, and then making 50 Cuts on it might be somewhat inefficient. I guess what I was really getting at with that last question was as opposed to doing that, if I could do that with a series of 6 or 7 sketched features instead of 50 features, do you think using the sketching functionality that way is beneficial?

P4: Sure. You don't want to… You have a choice between one elaborate sketch to make your model and a block with 50 cuts on it, and then all of the different variations in between. Six or seven simpler sketches to make simpler features right in order is a happy medium. And often times, that is what you are looking for; something that is between the two extremes.

According to Participant 4, the goal of using a CAD tool is to design a product, and a good model is one that “holds up to changes and fulfills the design requirements.”

Participant 4 appears to view expertise in the use of constraint-based CAD tools as a complex phenomenon controlled by the expert’s ability to recognize the conditions of his situation and create or edit geometry as the situation requires. Accordingly, expertise is influenced by past experiences in using the CAD tools, as well as by interaction and collaboration with coworkers at various levels. To accomplish their task, it seems they must have a fundamental knowledge of software processes and their design intent, which is influenced by many factors within and beyond their control. Appropriate geometry creation and editing techniques seem to be important factors for Participant 4, and it appears that they should be selected for the object in question based on the information collected to develop a problem solution.

Structural Description of Expertise for Participant 4

Given his age, Participant 4 has made the transition from using traditional tools and techniques to using 3D constraint-based CAD tools. Within that time, he has also used 2D CAD tools for drafting purposes and 3D wireframe CAD tools. All of these tools, and their associated techniques and processes, have given him a unique perspective from which to attack his daily design problems. Participant 4 is able to effectively plan his designs and account for potential changes through his knowledge of sketching and layout drafting that he learned when “creating designs from scratch.” Having used these tools in the past has also aided him in his geometric construction activities in the CAD system, which are used for creating various geometric features. He has also seen the transition of using the drawings as a communication and inspection device to using the CAD model to do those same things. Participant 4 laments though that using the CAD models in this fashion requires a much more accurate database to begin with, and that basic geometry creation and editing functions are critical to making 3D models that can be used for such purposes.

Participant 4 has a large internal support structure to assist him in his use of CAD tools. He has taken formal training courses for using the CAD tools, which has exposed him to the basic concepts of the software. He also has access to an internal technical support group and help desk to which he can pose questions. While that is useful sometimes, he has stated that it is often not fast enough to address his needs. Participant 4 uses his training manuals occasionally in developing solutions to problems he has in using the CAD system. Due to the absence of timely feedback, Participant 4 often turns to his own methods for gathering information and problem solving.

Participant 4 does not use every command that is available to him due to the nature of the geometry that he creates, so when he does encounter a unique problem instance, then he uses the reference materials available to him. “It is just a matter of knowing where to look to get what you want.” Participant 4 uses a visual, hands-on approach to problem solving by experimenting with the problematic command, either in another file or on the current part. However, time is always of the essence in his environment, so he must often strike a balance between what might be considered “proper” modeling techniques and those that get the task finished on time. Due to the enabling conditions of his work setting, he and his colleagues also collaborate on the solution to a problem as well, in many cases when the answer is not easily found in a reference boOK. The data suggest that these collaboration sessions are based on the particular frame of reference that each person brings to the meeting and their conceptions of the solution based on past experiences.

Participant 4 considers expertise in any field to be heavily based on a person’s various experiences and their background knowledge of the subject. Awareness of the factors that impact a situation and how certain modeling techniques will affect downstream changes are also important characteristics of an expert. According to Participant 4, these characteristics of an expert are affected in part by experiences of collaboration with colleagues, communication via the CAD model, and consideration of multiple design factors. He also sees experts as those people who have the ability to overcome unexpected challenges that arise by combining knowledge with the confidence to experiment with various solutions. In addition, Participant 4 considers expertise as having the ability to communicate information to others in a fashion appropriate to that other person. He has become much more efficient with regard to geometry creation and his ability to recognize the correct geometry for the given modeling situation. Efficiency in this case has come from being immersed in a design situation where his model is used to make tooling for the parts and to communicate with other members of the design team.

According to Participant 4, his experience has been that a great deal of hype surrounds the use of constraint-based CAD tools as being the perfect solution for documenting the engineering design processes. However, he stresses that expert users will always consider the required design intent for the given situation and not be compromised by gaudy claims of software superiority. He states that the designer must still develop a solution to the problem. It is important to consider how the model will be used in the future, even though Participant 4 stresses that it is impossible to account for every design possibility. Participant 4 contends that the "basics" of solid modeling center on the creation of the first feature, and it is here that a fundamental understanding of geometric constraints, sketching techniques, and parent/child references are important. He also contends that development of this knowledge can come from being placed in a scenario where the implications for disregarding this background knowledge are obvious. Planning in the use of parent/child references, using features of adequate complexity, and understanding the fundamental processes that underlie the software are critical in building reusable geometry.

Textural Description of Expertise for Participant 5

The data relevant to Participant 5 show that he is similar to Participant 2 in his development of expertise. Participant 5 began using 2D CAD tools in high school, and has progressed from that point to the use of 3D constraint-based CAD tools. He has never used traditional drafting tools and techniques, although he has used a variety of 3D CAD packages, including several different constraint-based CAD tools.

> (N): To get started, describe a little bit about your past work experiences, and particularly, how CAD was involved with those past experiences?
>
> (P5): OK. Um… I had some work experience while still in college that primarily used AutoCAD which you could pretty much describe as detailing work. It was all 2D detailing work. AutoCAD was… I first learned AutoCAD in high school and in college, and I also took a couple other CAD classes in college.

> I think it was sophomore year that I got my first real job doing CAD work. It was doing detailing work, 2D stuff, marked-up prints. From there I got a job doing design work, again with AutoCAD, which eventually went into using Inventor. I… did some new design work, but it was mainly detailing or routine work or mark-ups for existing parts.
>
> After that, after doing Inventor work, doing 3D design work, I came here. I started out here with Pro/E. Mainly when I first got here, Pro/E was… my task was assemblies, which I never really completed… My task was to existing parts, existing assemblies and build assemblies in Pro. That lasted for maybe three or four months, and we decided to go to SolidWorks, which is what we're doing presently.
>
> Going from that, I'm doing parts, assemblies, drawings… everything that SolidWorks can do, we're doing it.
>
> N: OK. Do you think taking that progression from working in a 2D environment to working in a 3D environment, and various 3D environments at that, has impacted how you choose to model parts or how you choose to create assemblies of parts now?
>
> P5: Um… obviously it's easier with the 3D software. I mean if AutoCAD in the beginning not being able to model parts… you don't get a good overview of how the part will work. Now, with the 3D aspect, obviously you can see how your part is going to work and make sure that its design is going to be correct. It definitely helped me know before I have parts made that it's going to work. So, it's definitely been a benefit… It will help you in the future. I think I would never go back to 2D.

For Participant 5, the data show that he has learned the majority of the CAD tools on his own, with little or no help. It also appears that much of this is due to the support structure that he has had within the companies where he has worked. He has worked for three different companies after graduating from college, and all of the companies that he has worked for have been small. It appears that in all of them, he was put into a position that required him to support other coworker's use of the CAD tools, and little or no training was offered for learning how to use the CAD systems. In doing so, he became the "go-to guy", and he was responsible for the implementation, maintenance, and training with respect to whatever CAD tools were being used at the time. There was a great deal of collaboration between Participant 5 and his coworkers in using the CAD tool, not only in the past but in his current position as well.

N: OK. In the past, you mentioned several different CAD tools that you had used. Did you receive any training in the use of those CAD training?

P5: No.

N: No… you had to learn them all yourself?

P5: Uh… yes. In college, they really didn't teach you how to use the tool. They really wanted to teach you the concepts of CAD. I take that back. AutoCAD… I knew 60% of AutoCAD coming into college from doing it on my own. I think in one or two of the CAD classes during freshman year they went over the basic functions of AutoCAD. Technically, that would probably be training, but I believe most of the people in those classes had used it in the past. I used to use CADKEY in high school, and I pretty much learned it myself. Pro/E… when I arrived here there was not time for training or having someone train you or take classes. I had some assistance of people answering questions, but it was pretty much self-taught. Inventor was self-taught. They gave me the program and said learn it so you can teach everyone else. SolidWorks was self-taught, but we did go to one CAD training class, although it would not have mattered. It was kind of… It didn't help really.

N: Do you have, or did you have, any kind of support structure in using the CAD tool? You commented that you could go to other people and ask a question here and there, or that you would talk among yourselves. It sounds like there was not anything like a company user group or a help desk or a help line or something.

P5: No, not really. When I learned Pro, it was mainly going to the person you thought had the most knowledge to answer your question… simply based on years of knowledge of using the program, I would go to this person and assume that they would know how to do this thing. Where they got their training, I don't know. They might have done classes in the past, and that's how they learned it, but when I got here, you were on you own. You had to find the right person to answer your question, but we really did not have any support structure at all.

N: OK.

P5: Now we do; it's me. It's me and another guy pretty much… for the other people that work in our group. We answer most of their questions.

N: How does that tend to work? Can you describe that as far as you being the Help desk provider?

> P5: It pretty much… if a current employee has issues, problems, or they don't know how to do this stuff… we've all sat in the CAD training. For me, it wasn't very helpful, but it was helpful to the other people because they have never used SolidWorks before. So, by default, me and this other guy who were only two people who had used SolidWorks before, became the gurus in the group. The other people in the group… most of them aren't designers; they're electrical engineers. They don't want to learn it… they want to learn it well enough to get there job done, but they don't want to learn every aspect of it. So they're going to have questions; they're going to come to me or the other guy and ask us questions. We'll drop everything they are doing and go help them. If we can't answer their questions, we can go to the SolidWorks training company and ask them. That's our next step. If I don't know an answer, or it's an error I can't fix, we'll go to them. Usually, they ask us to send them our files, and they will look at it and take three weeks and get back to us with not much of an answer. That's kind of the chain we go through.

This experience appears to not only have given him exposure to a variety of CAD tools and their techniques, but it also seems that he has been forced to learn the CAD tool well enough to develop a solution to his own problems as well as those of his coworkers. It appears that his methods of using CAD tools have become more sophisticated as the CAD tools have become more complex.

> P5: It's much more advanced now obviously based on the advances in the software. Uh… basically when I started out with CAD it was not 3D-driven, so my whole design focus was in 2D. When I went into 3D, with the improvements of software, it's been able to improve my techniques in using the software.
>
> Actually, now is when I'm doing all of my fully constrained assemblies and incorporating design intent. In the beginning, it wasn't much of a requirement; the company didn't require it. We didn't have to worry about the next guy.
>
> For the past three years, it has been the time when design intent and those sort of things came into the forefront. From now on, that will be the way that I create things.
>
> N: How has your thought process changed?
>
> P5: The more experience I have, the better understanding I have of what needs to be done. Whether it be for the machine shop or production or fellow engineers, or that sort of thing… in the past, it might not have been

> that big of a deal. Now I understand more of the everyday life and what needs to be done to keep that going smoothly.

His past and current experiences have also required that he spend time in the shop testing and building prototypes for the products that he designed. According to the data, this has given him firsthand feedback about his use of the CAD tool in terms of such things as the fit between parts in an assembly and whether or not a part was made correctly.

> N: Can you describe a typical day on your job?
>
> P5: My typical day right now for about the last year and a half is focused on this new project. This project from start to present has been really all that I have done since I have worked here. Starting a new design from scratch. Design it. Prototype it. Build it. If it works, release the drawing to manufacturing for production. Have production machines come in the door… and some of these stages go for months at a time.
>
> Interacting between machine shop and the manufacturing floor can be a big part of my day. They are the ones that find the issues and bring them to me, and I'll get those resolved and put them back on the machine.
>
> N: It sounds like you do a lot of other things besides simply sitting at your desk using the CAD tool. Such as what?
>
> P5: Prototype assembly…
>
> N: Where you are actually out in the shop putting things together?
>
> P5: Yes. That helps a lot with doing design work. It gives you hands-on experience of how the machine works. If you make a design, and you go out there and try to put it together, and the things don't go together, you think, "Who designed this thing? Oh that was me."
>
> You'll remember that you have to go back and fix that. That's something… I do a lot of that after the initial design work is done. Once you do a design, now you're in the prototyping stage. Design work goes down, and prototyping work goes up and assembly gets involved. You're doing hands-on work for a period of weeks or months. And then production starts, and you go back to doing design work to make newer or better products.

In the design environments where he has worked, Participant 5 also appears to interact with the products he designs in a rather cyclical fashion, moving from design to prototyping to production as the product made its way from one stage to the next. This means that he has to interact with parts, assemblies, and drawings, which required him to move CAD data through the various modules of the software.

> N: For example, I assume that you don't just sit there and model parts or make drawings all day long. You do all three. Why is it that you work that way, as opposed to me just being a detailer and making drawings?
>
> P5: Well… first of all, my job requires me to do all three form start to finish… models, assemblies, and drawings. The software I use allows me to do all three relatively easily. I would think some of the other software doesn't allow you to do that very easily.
>
> So, the ease of making those parts, assemblies, and drawings is one reason why I do and the job requires that I do all three. Some people might not have those requirements.
>
> N: Do you think having the ability to do that, or the fact that your job requirements dictate that you do that, has an affect on your knowledge of constraint-based CAD tools?
>
> P5: If I only create detail drawings, then all I really have to worry about is drawing functions. But if I have to do all three, then I have to understand something about each one of those sets of functions. But also, that may also impact the way I think about strategy and planning as I use the CAD tool.

This also requires that he interact with products that have hundreds, if not thousands, of components, each one of which could potentially be affected by the decisions that he made in using the software. It seems as if that this has given him fundamental knowledge of the processes that drive the constraint-based CAD tools.

> P5: The fact that I need to create assemblies from parts that I've made makes my thought process… I think we were talking about this the other day… about how I create my parts knowing that when they go into the assembly I create a part off of a certain plane so that when it goes into the assembly I have an idea of where it's going to show up.
>
> Creating my part on the center of the datum planes… knowing that the view of the part in the assembly is going to be oriented the way that I want to. It's intentional; I want that to happen. If you were only doing drawings, you would not care about that. It doesn't matter to you. I always thought the parts should describe the way they were going to be used. Like if I know that the part is going to come into the assembly vertically, then I will create

> it in a vertical orientation. If I know the part's going to be oriented vertically, I'm not going to draw it horizontally. I think knowing that you are going to create an assembly after creating a bunch of parts; it puts you into a different view of how that part should be created.

His previous knowledge of constraint-based CAD tools seems to have helped him become proficient at using his current CAD system. In regard to the way CAD tools operate, Participant 5 implies that the semantics of a CAD tool should match the thought process of the user, and if that is not the case, it has been his experience that people will have difficulty learning to effectively use the tools. In his various roles as the resident technical support person, Participant 5 has developed a particular problem solving strategy, influenced by the operational characteristics of the CAD tool, to aid him in the use and support of these tools, part of which appears to be enabled by his visual nature. "I like to see the effects of my changes right away."

> N: So how would you describe your personal learning style? How do you best learn?
>
> P5: I'm definitely a visual learner; I'm not an auditory learner. I need to see it… to see how it works, see it in my mind more than somebody telling me how it works… So being a visual learner probably allows me to be more of a trial and error learner also. I do something, look at it, and decide if it is correct or not. Like I was saying before, some people might be more of a thought process learner where they think about it, because they have everything in their mind what they are going to do and they do it. Well, I need to see something first.
>
> For example, if we need a new cover let's say for this machine. I'm going to first draw the box, and then now what. Here's how I would put the flanges on, and then I would decide to put the holes in. If the holes change, I can change them. But I've got to be able to see it.
>
> N: It sounds like not only visual, but also hands-on.
>
> P5: Oh yes. I think that's necessary for everyone. You need to have hands-on to be sure everyone is up to speed. If you don't… if you're only doing the geometry and drawings, you might not really care what you just did and how it affects the next guy.

> N: Some people say that engineers and designers, people like that, have a very acute visual ability. Do you think visualization is important in learning to use CAD tools?
>
> P5: You should be able to. Yes. I mean it is a 3D model you're doing, but you're looking at a 2D screen. So even though it's 3D, it's still 2D. So you do have to visualize it in your head. It was before my time when everything was 2D on 2D, and I can't imagine how they could make such a complicated part in that way. Now, we're in 3D, but still on a 2D screen, so you still need to see it. That's what the prototype unit is for. So you can see it clearly.

According to the data, it appears that Participant 5 also has a problem solving style predicated on experimentation or trial and error. It appears that his thorough knowledge of the fundamental processes of constraint-based CAD tools allows him "to just try it out."

> P5: Well, if I don't remember how to use it, I would… the first thing I would do is to use the Help menu in the program. Maybe try to make an example part on my own to test the function. Just research within the software to refresh my memory and also create a temporary part.
>
> N: OK.
>
> P5: If it's something I've never used before, I guess I would do the same thing. I would try to learn as much as I can about it from the program, and then try to experiment with it.
>
> N: Has that process been successful for you?
>
> P5: For the most part. I mean there is… the majority of the stuff I need to do is either not that complicated for that process not to work. If there was something more like stress analysis or anything like that, which would take a little more time and resources, then that method may not work. Then you may need some official training.
>
> Most things I've done in the past, though, have not been too complicated to figure out you know.
>
> N: OK. What do you think allows you to be able to experiment and have that process be successful?
>
> P5: [long pause]

> Um… I guess if you have enough of the knowledge of the program to allow you to experiment, you won't need to take… you won't be alarmed at the time it takes to figure out how the part works. For instance, just knowing how to use the program is going to help you learn sheetmetal than learning sheetmetal from the beginning. Also, maybe my ability to work quickly will give me the free time to experiment if I know that I have this amount of time to figure out what I need to do before I need to actually start doing it. If you're slow and you don't really know what you're doing with the basics, it's going to be hard to figure out more of the advanced stuff.

If his particular solution does not work, he will refer to the reference files located in the software, or contact directly his technical support person at the software vendor. It appears that he does only a very small amount of research before commencing with his trial and error approach.

> N: How would you go about figuring out how to use that sheetmetal module?
>
> P5: Um… trial and error. I went through a couple of times with the Help tutorial in the software. I printed that tutorial out and followed it word for word and made their part. But like I said, that's the… of course that will work, you know. Then, the first time I tried to make a part for here, I couldn't get the flange to bend, so I went back to the tutorial and said this is exactly what I want to do based on what the tutorial is saying, why won't it work. So it's a trial and error thing. Try this… oh, now it works. Write that down, and that's how you do it.
>
> N: Were you able to take anything from your past experience of just SolidWorks modeling in general to help you solve the sheetmetal problems… or anything from your experience at all?
>
> P5: Um… The stuff that I did with Inventor would help me, but only to some extent. I think it is a lot different than straight modeling. When you're bending something, you need to know where you're bending it. It is stuff like that that you don't catch when you're doing it. There are so many other factors that you have to account for. I think it's different, a lot different than regular modeling.
>
> N: Can you give me an example of some of those other factors?
>
> P5: Well, different terminology… tabs and flanges are two very different things. Mitered cuts, straight cuts, rips…

> N: Is there anything else other than the CAD commands that you need to take into account when making the sheetmetal part?
>
> P5: The position of the bend radius affects how the part is positioned in the machine and the ability to manufacture that object.
>
> N: Is there anything else besides the CAD commands you have to consider in making the sheetmetal parts, or any part for that matter?
>
> P5: Um… well… To… you need to know how it goes together. Anyone can draw a part and claim it will work. Until you put it on an application, you won't know if it's exactly right. When it comes to sheetmetal, the bend radius and things like that may not allow your part to work if not done properly. So the commands… you need to know what they are going to do, but really in the long run, you need to know what you're doing is going to work in the end and fit on the machine.

The experiences that Participant 5 has had learning to use the CAD tool in this manner, along with his background knowledge of various CAD tools, appear to have impacted his level of expertise in the use of constraint-based CAD tools.

However, Participant 5 readily admits that having had training is often confused with having expertise, which it appears is often not the case. "The training courses that we have had in using SolidWorks have not been real good. They talked about molded parts, and all we do is sheetmetal stuff." Participant 5 raises issue with professional training courses that he has had, because they tend to lack applicability in his opinion.

> P5: They would have my product up on screen there. Even in training classes… you go to a training class or a user meeting, and they bring up the demo. The demo always works. Like the training class stuff… they show this tractor with a four-bar linkage or whatever; it always works. All you have to do is this, this, and this. Click, click, click… and that's all. Then we come back here and try something like that, and we've got Mate errors all over the place.
>
> What I would like to see in a training class or a user meeting would be realistic products.
>
> N: It sounds like then… I'm going to make a general statement, and you tell me if this is true or not in your opinion. CAD usage and the experience or knowledge that goes along with it is very specific. It is context specific.

> P5: Right. We do a lot of machining, we do a lot of sheetmetal. We don’t know anything about molds. Let’s say I’m here for ten years. I’ll have ten years experience in sheetmetal and machining, and then I’ll go to my next company and it’s going to be an extrusion or molding company. So then I’ll learn and focus on that aspect of the CAD tool, so it is specific for the industry that you’re working in and the training should be focused that way too.

It is apparent that participant 5 felt that the training would have been much more beneficial if it was specific to their professional environment. This matches his conception of expertise, which appears to be based on extensive experience and near-perfect performance in the particular field in question.

> N: As I mentioned before there are certain conceptions of what an expert is. In your opinion, in general, how would you characterize an expert in any field?
>
> P5: Having total knowledge of the situation. Pretty much an expert should be able to answer every question with the right answer I would think. If he’s an expert in…If he were an expert in training for CAD systems, I would expect him to have pretty much every answer to the questions. I’m not an expert; I know that. A lot of times I don’t have an answer, but I can go find it. I’ll call a supposed expert to get the answer from him.
>
> N: OK. Other than the person’s depth of knowledge, what else might an expert have or how else might you describe an expert?
>
> P5: Probably experience level is high. In being an expert… obviously you need to experience it to know the answer… to have knowledge in that area. You need to have knowledge; you need to have experience. You need a general idea of the workings of whatever it is they are an expert in.

He also alludes to experts being aware of their actions and the consequences of them; they are able to see the problem in a more global sense. All of these factors appear to have affected his conception of expertise in the use of constraint-based CAD tools, in which he considers and expert user to be a person who can effectively capture their design intent in the model using appropriate modeling strategies and techniques. They also employ a logical procedure that is consistent from one scenario to another.

It is apparent through the data that Participant 5 possesses each of these characteristics to a certain degree. He credits his level of expertise to his ability to draw and visualize things, a hands-on approach to learning, and desire to build things.

N: So is expertise always contingent upon 100% performance?

P5: No, but it should be close.

N: I would think from what you said previously that in your current position there are many times when you know more than someone else… that someone else seeks you out for your particular knowledge.

P5: But that doesn't mean I'm an expert.

N: But you know more than they do in that situation. So, I guess that answers most of this question then. But you exhibit certain characteristics that experts have.

P5: Knowledge. Experience…

N: Right. Expertise is also one of those characteristics that is often times attributed to someone by someone else. So as people seek you out and ask you questions or your opinion, why do you think they do that?

P5: Well… probably because I do have those characteristics. I do have the experience of 3D modeling. The knowledge… at least more than they do. I have the past experiences…they probably seek me out for that reason. Maybe that's seen as more of my job requirement than for some of the other people; they expect me to have those answers. They may say that this is what I do all day, so you should be able to answer this for me.

N: OK. Is that it? What does expertise in the use of constraint-based CAD tools mean to you? If someone were an expert constraint-based CAD user, how would you describe him or her?

P5: They should be able to create their assembly with no errors. The ability to… it's that design intent terminology. The ability to create a part that is designed efficiently… to create assemblies that are constrained and Mated correctly…to… basically, if you're an expert in doing that, then your parts and assemblies should be able to be used by others without problems.

That's probably one of the biggest problems we have… is we have parts and assemblies that were created and put together that were not friendly to their next user.

N: What did you mean by “without any errors?”

P5: It might not necessarily mean errors, but it could be more of an inconvenience. If you dimension certain holes off of one corner with a certain size dimension, and similar holes off of another corner, or not dimension them off of the corner at all and off of the centerline… it just makes for a mess. It doesn’t…there is no logic to it. It might not be an actual error; it’s fully constrained to all points of motion and all of that stuff. The sketch is black, which is often the whole point of doing it.

But the fact that the dimensions are from this corner, or this corner, or this centerline, or this plane… if it’s not consistent, then I’m going to have to go back and figure out where the constraints are if I want to use this part. Whereas if I look at it before I even try to go to that specific hole, I should be able to tell that it is coming off of that corner.

N: OK. We were talking about expertise and what an expert is… just to kind of summarize what we’ve come up with… depth of knowledge, breadth of knowledge, experience…

What about a person’s problem solving abilities or their strategies or techniques that they might employ. Do you think that’s important for an expert?

P5: Yes.

N: Do you think an expert has a particular problem solving style or methods they employ?

P5: Probably. I’m sure at a personal level they do. I wouldn’t know exactly what that was. I guess it may depend on the way you learn. That would influence the way you would try to teach… specifically, if your problem solving technique was visual or if you have to write it down, then you’re going to teach that way. You’re going to try to explain to someone else using that same method.

N: OK. How would you characterize your own level of expertise in the use of constraint-based CAD tools?

P5: Uh… Seven. Because I have not mastered everything that the software can do yet. If I don’t know… whether to learn it or not if it’s not related to my job. If it’s not related to my job, I may never learn it, because I would never have to learn it. So then I couldn’t be an expert.

> I might be an expert in specifically the part of the software I use on a daily basis, although I would say I'm not, because there are some things that I do that might not be recommended.
>
> N: OK. But what you do works for you though right?
>
> P5: It works for me, and I try to make it work for everyone else. And I think that is the point… If it works for everyone else, then we're all much better off.
>
> N: OK. What kinds of experiences have you had, and you can generalize these, that contribute to that level of expertise?
>
> P5: Um…
>
> N: What did it take to get there?
>
> P5: Well, I think way back when I chose my career, I base that on my desire to draw… I enjoy drawing, and I am good at it, and I think that led to drawing with CAD and design work. And also my ability to… my desire to build stuff, I love the hands-on… Kind of a childhood that has pointed me in the direction of where I am now.
>
> Um… I think it started with my job description… to have as much knowledge and expertise as possible. I've always been… I've always had jobs that have been, from designer to beginning drafter, the kind of jobs where you have to have some level of expertise to perform your job functions.

Participant 5 works in a group that has used three different CAD systems in the last four years, and because of that, there is a many 3D models that have been made in the old systems that now have to be imported into the current system. This process is often fraught with its share of problems, but it appears that he is able to overcome them by a good understanding of geometry creation, the processes inherent in the software, and a clear picture of the design intent to be captured in his model.

> N: How would you describe the differences between an expert, or a more experienced constraint-based CAD user, and a non-expert, or a less-experience constraint-based CAD user?
>
> P5: One was just… to be more… more experience, more knowledge. I mean that's… more desire to do the job.

> Design intent would be in place with that more experienced person. The non-experienced person would probably focus more on getting the part done and out the door, and less on doing the parts right.
>
> N: When you say “right”, what do you mean?
>
> P5: Making sure the part is design correctly, which means they are usable for the next user. We keep coming back to that, but…there is more than just getting the part created right. It has to be put on the machine; you have to make sure that the part is designed right. You have to make sure that the specific file you used… a less experienced user would not care as much about all of those things.
>
> I know a person who is intelligent and he knows his stuff, but we cringe when we get stuff from him. He doesn’t Mate things right, he doesn’t fully constrain his sketches… he just puts holes in without any diameter dimensions and creates that information on the drawing. You usually have to go to him to ask him what size the hole is. So when you open the model, there is a bunch of random holes that don’t mean much because the dimensions are wrong. You usually see a whole bunch of blue when you open his models. The part look “right”, but it can’t be used for much.

In addition, his company uses CAD modeling standards, so those appear to have helped him update the old CAD files as well. According to Participant 5, a “good” CAD model yields accurate physical geometry, and he emphasizes that one should not compromise design intent simply to create a drawing.

> N: How do you know when you have modeled something “correctly”?
>
> P5: Well, two things. One is that the part comes in and it’s correct on the machine and the fact that someone else can use it.
>
> N: Used for what… anything in particular?
>
> P5: Used for another part. It could be used in another assembly without having to be re-modeled. If the design can be done the first time and it works for its intended situation, and then also works somewhere else, it saves that person time in his design or money in ordering part quantities in bulk. So if my model and my part is made correctly to our standards, it needs to work in that application and in other applications.
>
> N: OK. What do you mean by “work for a particular application?” Is that in terms of the function of product A and now it can be used in product B, or

> is does it mean that the person can go in and modify it to make changes and it doesn't fall apart on them?
>
> P5: Both. I mean… I guess if they can use it as-is, that's great. If they can use it for a starting point for a modification for something later without having to do a massive re-model on it, then that's good too. If they are going to make something really different, and you have to delete a bunch of stuff, then that model really didn't help you. You might as well have started from scratch.
>
> N: OK. This next question is almost the reverse of that. If you come across a model that was not modeled in that "optimal" fashion, what do you do?
>
> P5: I would probably delete it right down to the first feature. It depends on how bad it is. I quite often delete a lot of models back to the very beginning.
>
> N: Do you find that easier than simply trying to Edit Sketch or Edit Definition?
>
> P5: Usually.
>
> N: Why?
>
> P5: A lot of times, they are dumb solids because they were converted. So you can't… you don't have the ability to Edit Sketch. Sometimes they were converted from Pro/E, and they were converted with features, but now you have 55 planes going through your part and you can't understand anything because all you can see on the screen is planes. All of your holes and stuff are made off of these planes. I'm not going to dig through that many planes to figure out what I need. I'll just delete it.
>
> You still have the drawing there, so it's not like you're going to lose anything. If you model it per the drawing, then you should be OK. Use design intent to draw it on the right planes…

Participant 5 sees expertise in the use of constraint-based CAD tools as a complex phenomenon controlled by the expert's ability to recognize the conditions of his situation and create or edit geometry accordingly. To do that, they must have a fundamental knowledge of software processes and their design intent. Selecting appropriate geometry creation and editing techniques for the object in question should be based on the information collected to develop a problem solution.

Structural Description of Expertise for Participant 5

According to Participant 5, expertise in the use of constraint-based CAD tools is developed through a wide range of past experiences. In his case, these included experiences with several types of CAD tools including other constraint-based CAD tools and work experiences that placed him in a position of distributing knowledge to the rest of the people in his group. His job experiences have included working with many different types of engineers and designers, and those jobs have always included some type of "hands-on" component, which means that he was actually assembling and machining the parts that he had designed. It was through this experience that he was able to see the impact that his design decisions in using the CAD tool had on the rest of the operation.

His previous CAD tool experiences have also affected the manner in which he addresses the problems he encounters in using the CAD tools. He has an extensive technological knowledge base to draw from concerning the CAD tools, which he uses in an opportunistic fashion to experiment with potential problem solutions. In addition, his strong visual sense gives him the ability to quickly and easily recognize the requisite geometry for a particular situation and then implement a solution accordingly. Finally, Participant 5 has developed nearly all of his CAD knowledge through his own devices. Given the size of the companies in that he has worked, there has been little in the way of support structures to aid him in developing his modeling practices. This has led him to a level of confidence in his modeling abilities that allows him to attempt most any scenario without hesitation.

In the process of implementing the solution, Participant 5 is able to incorporate the design intent into the model that he is building based on his past experiences and a thorough knowledge of the basic software processes. He is mindful of corporate modeling standards and the fact that other designers will someday use his models. He chooses geometry creation techniques that are appropriate for the situation at hand and does not make his models unnecessarily complex. Participant 5 also develops a strategy for modeling in which he gives consideration to feature order, parent/child references, and dimensioning schemes in an effort to build valid, robust geometry.

THINK-ALOUD MODELING TASKS: EXAMINING CAD USAGE

The third stage of data collection for this study involved conducting a think-aloud modeling task with each participant. The goal of the think-aloud modeling task was to gather information that would give a deeper understanding of the procedural and declarative knowledge used in the operation of the CAD tool, both of which were witnessed in the observations and the interviews with each participant. The think-aloud modeling tasks gave an indication of the geometry creation techniques used by these five participants, the factors that they considered while creating that geometry, and the general nature of their decision making process while using the CAD tool. Presented in this section is a summary of the modeling procedure used by each participant, as observed by the researcher, which includes each participant's own words to describe the process when appropriate.

As mentioned previously, included in Appendix E is a description of the modeling task as well as the accompanying explanatory figure that the participants used to create the 3D model. These terms became the basis for discussion after each participant's modeling session. Table 4.3 gives a summary of each of the modeling procedures used by the participants. It lists the order in which the features were originally created.

Table 4.3

Summary Modeling Procedure for Each Participant

Participant 1*	Participant 2*	Participant 3*	Participant 4*	Participant 5*
1. Outer Body/Center Bore 2. Inner Core 3. Mounting Boss 4. Mounting Hole 5. Spotface 6. Pattern 7. Lifting Lug 8. Lug Boss 9. Mirror 10. Port Boss 11. Threaded Hole 12. Rounds 13. Pilot Hole	1. Outer Body 2. Center Bore 3. Inner Core 4. Mounting Boss 5. Pattern 6. Mounting Hole 7. Spotface 8. Reference Pattern 9. Reference Pattern 10. Port Boss 11. Pilot Hole 12. Threaded Hole 13. Lifting Lug 14. Lug Boss 15. Mirror 16. Rounds	1. Outer Body/Inner Core/ Center Bore 2. Mounting Bosses 3. Mounting Holes 4. Spotfaces 5. Port Boss 6. Threaded Hole/Pilot Hole 7. Lifting Lug 8. Lug Boss 9. Mirror 10. Rounds 11. Cosmetic Thread	1. Outer Body 2. Mounting Bosses 3. Mounting Holes 4. Spotfaces 5. Center Bore 6. Lifting Lugs 7. Lug Boss 8. Lug Boss 9. Inner Core 10. Port Boss 11. Threaded Hole 12. Pilot Hole 13. Rounds	1. Outer Body/Inner Core/Center Bore 2. Mounting Boss 3. Mounting Hole 4. Spotface 5. Rounds 6. Pattern 7. Lifting Lug 8. Lug Boss 9. Rounds 10. Pattern 11. Port Boss 12. Threaded Hole 13. Pilot Hole 14. Rounds

* These were the original feature creation sequences for each participant. As discussed in the following sections, these sequences were sometimes changed to reflect the strategy of the individual participant.

Figures 4.1 and 4.2 label each of the major features on the object for purposes of discussion. Following is a presentation of each participant's modeling procedure including the major steps they performed and their decision-making process while doing so. A comparison of these results to those of the knowledge-mapping task will be made in chapter five.

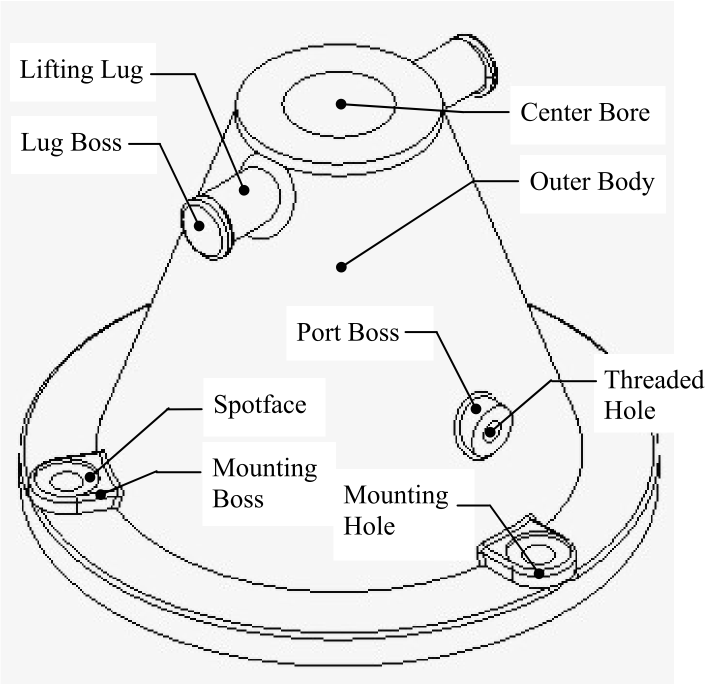


Figure 4.1: Feature Labels for the Think Aloud Modeling Task

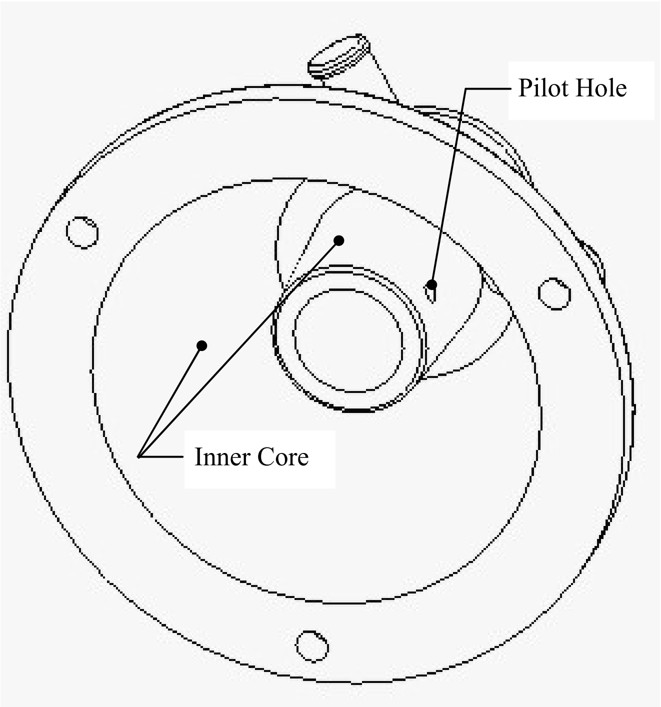


Figure 4.2: Feature Labels for the Think Aloud Modeling Task

Modeling Procedure for Participant 1

Prior to beginning the task, Participant 1 studied the drawing for quite a while, and he asked several questions about the way that the assembly functioned. He said that the part in question was highly symmetric, and he noticed the position of the mounting bosses right away. To begin the creation of the model, Participant 1 started a new part file, and the first feature he created was a revolved feature for the Outer Body of the part. He sketched a centerline right away when he began creating the profile, and he spent a few minutes deciding whether to make a single feature, including the Inner Core and the Center Bore, or two separate features, one to create the Outer Body and one to remove the Inner Core. It appeared that Participant 1 was weighing in his mind relative to the consequences of his actions and their attractiveness for capturing the design intent of the model.

> N: OK. You used Revolved Protrusions, Revolved Cuts, Mirroring… you did all of those things when you created this model. Why did you use those particular techniques instead of other options that were available?
>
> P1: When… Any feature that is repeated circularly can be produced easily with the help of Rotational Patterns as per Pro/E CAD package fundamentals. If it is not rotational, you have to do linear. If any feature is repeated, you should do it as a Pattern and not as individual features. That’s what Pro/E tells. Then, if you’re not proficient at using those commands, you can create them as separate features. But it takes more time and effort, and it is not a one-hundred percent good way of creating a model. So I felt like I should used the functionality of Pro/ENGINEER and I did it that way.
>
> N: OK. Um… It sounds like that you were trying to take advantage of the functionality of the software to try and make your job easier. Is that right?
>
> P1: Yes… to some degree.
>
> N: The feature order… the order you created the features in… What is it that made you create the features of this model in the order that you did?
>
> P1: Um… By looking at the drawing it seems that the lug does not go through the center hole? Well… that’s why I didn’t choose a sketching plane at the center. I have chosen it offset and then protruded it towards the surface [main body]. So that’s basically to… If I had chosen the center plane and then created the feature, and then did the lug, things might have

> been different. But *this* is the way that I would have done it. It's not the right way also.

He decided to create one feature that included both the Outer Body and the Center Bore, and before he did this, the researcher noticed him making a rough sketch on a notepad. The researcher asked why he did this and he said that he often does that when he models something that is visually confusing to avoid making any errors. After working through the sketch on the notepad, he decided to make two features. He created the Outer Body as a revolved feature on one of the vertical default datum planes, and he used the horizontal datum plane as a reference. He seemed to have little difficulty making the sketch, although he did check his dimensions several times. Participant 1 chose the 360-degree menu selection and finished the revolved feature apparently without too much trouble – once he had decided to do it that way.

His next feature was the revolved cut feature to remove the inside material of the Outer Body, thereby creating the Inner Core. He used the same sketching and orientation references that he used for the previous feature, and he started the sketch by using the Offset Edge command to establish the wall thickness of the part. It seemed to take him a while to create the sketch, as if he had become obsessed at times with the creation and placement of constraints. He eventually finished the profile, and it appeared that he was quite thorough in making sure all of his dimensions and constraints were placed. He checked the sketch twice before he continued on. It seemed that Participant 1 did have some difficulty visualizing the finished cut however, because his cut did not extend through the bottom surface of the part. Upon his initial creation of the cut feature to create the Inner Core, it was contained within the Outer Body and basically just hollowed it out. Participant 1 realized this when he rotated the part to inspect it, and he simply edited the cut to adjust the profile geometry accordingly.

Participant 1 then created the three Mounting Bosses at the bottom of the part. He stated right away that he was going to use the Pattern command to create them. Participant 1 could have made the Mounting Bosses as three separate features, but in doing so, he would have had to edit each one of them if they were to ever change. In Pro/ENGINEER, using the Pattern command to duplicate his original Mounting Boss required him to create the original Boss's sketch in such a fashion as to establish the orientation reference while in the process of making the feature as opposed to selecting an existing reference. In doing so, he was able to create the sketching plane that he needed for the feature creation process, but it would then disappear when he was finished with it. This technique is used so a person does not end up with many datum planes being visible and cluttering their screen. He explained this procedure quite well, but I think he lost focus just a bit, because he began to create his sketching plane in that fashion instead of his orientation plane. Participant 1 did eventually figured this out and, and he corrected the situation.

Once he had established his sketching and orientation planes, he took his part display out of shaded mode and into hidden-line mode so that he could see the interior boundary of the wall thickness of the Outer Body. He stated right away that if he wanted to extrude the Mounting Boss in the manner that he had chosen, then he would have to "bury" the end of the boss in the wall thickness of the base feature. Extruded features are created in a perpendicular direction away from the sketching plane. However, in this case, the adjacent surface of the Outer Body was tapered, and if he had not sketched the Mounting Boss profile in this fashion, a gap between the geometry of the Mounting Boss and the geometry of the Outer Body would have been created. By "burying" the end of the Mounting Boss inside the wall thickness of the Outer Body, Participant 1 was able to find a quick solution to his problem that still maintained valid geometry.

He chose the top surface of the Outer Body base flange as a sketching plane and accepted the default orientation of the model. He selected the outside diameter of the Outer Body base flange as a sketching reference too, as well as the on-the-fly datum plane as a reference. Participant 1 sketched the Mounting Boss so that it was tangent to the outside diameter of the flange. He had some trouble with the arc and line in the Mounting Boss profile and their tangent relationship, as well as their relationship to the other geometry that he created, which he overcame by pausing to evaluate his situation in light of his objectives and then making the appropriate corrections. He extruded the Mounting Boss to a Blind depth when he was finished with his sketch, and he rotated the model in space to examine his geometry. By selecting existing geometry as a location or size reference for the sketched entities, he was able to tie them together in the event of future changes. In this case, he wanted the Mounting Boss to remain tangent to the flange of the Outer Body, as opposed to using an explicit dimension.

The next feature Participant 1 created was the Mounting Hole in the Mounting Boss. He initially started with the Hole menu, but later switched to creating a cut feature which he was going to sketch on the top face of the Mounting Boss, and before he was finished with it, he stopped and decided to go with the Hole command again. It appeared that he was trying to create an angular dimension in his feature somehow and was becoming somewhat conflicted as he went about it. It also appeared that he was trying to incorporate the given bolt circle dimension into this feature, and was not exactly sure how he was going to do that. Participant 1 eventually settled on a Radial hole, which actually enabled him to incorporate both pieces of information. His placement plane was the top surface of the Mounting Boss, and he used the Through All depth option. He mentioned that by creating a Radial Hole that he could "get the dimension needed to make the Pattern." His intention here was to duplicate the Mounting Hole in a similar fashion as he was going to use to duplicate the Mounting Boss.

Participant 1 then created an extruded cut for the Spotface that goes with the Mounting Hole on the Mounting Boss. He chose the top face of the Mounting Boss as the sketching plane and accepted the default orientation and sketching references. It took him a while, but he realized that the dimensions for the Spotface and the boss were in conflict with each other. He also realized at this time that the top view and the front view of the drawing are in conflict concerning their depiction of the boss as being tangent to the outside diameter of the flange. He assumed that the Spotface diameter was correct and that it was a standard size, so he decided to increase the size of the boss to maintain the functionality of the part. "I felt that any boss should support, or give enough strength around the hole or Spotface, and I felt that increasing the boss would be better than reducing the Spotface diameter. I have to think in terms of functionality."

Participant 1 had some trouble during his modification operation on the Mounting Boss, particularly with recognizing the relationship of the bolt circle reference dimension to the Mounting Boss. When the researcher asked him about this, he said that he had assumed that the bolt circle only applied to the Mounting Holes and not to the Mounting Boss. He did not initially make the assumption that the Mounting Hole and the Spotface were concentric with the boss. Participant 1 had a lot of difficulty with this modification process on the boss, the reason for which was not apparent at the time. He started to use lines, arcs, and circles – all kinds of things – in his modification of the boss and its profile. It is possible that some of his indecision came from the fact that he was trying to think too far ahead about duplicating these features and the required dimensioning scheme for that operation, and he was mixing up the details of each one. He eventually finished the modification operation of the Mounting Boss with the dimensions being taken from the problem sheet.

His next feature was the Pattern of the Mounting Bosses, which is a method in Pro/ENGINEER for duplicating similar geometric features on a part. Participant 1 was able to duplicate the Mounting Bosses without a problem, but when he tried to use the Pattern command with reference to the Mounting Bosses in order to duplicate the Spotface cut and the Mounting Hole, Pro/ENGINEER would not create them for some reason. Participant 1 quit the command several times and started again, but it did not make a difference. He thought that he might have made a mistake in the creation process, so he deleted the Spotface cut and tried to create the Spotface using the coaxial option of the Hole command. The Reference Pattern command still did not work.

Participant 1 then decided to delete all of the duplicated geometry and decided to use the Group command to select the Mounting Boss, the Mounting Hole, and the Spotface together and then duplicate them all at one time. That still did not work. So he then duplicated the Mounting Boss, the Mounting Hole, and the Spotface individually, which finally gave him the geometry he wanted. It appeared that he knew what he was doing in terms of understanding the concepts of creating Pattern features, and he certainly had appeared to have a good strategy in trying to take advantage of the symmetry and equality between the features in the model. It might be that he simply made a mistake early in the process of creating the Mounting Boss that was not allowing him to continue in the direction that he initially wanted to go.

Next, Participant 1 created one of the Lifting Lugs at the top of the part. He determined fairly quickly that he could not use one of the default datum planes because he already had the Center Bore in place. He stated that he would create the lug and then use the Mirror command to copy it to the other side. So he used the Make Datum command to create his sketching plane and used one of the vertical default datum planes as the Offset command reference, and he accepted the default sketching and orientation references. He sketched a circle on the plane so that the center was aligned to the vertical datum plane reference in Sketcher, and then extruded the Lifting Lug, using the Up to Surface depth option, so that it terminated at the conical surface on the Outer Body. Participant 1 asked the researcher for clarification about the thickness of the Lug Boss and the overall dimension of the Lifting Lugs. He then modified the Offset dimension for the sketching plane of the Lifting Lugs to be three-quarters of an inch shorter than it originally was to account for the thickness of the Lug Boss.

Participant 1 then created the Lug Boss on the end of the Lifting Lug. He chose the circular end face of the Lifting Lug as the sketching plane for the Lug Boss, and he accepted the default orientation of the sketch. He also selected the outside diameter of the Lifting Lug as a sketching reference in order to establish the tangency location for the Lug Boss profile. He noticed right away that the Lifting Lug and the Lug Boss were not concentric, and he sketched the circular profile in such a fashion that its center was offset from that of the Lifting Lug. He created a tangency constraint between the Lifting Lug and the Lug Boss and gave it a diameter dimension, and then he extruded the Lug Boss using the Blind depth command option. He then used the Mirror command with the Dependent option to duplicate the Lifting Lug and the Lug Boss to the other side of the part.

The next feature Participant 1 created was the Port Boss on the side of the part. Again, he made the sketching plane using the Make Datum option and accepted the default orientation plane that the software gave him. He sketched the circular profile so that it was aligned to the vertical sketching reference, and he selected a Blind depth option. The feature creation direction was initially going the wrong way after he had specified all of his feature options, and he confirmed this when he rotated the part to check the Preview. He was able to easily correct this by redefining the Depth direction before he even finished creating the feature. Participant 1 then created the Threaded Hole in the port. He first made an extruded cut that was concentric to the Port Boss feature. He sketched on the circular end face of the Port Boss, and he extruded the cut through the Port Boss.

At this point, all of the model geometry was done except for the Rounds. He first selected the edge between the flange and the body on the Outer Body feature, as well as the upper edge of the Mounting Bosses, to create a one-eighth-inch fillet. This gave him an error, so he unselected the edges of the Mounting Bosses only and the Round worked, but he commented that the geometry "does not look right." He continues with another Round feature, but this time he used the One-by-One option to select the upper edges of the Mounting Bosses. He made an assumption of a smaller radius of the fillet and this time it worked. He then created the Round feature along the edge where the Port Boss meets the Outer Body of the part. He again made an assumption about the value of the radius, and it worked. He in now creating another Round feature for the outside edge of the Port Boss, which he made at a smaller radius because the one specified on the drawing was too big in his opinion.

Participant 1 then created the three-eighths-inch fillet between the Lifting Lug and the Outer Body of the part, and it went on with out a problem. He then created the fillet between the Lifting Lug and the Lug Boss. He used a small radius value, and it went in without any problems, but he still had some room. It should be noted that all of these Rounds were created with the Simple-Constant-Edge Chain-Tangent Chain menu sequence except as noted. Before he was finished, Participant 1 made a temporary drawing file that he used to see how his Rounds would look when finished. He stated that because the audiences that he prepares the drawings for are not sophisticated Pro/ENGINEER users they are often unprepared to visually and cognitively deal with Pro/ENGINEER's treatment of fillet edges on a drawing. They often assume that there is an error when there really is none because of this lack of understanding. So, if he finds a fillet to be suspect during his quick check of the drawing, then it is likely that his coworkers will as well. One thing that the researcher noticed as he created the fillets was that he tended to group them according to the major feature to which they were attached. Some of the other participants would do that also, but they would group the fillets according to the radius value that they used. In that case, they would select multiple edges, possibly from different features, that had the same radius and create them all at once.

Participant 1 now realized that he had forgotten to create the small Pilot Hole in the Inner Core. He selected the Front datum plane as the sketching plane and accepted the default orientation option. He created an extruded cut with a circular profile, and he used the Up to Surface depth option. He picked the outer cylindrical surface of the Inner Core as the depth reference because he wanted the hole to stop at that surface. As before, he rotated the model to verify the preview before actually accepting the feature.

Modeling Procedure for Participant 2

> P2: OK. I guess we've been given the task to model the stock support base. And I guess to start off… we seem to be given quite a bit of detail. So I'm going to make a Revolved solid part… um, with the outside geometry defined, and then I'll fill in the inside geometry.
>
> Then what I was planning on doing was creating the center hole through the center of the part. And after that… we can take one of two routes. We can make the reinforcements for the bolt circle holes, or we can… We can't Shell out this inner structure, but we can make a Revolved Cut.
>
> Um… after that, we'll go through and put this protrusion, the threaded protrusion, in as a feature… creating a datum plane offset from the center. We'll create that internal to the feature. And then we'll cut our threads and hole through there.
>
> After that we can create these "lifters" as they are called. And, hopefully we'll be pretty much done with the part other than some Rounds and other small features.

Participant 2 began by discussing his overall plan for modeling the object. Participant 2 created the Outer Body base feature of the part as a revolved protrusion. He sketched the profile on datum plane three and used the default orientation and sketcher references. "That will leave me with an all-yellow… I do that because of the way things are usually oriented to default to the yellow side. So if the yellow is up, then you can usually assemble things easier in the upper-level assembly." The centerline was the first piece of geometry he sketched. He sketched the profile in a proportional nature and then added dimensions. He modified the dimensions to match those on the drawing after placing them on the appropriate geometry. He used a 360-degree Depth option to complete the revolved feature.

Next he created the Center Bore in the middle of the part. He used an extruded cut, which he sketched on the top surface of the part. Again, he used the default orientation and sketching references. "It saves a couple clicks, that's all. If I know I'm going to be starting out and I know that I'm going to end up choosing a Base datum… you only have one other one to choose from." He sketched the circular profile such that the center of the circle was coincident with the axis of the part. "You don't have to worry about dimensions too much in the Pro/E Sketcher [initially], so we're just going to roughly sketch out the outline here." He finished by using the Through All depth option. This feature will be important later concerning the creation of the Mounting Bosses and the Lifting Lugs

The revolved cut to make the Inner Core was the third feature he created. He used the same sketching plane and orientation plane that he used for the Outer Body due to the same vertical orientation in the model. This time he selected additional sketching references, specifically the silhouette edge of the conical portion of the Outer Body and the bottom surface of the Outer Body.

> P2: For this feature, I'm going to turn my Hidden Line [mode] on just so I can kind of get an idea where that is. I'm going to choose the side [the silhouette edge of the conical outside surface] for a reference because it uses a constant wall thickness. It keeps you from having to create a lot of extra dimensions and constraints… you don't have to figure out the geometry. All you have to do is create a wall thickness.

Participant 2 sketched the centerline and the profile geometry, and he commented about the obscurity of the dimensioning scheme for this feature, particularly the diameter dimension to the upper tangency point between the arc and the tapered side of the Inner Core. Participant 2 completed the feature as a 360-degree revolved cut.

Participant 2 next created the three Mounting Bosses at the bottom of the Outer Body. He selected the top surface of the flange at the bottom of the Outer Body as the sketching plane, and he created a datum plane "on-the-fly" as his orientation plane. Creating the datum plane in this manner allowed him to use it during the feature creation process, but then have it disappear when he was finished. "I'm going to create a Pattern, and the way Pro/E works… It gets pretty interesting when you do this because you need a dimension to Pattern a radial off of." Again, this is a manner in which to reduce display clutter. As he sketched the profile for the Mounting Bosses, participant 2 made the arc in the profile tangent to the outside surface of the flange. He later commented that, if he had paid more attention to the dimensioning scheme on the drawing, he would have selected the bottom surface of the Outer Body or the horizontal default datum plane as the sketching plane for this feature.

> Now… we're looking at the top of it. I know that this has a taper to is [the body of the part] so I'm going to cheat a little bit. I guess if I do come into problems, we can Redefine this cut.
>
> N: Which cut?
>
> P2: The internal cut.
>
> N: The Revolved cut?
>
> P2: Yeah… the Revolved cut.
>
> The reason is… you've got a taper there, and I didn't know if there was enough wall thickness when I started. But a better practice would be to create that first [the bosses] and then create your cut. Now that I've done it, I can see the problem. Then it will always intersect without causing a problem on the inside… by having a small protrusion on the inside [where the boss comes through the wall thickness].

He created the orientation datum plane at a 60-degree angle. He also did this in order to incorporate an angle dimension into the feature so that he could use the Pattern command later to duplicate the feature. As he created this, he realized that he might have trouble with the wall thickness of the Outer Body and the end of the Mounting Boss protrusion coming through the wall.

This is an issue due to the taper on the side of the body, and the order in which he created the features. He cannot simply extrude the Mounting Boss up from the sketching plane, because the Mounting Boss would not follow the taper of the body if he did that. In order to overcome this problem, he sketched the profile of the Mounting Boss so that it continued all the way to the axis of the part. He stated that he would later use the Reorder command to change the regeneration sequence of the features, because as it stood, the Mounting Bosses would be coming through the open cavity in the model. Participant 2 finished the feature by extruding it to a Blind depth according to the dimensions.

> P2: Um… to be… The way that parts are built, solid geometry is built upwards or it extrudes outward, away from the model. Cuts are created inwards. So just to my own thought process, I know that I wanted to create something going up. So I picked the surface that I wanted to create it up from. And when I looked at the drawing for the dimension, I noticed that it was dimensioned from the bottom, which is a good way to dimension it.
>
> We could have done that same thing… or picked the base datum and extruded up. It would have been smart enough to do that. You could have had one dimension that was the same dimension as your drawing dimension. That works if you're going to show the dimensions on the drawing later on. It keeps you from having to that little bit of math in your head if something changes. If it changes, you can change it quickly.

He then used the Pattern command to duplicate the Mounting Boss around the circumference of the Outer Body.

His next feature was the Mounting Hole in the Mounting Boss. He used the top surface of the Mounting Boss as the sketching plane and the default orientation and sketching references. For this extruded cut, he sketched a circle concentric to the radius of the Mounting Boss, and he completed the feature with a Through All depth option. However, he did not use the bolt circle dimension on the drawing to complete this feature. It is important to note that Participant 2 used the top surface of the *original* Mounting Boss as his sketching reference for the Mounting Hole, which would allow him to use the Reference Pattern command later.

The next feature he created was the Spotface. He selected the top of the original Mounting Boss as a sketching plane and again accepted the default orientation options.

He commented that he was using the same references for the Spotface cut and the Mounting Hole cut so that he could Reference Pattern them after he duplicated the Mounting Boss. As he sketched the profile of the Spotface, he thought that he had created the Mounting Boss incorrectly. He checked his dimensions and found that the Mounting Boss was correct, so he assumed that there was an error in the drawing, particularly in the dimension of either the Spotface or the Mounting Boss. In this case, he decided to change the Mounting Boss radius to make it larger so that the model resembled the geometry shown on the drawing instead of making the Spotface smaller. "So if I know one and three-quarter [for the spotface], then I'm going to use a one-inch radius [for the boss] to make it look like the print looks."

At this point, Participant 2 used the Reference Pattern command to duplicate the Mounting Hole and the Spotface respectively so that it was associated correctly to the Mounting Bosses. Again, he was able to do this by using the same sketching references for the Mounting Boss cut and the Spotface cut as he used for the Mounting Boss.

Participant 2 then used the Reorder command to change the order of the features that he had created. He had to do this because he had created the Center Bore and the Inner Core cut too early. Originally, when he sketched the Mounting Bosses, they extended into the open middle of the part, and that was obviously not correct. By altering the order of features in the model, he was able to achieve the correct geometry *without* deleting and re-creating any of the features.

> So then… you can see here [rotates the part to see the bottom of the part where the bosses are coming through the body] that we still have a little problem. So what I'm going to do… Pro/E is nice, we can Redefine [Reorder] these. I know that I have two cuts… and I'm going to just drag these down [he moves them in the Model Tree] and put it under my Pattern. It's not letting me do that one [the second one]… I'll just try that one by itself. It worked. Just to be safe I'll get them down to the bottom.
>
> So now you can see we got the part. All I did was switched up the order. So now if we do a … The first feature that I made was… The order of the part… I created the first protrusion [the revolved protrusion], then I created the Pattern of the little bosses, then I created the Pattern of the small holes, then the Pattern of the spotfaces, and then we created the [Revolved] cut in the center. So that's the order of the part now.

His next feature was an extruded protrusion for the Port Boss on the side of the Outer Body. He created the sketching plane “on-the-fly” by using the Make Datum command to create an offset datum plane that referenced default datum plane one. By doing so, he was able to position the Port Boss feature where it needed to be according to the drawing. On this plane, he accepted the default sketching and orientation references, and he sketched a circle to represent the diameter of the Port Boss. “Now I’m going to pick the axis of that hole as a datum [Sketching] reference, and that will make sure that those always stay in line, that this small hole always stays in-line with that small boss.” He made sure the center of the circle was coincident with the axis of the part, and he then extruded it outward, away from the datum plane to a Blind depth according to the dimension on the drawing.

The next feature that Participant 2 created was the small Pilot Hole. He used one of his vertical default datum planes as the sketching plane and the same basic orientation as he used with the Port Boss protrusion. He made the circular profile concentric with the Port Boss by selecting the port diameter as a sketching reference. He finished the feature by extruding it using the Up to Surface option and selecting the outer surface of the Inner Core. He stated that he made the Pilot Hole concentric to the Port Boss so that if the port moved then the hole would move as well.

Participant 2 then created the Tapped Hole. He used the end face of the Port Boss as the sketching plane and accepted the default sketching orientation. He chose the cylindrical edge of the Port Boss as an additional sketching reference and then sketched a circle that was 5/8 of an inch in diameter. He mentioned that if he had a standard drill table then he would make it the exact size. He used the Up to Surface depth option and picked the rear face of the Port Boss as the depth reference so that if the length of the Port Boss changed then the Threaded Hole depth would follow it. He created a Cosmetic Thread on this feature that contained the thread information for the hole.

The next feature was one of the Lifting Lugs at the top of the part. He chose one of the vertical default datum planes as his sketching plane, and then he accepted the default orientation references. He said that his intention was to extrude it to a Blind depth equal to half of the overall depth dimension, and that he would then create the Lug Boss on the end of the Lifting Lug by extruding it backwards along the Lifting lug protrusion. He would then use the Mirror command to duplicate the Lifting lug and the Lug Boss about the sketching plane in order to the identical geometry on the other side.

He then created the Lug Boss on the end of the Lifting Lug. Participant 2 selected the circular end face of the Lifting Lug as the sketching plane and then accepted the default orientation direction. He selected the circular edge of the Lifting Lug as a sketching reference, which allowed him to get the offset distance between centers that he needed as well as the tangency condition between the Lifting Lug and the Lug Boss. He gave it a diameter dimension and extruded it to a Blind depth. As was the case with the Port Boss and the Lifting Lug features, Participant 2 had to consciously be aware of the creation direction of the feature and it's relationship to the viewing direction of the sketching plane. It was of particularly relevant in the creation of this part.

Participant 2 then used the Mirror command to duplicate the Lifting Lug and the Lug Boss. He got the geometry that he wanted in terms of the Lifting Lugs and the Lug Bosses, but he then had a similar scenario as to the one he had with the three Mounting Bosses – the Lifting lugs extended into the Center Bore from one side to the other. Participant 2 again used the Reorder command to remedy this problem, which required him to move the offset sketching plane, the Port Boss, the Tapped Hole, the Cosmetic Thread, and the Center Bore to come *after* the Lifting Lugs and the Lug Bosses. In doing so, he was able to achieve the desired geometry according to the drawing.

> Well, the big thing was to end up with the resultant geometry that you were looking for. I had to change the order on some of the features, because I didn't have the foresight to look at this and know that they were going to cause a problem. And a lot of time you don't. I don't look at every part… I sort of take it as a whole, and then start taking away things and adding things, which is when I find problems. But you can correct them later. But you have to start with a chunk of material, and you have to add on… Now the perfect way to make this, in hindsight, would be to *add* as much material as possible, except for the small, threaded boss. And then you would do your cuts and add your threaded boss in. If I had to do this over again, that is how I would do it.

The last features he created were the Rounds. He decided to group these into what he called "easy" and "hard". In addition, he tended to create Rounds on one feature at a time before moving on to the next one. He was able to get all of the Rounds on the part, except for the ones where the Lug Boss meets the Lifting Lug and the ones where the Mounting Bosses meet the flange of the Outer Body. In each of these cases, the adjacent geometry to the Rounded edges results in a zero-radius condition, which cannot be addressed with the use of the Simple Round command options. Participant 2 also encountered situations where he had to change the radius value of the Rounds in order for them to be created. He attributed this to his lack of use of Advanced Round functionality and to the shortcomings of the software itself. Trial and error on his part eventually worked in most cases.

Modeling Procedure for Participant 3

Participant 3 started with his corporate start part so that he would have default layer, view, and datum plane settings. It also gave him custom parameters that he uses in the title block of any drawings that he creates. He stated that this was critical because the default datum planes gave him stable references from which to build his initial features.

The first solid feature that participant 3 created was a revolved protrusion that embodied the basic geometry of the part, including the Outer Body and the Inner Core of the model. He sketched the profile on the Front datum plane and he accepted the Default orientation for sketching. “I’ll align the centerline to the [vertical datum plane in the sketch], and I’m going to make the top-most surface, which would be the mating surface for the assembled part.” He accepted the default sketching references. Somehow, he ended up in an extremely magnified zoom scale and could not get out, so he closed the part without saving and started again. Selecting the same sketching plane as before and using the Top datum plane as a sketching reference, he sketched the desired profile at a basic proportion. When he was finished, he used the Modify Scale functionality to set the dimensional values to more manageable ranges. However, the first time he tried this, the sketch did not behave as he anticipated. It had over-constrained geometry and conflicting references in several places.

He performed an Undo operation and after that he took more care in initially arranging the dimensions in order to modify them. “So it helps in Pro/E to think about two or three steps ahead. If I needed to go back and verify or modify later on, those dimensions are where they are clearly visible.” He used the Strengthen command to incorporate all of the default dimensions that he needed. It should be noted that Pro/ENGINEER applies dimensions and geometric constraints to a sketch as the user creates the geometry. It is up to the user then to decide whether to keep those dimensions and constraints or to override them with ones of their own. Participant 3 then used the Modify Scale option again using the overall height dimension as the scaling factor. The sketch was now in proportion and ready to be assigned the actual dimension values according to the drawing. After editing the dimensions, he examined the sketch and its dimensions one last time, and then accepted the profile and revolved it 360 degrees. "I've got a pretty detailed sketch here, but I would rather do that and keep the number of features down. It will save me time in the long run." He commented that he had wanted the top surface of the part to be aligned with the Top datum plane so that it could be more easily assembled, but he never actually did that. As it turned out, the Top datum plane ended up being aligned to the bottom surface of the Outer Body/Inner Core combination.

Next he created the three Mounting Bosses at the bottom of the Outer Body base flange. Participant 3 selected the top surface of the base flange as the sketching plane. He assumed the default orientation references, but he also picked the Right datum plane as a sketching reference because it coincided with the axis of the part. In addition, the outer cylindrical surface of the flange base and the inner diameter edge of the Inner Core were also selected as sketching references. He selected these references so that there would not be a gap left when he extruded the protrusion up the tapered side of the part. This would be caused by the fact that Pro/ENGINEER's extrude operation creates depth in a linear fashion away from the sketching lane in a perpendicular direction.

He decided to create all three Mounting Bosses as part of the same protrusion feature, which required him to create a fairly elaborate profile. He sketched a construction circle to be used as the bolt circle reference dimension to locate the centers of the Mounting Bosses. Participant 3 also sketched three angled centerlines to be used as construction lines: one at the horizontal position, one at 120 degrees from horizontal, and the third one 120 degrees off of that. Participant 3 addressed the size issue of the Mounting Boss radius by sketching it tangent to the outer cylindrical surface on the base flange of the Outer Body.

> P3: It just looks like… It looks like the illustration is not correct. It is showing this three-quarter inch radius to be tangent to the main body, but also with the same… It's showing it from the radius form the center… to which if that's true, that should be an inch.
>
> N: So… how are you going to make it?
>
> P3: Well… in looking at the function of the part, I will ignore the dimension and make it look like the picture. I think you'll end up with a more functional part. And to do that, I'm simply going to constrain it to be tangent to the base.

As he created the boss, the researcher asked him why he did not use the Pattern command to duplicate the Mounting Bosses, and his response was that "there's not that many of them." Rather than experiment or hassle with a command that he does not readily use or understand he simply creates the geometry using the most productive technique in his repertoire. "I find that with this sort of feature, I find that it's quicker to just go ahead and do Cuts like this. That way, not only is it just as quick, but it's a lot cleaner when you need to go in and make a change."

The next feature he created was the Mounting Hole in the Mounting Boss. He picked the top surface of the Mounting Boss as a sketching plane, and he used the default orientation references by default. He picked the circular edges of the three Mounting Bosses as sketching references, and he was able to create the extruded cut feature concentric to the Mounting Boss and to keep it there if the Mounting Bosses were to ever change positions. Just like the sketch for the Mounting Bosses, he created the three Mounting Holes as one cut feature. Participant 3 used the Through All depth option to finish the feature. He then created the Spotface cut using the exact same sketching and orientation references as he used for the Mounting Hole. Participant 3 used a value of .060 for the Blind depth of the Spotface, which he said "looked functional", because it was not given on the drawing.

The next feature was the Port Boss on the side of the Outer Body. For this feature, he created an extruded protrusion feature by using the Make Datum option to create an offset sketching plane from one of the default datum planes. He accepted the default orientation and dimensioning references, and Participant 3 sketched a circle that was aligned to the vertical datum plane in the sketch. He extruded it to a Blind depth according to the dimensions on the drawing, after which he rotated the part for a visual inspection to ensure that the feature he had created worked properly.

Participant 3 then created the Threaded Hole in the Port Boss. He used the same sketching and orientation references as for the Port Boss protrusion, and he commented that not only did it save time, but it also seemed like a functional choice as well. He also used this same extruded cut feature to create the small Pilot Hole through one wall in the Inner Core. He used the Up to Surface depth option and selected the inside cylindrical surface of the inner bore of the part. When finished with this feature, he used the cosmetic cross-section function to view the interior details of the part and make sure they were created properly.

Participant 3 then proceeded to create one of the Lifting Lugs. He used the Make Datum option to create a sketching plane for this feature that was offset from the Front default datum plane. He extruded the protrusion back towards the model using the Up to Surface depth option and picked the conical surface of the Outer Body. Participant 3 used the default orientation and sketching references, and he sketched a circle by aligning the center point to the vertical default datum plane, which he also used as a sketching reference for the Port Boss protrusion and the three Mounting Bosses.

He then created the Lug Boss on the Lifting Lug. He used the same sketching plane and orientation plane from the previous feature. He selected the outer edge (circumference) of the Lifting Lug as a sketching reference and he sketched the profile for the Lug Boss slightly offset from the center axis of the Lifting Lug. He extruded the Lug Boss to a Blind depth back towards the Outer Body of the part along the axis of the Lifting Lug. After it was complete he used the Mirror command to duplicate both the Lifting Lug and the Lug Boss using the Dependent option to create the ones on the other side. He chose the Dependent option so that if the original Lifting lug and Lug Boss were ever modified, then the duplicated features would update.

Participant 3 then surveyed the part to see if he had created everything. It looked good, so he proceeded to create the Rounds. He stated that it appeared as if most of the Rounds and fillets were one-eighth of an inch radius and that he would first do those. He said that if he had trouble with them, that he would go back to the first base Revolve feature and add them to the sketch for that feature. So he selected the upper edges of the Mounting Bosses and the outer edges of the Outer Body upon which to create the Rounds first. As he was doing the Rounds, he noticed that one of his Mounting Bosses had developed a gap between it and the Outer Body of the part. He was surprised given the diligence that he had shown in selecting sketching references, however when he examined it using the Redefine command, it had in fact lost one of its sketching references – the alignment to the inner diameter of the Outer Body at the bottom of the sketch. He then used the Redefine command to edit the Mounting Boss feature and re-select the correct reference. Participant 3 trimmed the profile again, and finished the feature. The next feature was the Round between the flange and the body. He selected multiple edges and used a one-eighth of an inch radius, and it regenerated without any problem. His next fillet was the one between the Lifting Lug and the Outer Body. A Simple Round with Constant radius did not work initially so he tried the Auto Blend option. This allowed Pro/ENGINEER to vary the radius of the fillet, as it deemed necessary, in order to create it under these conditions. When the researcher asked him about giving up that much control, Participant 3 responded that he does it often and finds that command indispensable. He took the same approach and got the same result with the fillets between the Lifting Lugs and the Lug Bosses.

Finally, Participant 3 used the Cosmetic Thread feature to denote the threads on the tapped hole in the port. He said he might have used that functionality three times in all of his years of experience of Pro/ENGINEER. However, he seemed to not have any problems, and he commented that it was much easier than trying to cut "real" threads into the geometry with a helical sweep. However, he did encounter one minor problem. Since he created the Threaded Hole in the Port Boss and the Pilot Hole as one feature, he had to go back and create another Hole feature partially on top of the Threaded Hole in the Port Boss. He used the nominal thread diameter for this newest hole, specified all of the parameters, and then placed it on the model. His last action was to use the cross-section visualization tool again to examine the interior of the part to make sure it was doing what he anticipated that it would so.

> P3: One thing I like to do as I'm working is to use the Section tool to help me see what I've done in the tool. It's just a real quick, handy feature that Pro/E has. It shows me real quickly that I've accomplished what I wanted to accomplish.

In addition, he scanned the model tree and the drawing to make sure he had not missed anything.

Modeling Procedure for Participant 4

Participant 4 began by using is corporate start part. He did this so that he would have his default datum planes, layers and views established in the model automatically. He also created a datum axis feature at the intersection of the default datum planes to use as a sketching reference for the revolved features in the model.

His first solid feature was a revolved protrusion to get what he called the "basic shape" of the part.

> P4: Looking at this part, it actually looks like a cone with a round base and a round top… with a center hole that supports a shaft. I think my approach would be to sketch the profile of this cone shape and do a Revolved section to get he majority of the base.

He chose a vertical sketching orientation by sketching on the Front datum plane and by using the Top datum plane as the orientation plane. Participant 4 stated that he would sketch the first profile as a solid chunk and "core it out" later. As he sketched the silhouette of the Outer Body, he made radius dimensions, even though he was given diameter dimensions on the drawing. He used the 360-degree Depth option to complete the revolved geometry, and after the profile regenerated successfully, he went back and edited the feature to include diameter dimensions from the drawing.

His next step was the creation of the three Mounting Bosses at the bottom of the Outer Body. After he considered parent/child references and various dimensioning schemes to get the desired geometry, he chose the Top datum plane (at the bottom of the Outer Body) as the sketching plane. "I'm trying to keep the relationships down as much as possible. It's just a thought process that you go through. Sometimes you win some, and sometimes you lose some. But it is a consideration." Participant 4 also chose a vertical default datum plane as the horizontal orientation plane so that he was "looking down" on the part. He used the outside diameter of the base flange on the Outer Body as a sketching reference.

> I spoke about trying to minimize the parent/child relationships, but I see that the bosses are tangent to the OD of the flange. So if I use that as a reference, then I'm tied back to it. So I guess there's really no way… I could put a dimension, which would be double-dimensioning, but… So I'm just going to go ahead and allow these bosses to be tangent to the OD of the flange. So I'm gonna select the OD of the flange as a reference also.

His sketching methods appear quite similar to traditional drafting techniques – he sketches geometry in such a fashion that he uses the Trim function quite a bit. Participant 4 did use a construction circle for the reference bolt circle to place the location of the center point of the Mounting Boss radius. He also sketched the profile of the Mounting Boss so that it went all the way through the part to the center axis in order to maintain his dimensioning scheme and to get the sketch to regenerate a little bit easier. He stated that this would not be a problem since he was going to come back and remove the inner area with a later feature. Participant 4 finished the feature by extruding it to a Blind depth according to the dimensioning scheme on the drawing.

Participant 4 then tried to use the Pattern command to duplicate the Mounting Boss, but he was not able to do so successfully on the first try. He had forgotten to create the orientation plane for the feature "on-the-fly" using the Make Datum option, and he was struggling a bit with the geometric constraints in the sketch due to making the boss tangent to the outside diameter of the base flange on the Outer Body. He then decided to create all three Mounting Bosses in the same sketch since he could not figure out how to use the Pattern command. He used the Redefine command to edit the profile of the first Mounting Boss so that it included the geometry for the other two Mounting Bosses. While this may not have been the most efficient procedure, it did produce the geometry he intended, and it was easily modifiable.

He then created the Mounting Holes on each Mounting Boss. He commented that they are on the same bolt circle as the bosses, so he selected the circular edge of each Mounting Boss as a reference for sketching. "I know that the lug pattern is on a fifteen-inch diameter bolt circle, so I can use the center of the arc [in the boss] to locate the center of the hole. I can use this reference [selected the datum planes and the circular edge of the boss].” For this feature, Participant 4 selected the Top datum plane (which was coplanar with the bottom surface of the Outer Body) as the sketching plane for this extruded cut. He did not use the Hole command, because he said that the cut feature is more flexible. Also, he stated that by sketching on the Top default datum, he was better able to control and minimize the parent/child references being created within the part. He finished the feature by choosing the Through All Depth option.

Next, Participant 4 created the Spotface cuts. Again, these were extruded cuts, only this time they were sketched on the top surface of the Mounting Bosses feature, and he used on of the vertical default datum planes as an orientation reference. As with the Mounting Holes, all three Spotfaces were created as one cut feature. Participant 4 reacted to the error in the Spotface diameter in a similar fashion to the other participants. “To keep it looking like the [drawing], I’m just going to change the diameter. So I’m going to move this line to the inside of here [within the boundaries of the boss feature], and I’m going to change that to one and three-eighths, thinking maybe that’s a typo on the drawing.” The depth of the Spotface was missing from the drawing, so he arbitrarily made the depth one-eighth of an inch. He said that it seemed proportional to the rest of the part.

His next feature was the Center Bore. He created an extruded cut feature that used the Up to Surface depth option. He picked the top surface of the Outer Body as the depth reference, because he had used the Top datum plane (bottom surface of the Outer Body) as the sketching plane. Again, his reasoning was to minimize parent/child references. Participant 4 also said that using the Through All depth option can “come back to get you if you’re not careful.” He said that if he were to create a feature “behind” that cut that he did not want it to be affected by the cut, and the use of the Through All depth option may cause a problem. However, he stated that it would just be a simple situation that would be easily fixed with the Reorder command.

Participant 4 then created the Lifting Lugs at the top of the part and realized that feature order was then important. He created them with the Center Bore already in place, and then used the Reorder command to move the Center Bore to come after the Lifting Lugs.

> P4: It's this one… the one at the top. The one on the bottom, I have to core it out first [then put it in]. I know I'm looking at the one at the top, and I know now looking at that that I should put that in first. But what I don't know… apparently there are two, one on each side. So what I'll do is put those in there and come back and Reorder the hole I have going through the center so that it takes that out. I can either do that or go straight into Insert Mode, but I would just as soon change the order of those and be done with it.

Because of the dimensioning scheme applied to the Lifting Lugs, an overall width dimension across the entire feature, he sketched the profile on the Front datum plane and extruded it outward. He used a Both-Sides creation direction for the protrusion and a Blind depth option in order to maintain the overall depth dimension given on the drawing.

His next feature was the Lug Boss on the end of the Lifting Lug. As he created the various features, the researcher noticed that he toggled the default datum planes on and off. He said that this was to keep the screen clutter to a minimum. He had a lot of trouble getting this Lug Boss on the Lifting Lug. He adjusted the overall width dimension of the Lifting Lug to account for the thickness of the Lug Boss, because he chose the circular end face of the Lifting Lug as a sketching plane for the Lug Boss. He had difficulty with the references in his sketch, due in part because he selected the circular edge of the Lifting Lug as a reference and did not know what to do with it afterwards. He expressed that the software doesn't like that scenario at times, and that "fudging is often necessary to get something to work." He altered the diameter of the Lug Boss and its placement dimension relative to the Lifting Lug in order to remove the tangency condition between the Lifting Lug and the Lug Boss.

Participant 4 next created the Lug Boss on the other Lifting Lug. The researcher asked him why he would not just Copy or Mirror the first one to the other side, and he commented that he "does not usually like to copy things." He said that he found it easier to repeat the same steps that he was familiar with already rather than introduce "another level of complexity" into the situation. So, he basically created the second Lug Boss in the same manner that he created the first one.

Next, Participant 4 used the Reorder command to change the feature order of the Center Bore so that it came after the Lifting Lugs and the Lug Bosses. This was so that the Center Bore would be clear of any extruding geometry, which was not the case before, since he had picked the Front datum plane as the sketching plane for the Lifting Lugs *after* he had already created the Center Bore.

His next feature was the revolved cut to make the Inner Core to "core out" the middle of the part. He sketched the feature on the Front datum plane and used the Top datum plane as the orientation plane. This was similar to his setup for the Outer Body. The first thing he sketched was a centerline to provide the axis of revolution. As he created this profile, he used a combination of sketching, dimensioning, trimming, and modifying dimension values to arrive at the correct geometry.

> P4: What I have found is that when you have a complicated sketch that… that kind of stuff gets cluttered. So I just decided to just make one solid first and then come back and then core it out later just to keep the sketch simple.

It appeared that he was working through some of the issues with the dimensioning scheme on the drawing, particularly the diameter dimension to the tangency point where the Inner Core meets the Outer Body. After arriving at his final profile geometry, Participant 4 rotated the part a few times, as he did after every feature, to determine if the resulting geometry was what he wanted.

The next feature that Participant 4 created was the Port Boss on the side of the Outer Body. He used the Make Datum option for the sketching plane and created it offset from the Profile default datum plane. As he sketched the circular profile, he included an Axis Point for a future reference for the Threaded Hole that would be made in the Port Boss. He extruded the Port Boss protrusion to a Blind depth according to the dimensions on the drawing. As always, he continued to rotate the model and visually inspect the part when he was done with the feature.

Next, Participant 4 created the Threaded Hole in the Port Boss. He used the Axis Point that he created in the previous feature as a reference when sketching the circular profile for the extruded cut. Participant 4 used the circular face of the Port Boss protrusion as a sketching plane for this feature. Since it is a 5/8-11 tapped hole, he is simply using a one-half inch diameter hole for the minor diameter of the thread. He also used the Up to Surface depth option and selected the opposite end surface of the Port Boss protrusion as the depth reference for the feature. He also added a cosmetic sketch to the hole to represent the threads, but it was not the standard Cosmetic Thread function in Pro/ENGINEER.

The last solid feature that he created was the small Pilot Hole on the Inner Core of the part. Since it was the same size as the diameter that he used for the Threaded Hole in the port, he simply changed the depth reference of the existing hole and picked the inner diameter of the Center Bore. There was no obvious reason why he tied these two features together by using the same geometry for both of them other than potentially for increased efficiency.

The last features that Participant 4 put on his models were the Rounds. The one at the bottom of the Inner Core went in without any problems, but he expected that it would. He initially had a failure with the Rounds between the Port Boss and the Outer Body on the inside of the part, particularly the one that is on the outside edge of the Port Boss in this area. It did not have enough surface material left to make the radius. So he just simply changed the radius value to be slightly smaller. He continued to adjust the value slightly until he got it to a size where the Round feature did not fail. He also had issues with the fillets on the Lug Bosses, especially in the area on the underneath side where the Lifting Lug and the Lug Boss meet and at the top near the tangency condition. Basically, the Lug Boss and the Lifting Lug are tangent at this location and the surface area is zero. Participant 4 did not know much (if anything) about Advanced Rounds, so his solution in this case was to again adjust the radius value until he was able to create the rounds successfully. In the case of the fillet where the Lifting Lug and the Lug Boss meet, he was never able to get that one to go in. He was able to get most of the other Rounds to go in by using these techniques when necessary, and those that he did not put on were cases when he would have needed the Advanced Round functionality.

Modeling Procedure for Participant 5

As he was evaluating the model, Participant 5 decided that it would be best to begin with a revolved base feature to form the Outer Body. He sketched on the Front plane, and as he did so, he sketched a centerline right away. Some of the other participants actually waited until they were finished with the sketched geometry to create the centerline. Although the true reason for this is unclear, it is often in response to the warning that the software gives the user in regards to not being able to create the revolved feature without a sketched centerline. He initially created only the "outside" of the body of the object using the 360-degree depth option; however, he soon realized his opportunity for creating the Inner Core of the part in the first sketch as well. One thing that the researcher noticed about Participant 5 is that he typically sketched feature profiles in the isometric view of the object as opposed to using the orthogonal view on Sketcher. "I'm going to try to adjust the sketch a little bit more proportionally so that when I actually do dimension, it doesn't blow up on me like it did." He did this throughout the modeling task and during the times that the researcher has observed him at work.

> N: All right. What factors contributed to your feature order? Why did you make this in the order that you did?
>
> P5: Uh… I started really from the bottom up. A lot of times, maybe not specifically this time, but I try to figure out what's the easiest thing to do that will help me with future features. That's how I knew to start out with the biggest, the overall outer shape.

He redefined the first feature by right-clicking it in the Feature Tree and choosing Edit Sketch. While using a calculator to convert the fractional inch dimensions on the drawing to decimal inches, he said that it had been a while since he had done this in his head. He now included the geometry for the Inner Core in the profile of the first feature, as well as the geometry that defines the Center Bore. Participant 5, just like several of the others, commented on the obscure dimensioning scheme of this portion of the object, but he had no problems creating it. When he went to exit the sketch, he got an "open contour" error.

> P5: Oh… five eighths of an inch here to here [the wall thickness of the body]. Fully defined. I'm going to Rebuild… doh, what's the problem here. [The software gave an error message that stated that there was an open contour in the section.]
>
> Oh… stupid. Trim [the lines along the centerline]. I don't know if that's going to work.
>
> Oh, it's an open contour. Never mind. Trim.

He had trimmed several entities in the creation of this geometry in the new feature, so he had lost some of his dimensions. He had no problem recovering from this minor setback, and with a quick survey of the drawing to find the missing dimensions, he was able to provide the missing information to the software.

His next feature was going to be the Mounting Hole in the flange of the Outer Body, when he realized that he had misread the drawing. He said that he was now going to create the Mounting Boss first. Participant 5 struggled a bit with the boss radius and its associated dimension. He determined that there was an error on the print, but he was not sure if the error was an incorrect dimension value, or if the geometry was drawn incorrectly. He continued to evaluate the potential options for addressing this problem, including the variation of the Mounting Boss radius or the adjustment of the diameter and depth of the Spotface cut.

> P5: What am I missing? Fifteen diameter… that's fifteen.
>
> [Continuing to survey the drawing to look for information and compare that with the dimensions he has in his model]
>
> I don't know. Maybe it's… Why…
>
> N: What are you thinking about here?
>
> P5: I don't understand why… unless… I guess I'm going to make the assumption that this circle is actually tangent to this part here.

He decided to finish the Mounting Boss with the given dimensions. He also noticed that he had to sketch the profile of the Mounting Boss so that it overlapped the wall geometry of the base feature. If not, he ran the risk of having the Mounting Boss geometry come out of the inside surface of the Center Bore.

> P5: Now, I can extrude up a half inch. [Rotates the part to check the inside cavity.]
>
> I just want to make sure that I'm… I am protruding through there [The boss is coming through the wall thickness on the inside cavity of the part]. So I want to edit my sketch, plus I don't have any dimensions on there. So I would want to go smaller [on the length of his boss so it does not come though the thickness of the wall], and that would be… I'm just going to pick a number, trial and error.

He sketched the boss on the top surface of the base flange of the Outer Body. In doing so, he did not take into account the thickness of the base flange in the overall height of the boss, which was accounted for in the dimension on the drawing, which was a common mistake made by several of the participants. His initial height dimension of the Mounting Boss was too large and the boss intersected the wall of the part. He was able to overcome this by simply modifying the dimensions of the Mounting Boss.

Participant 5 created the Spotface next using the top surface of the Mounting Boss as a sketching plane. He sketched a circular profile and extruded the cut to a Blind depth of one-eighth of an inch. Participant 5 created this sketch concentric to the Mounting Boss, but not with an explicit geometric Relation. He did it by using the Sketcher's functionality that controls the mouse and let SolidWorks make the implicit assumption. The depth dimension for this feature was not given, so he made an assumption that looked proportional to the rest of the part.

His next feature was the Mounting Hole in the boss, and it was created in basically the same way that the Spotface was created. The bottom surface of the Spotface was selected for the sketching plane and he used an implicit geometric relation created by sketcher to position the hole concentric to the Spotface. He used a Through All depth option according on the information on the drawing.

After he was finished with the Mounting Hole, he made the Fillets between the Mounting Boss and the Outer Body base flange. He created the Fillets now because his intention was to use the Pattern command to duplicate the Mounting Boss, the Spotface, the Mounting Hole, *and* the Fillets all at the same time. In the previous step, the researcher asked him about creating the Fillets so early in the design, and he explained that the feature order that he was using was conducive to his intentions to duplicate the geometry using the Pattern command in order to create the geometry more quickly. “I’m just trying to keep the related features together.”

Participant 5 then created the Lifting Lug features. He created an offset datum plane, using the Front plane as a reference, to use as the sketching plane. As he sketched the circular profile of the lug, he made an explicit geometric Relation to make the center of the circle coincident with the axis of the part. He created the sketching plane in that manner because he recognized that if he had used one of the default datum planes as the sketching plane, then the Lifting Lugs would have been passing through the Center Bore in the part. And, since he created the geometry for the Center Bore as part of the Outer Body/Inner Core feature, then there would have been nothing to involve in the use of the Reorder command in order to make the geometry as required.

> P5: I realized after I finished doing the outer core, I realized even if I did it without the tower on the inner part, that it would have been too complicated to do a Shell or anything like that to get the inner part of the part.

By doing it this way, he could extrude the Lifting Lug back into the Outer Body using the Up to Surface depth option. Initially, he made a mistake in the value of the depth option for the lug, so all he had to do was modify the offset dimension for the datum plane.

His next feature was the Lug Boss. In order to maintain the overall width dimension of the Lifting Lugs and the Lug Bosses combined, he decided to modify the offset dimension of the offset sketching plane in the Lifting Lug to account for the thickness of the Lug Boss. He then selected the circular end face of the Lifting Lug and used that as the sketching plane for the Lug Boss. He also made the outside diameter of the Lug Boss tangent to the circumference of the Lifting Lug by using a tangent geometric Relation. This gave him the offset distance between the two diameters that he needed and all that was left was to create the diameter dimension for the Lug Boss. Participant 5 extruded the Lug Boss to a Blind depth according to the dimensions on the drawing to finish the feature.

He then created the Fillets between the Lifting Lug and the Outer Body and between the Lifting Lug and the Lug Boss. He assumed a radius of one-eighth of an inch for the latter and he used the given three-eighths of an inch radius for the former. Each Fillet feature was created successfully. The researcher initially questioned Participant 5's feature order here, but he used that feature order to coincide with the symmetrical nature of the geometry of the part. His intention was to duplicate the Lifting Lug, the Lug Boss, and the associated Fillets using the Pattern command, which he performed successfully. When he was asked about using the Circular Pattern command instead of the Mirror command, he said that when he has symmetrical geometry that it is cylindrical or circular by nature, he always uses the Circular Pattern command. He finds that command more intuitive.

He then created the Port Boss in the side of the part. This time he offset a datum plane from the Right default datum plane. This served as the sketching plane for the extruded boss feature that would make up the Port Boss. He positioned the circular profile aligned to the axis of the part using a coincident geometric Relation, and then he extruded the feature to a Blind depth. Participant 5 then created the Fillets between the Port Body and the Outer Body. When the researcher asked him about feature order again, he simply commented that while he often times will keep the creation of most fillets until the end of the model, if they makes sense to put them in sooner, then he will as in this case.

Next, he made the Threaded Hole in the Port Boss. He sketched on the outer circular face of the Port Boss, and he made the circular profile concentric to the Port Boss so that if the Port Boss moved then the Threaded Hole would move with it. He wanted to use the Hole Wizard, but for whatever reason, that function would not work on the machine that he was using. He wanted to use that function because he could type in the thread specifications that were given on the drawing and the software would create the type of hole that he needed automatically. Instead, since he did not have a standard drill table with him, he simple made an extruded cut that had a diameter equal to the minor diameter of the tapped hole, which he assumed in this case to be one-half inch in diameter.

His next feature was the small Pilot Hole, which he sketched on the same plane as the previous Threaded Hole. He said that he did this to save time, and he realized that he was “cheating a little bit.” By making the circular sketch for the Pilot Hole concentric to the Port Boss, he could be sure that the Pilot Hole and the Threaded Hole in the Port Boss would always be in line with each other. But he also acknowledged that, from a manufacturing point of view, the Pilot Hole would likely be made first. So, he used the Reorder command to move the Pilot Hole so that it came before the Threaded Hole in the Port Boss. He used the Up to Surface depth option for the Pilot Hole and selected the inner surface of the Center Bore as the depth reference.

At the end of the modeling session, he came back to the Fillet feature between the Lifting Lug and the Lug Boss and added the reference edges for the fillets where the Outer Body meets the flange at its base. When asked why he did this, he replied that the fillets were the same size, so it seemed to make sense to group them together. It did not cause a feature failure in this case. As a finishing touch, he used the Roll Back functionality of the Feature Tree to step through the creation of the model. He commented that he usually does this with his models to expose any glaring errors that might be present before he begins to create the drawing or place it in an assembly.

The final section of this chapter presents the results of the knowledge-mapping task, which sought to elaborate on the relationships between the various factors that impacted the attractiveness of the participants’ choices in the use of the software.

KNOWLEDGE MAPPING TASKS: ORGANIZING CAD DOMAIN KNOWLEDGE

The knowledge mapping tasks for this study produced a graphical representation of each participant’s mental model of the knowledge domain surrounding the use of constraint-based CAD tools. These knowledge maps denote the structural relationships between the major concepts and groups in each participant’s mental model. Each of the knowledge maps is included in this section, as well as a description of each model based on elaboration by the participant during the knowledge-mapping task and afterwards.

For the purposes of this study, only the major groups or hierarchical structures will be presented in these results. A list of the concepts is included in Appendix F, in the order in which they were presented to the participants during the task. Due to the nature of the differences between the actual CAD software packages used in this study, the nature of each concept by itself was only of importance to each participant as it related to his own personal knowledge structure. The information of importance to the researcher was the final arrangement of those concepts, the labels that they applied to the various groups and structures that resulted from that arrangement, and any reasoning that the participant might have provided to explain those relationships. Following are the graphical representations of each participant's mental model in Figures 4.3 through 4.7, which is in turn followed by a description of each model.

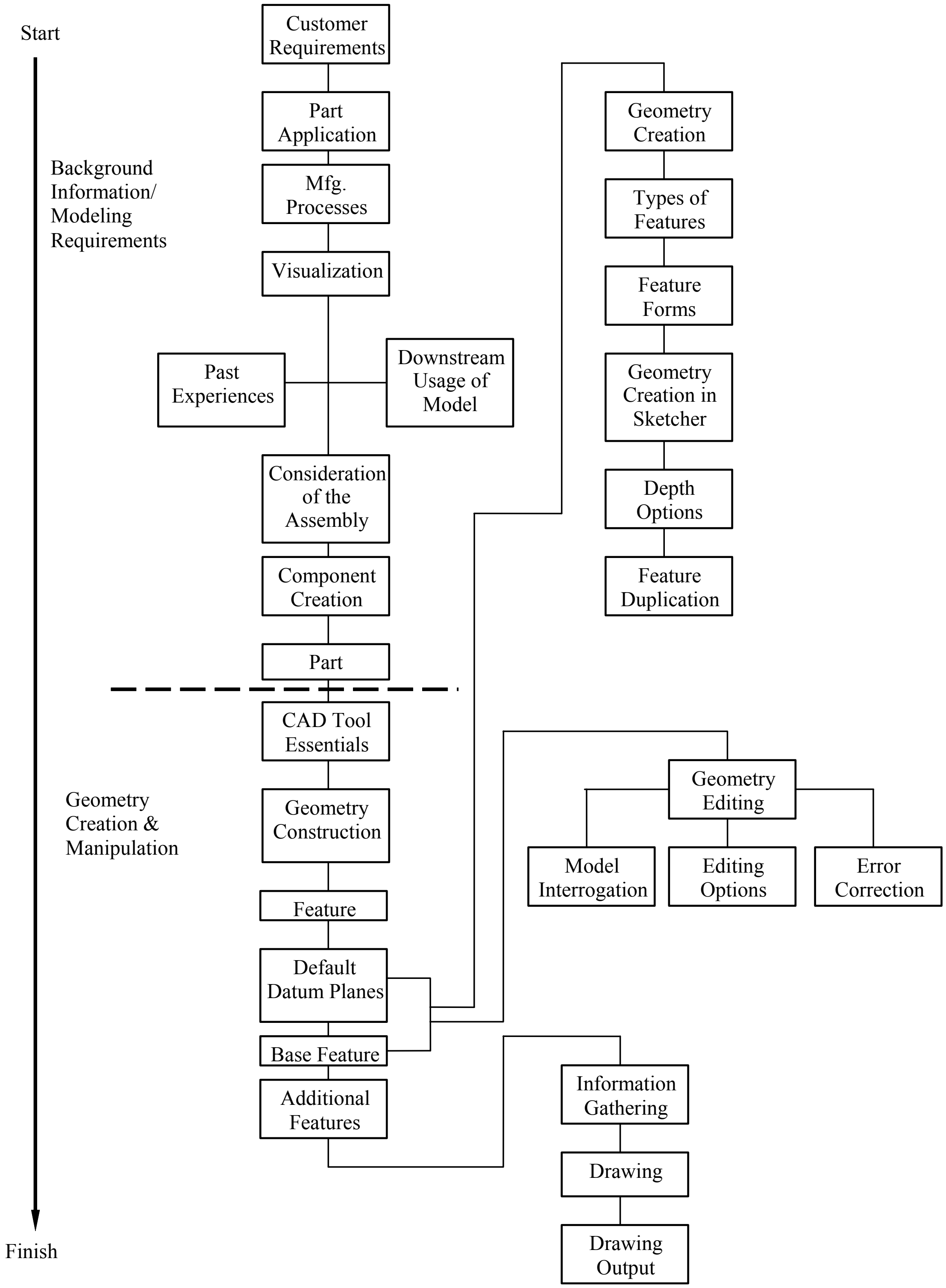


Figure 4.3: Graphical Representation of the Mental Model of the Use of Constraint-based CAD Tools for Participant 1

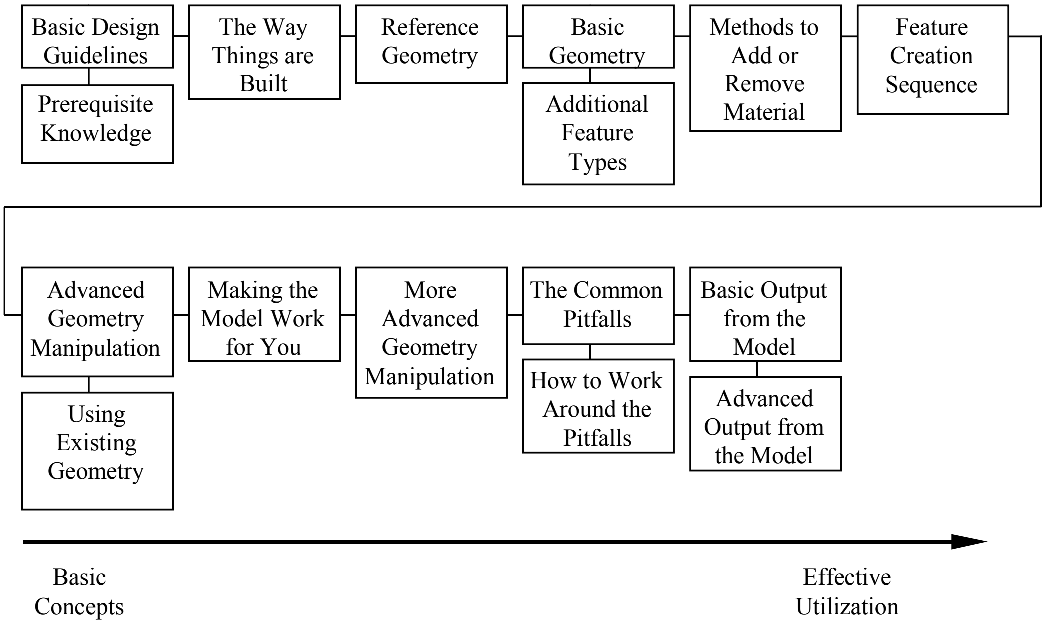


Figure 4.4: Graphical Representation of the Mental Model of the Use of Constraint-based CAD Tools for Participant 2

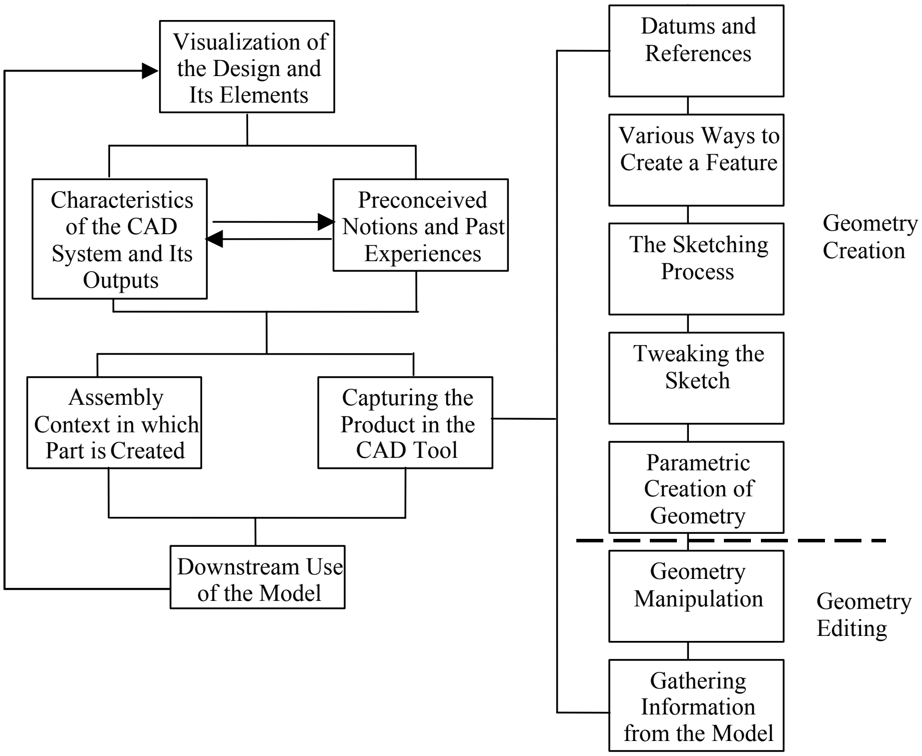


Figure 4.5: Graphical Representation of the Mental Model of the Use of Constraint-based CAD Tools for Participant 3

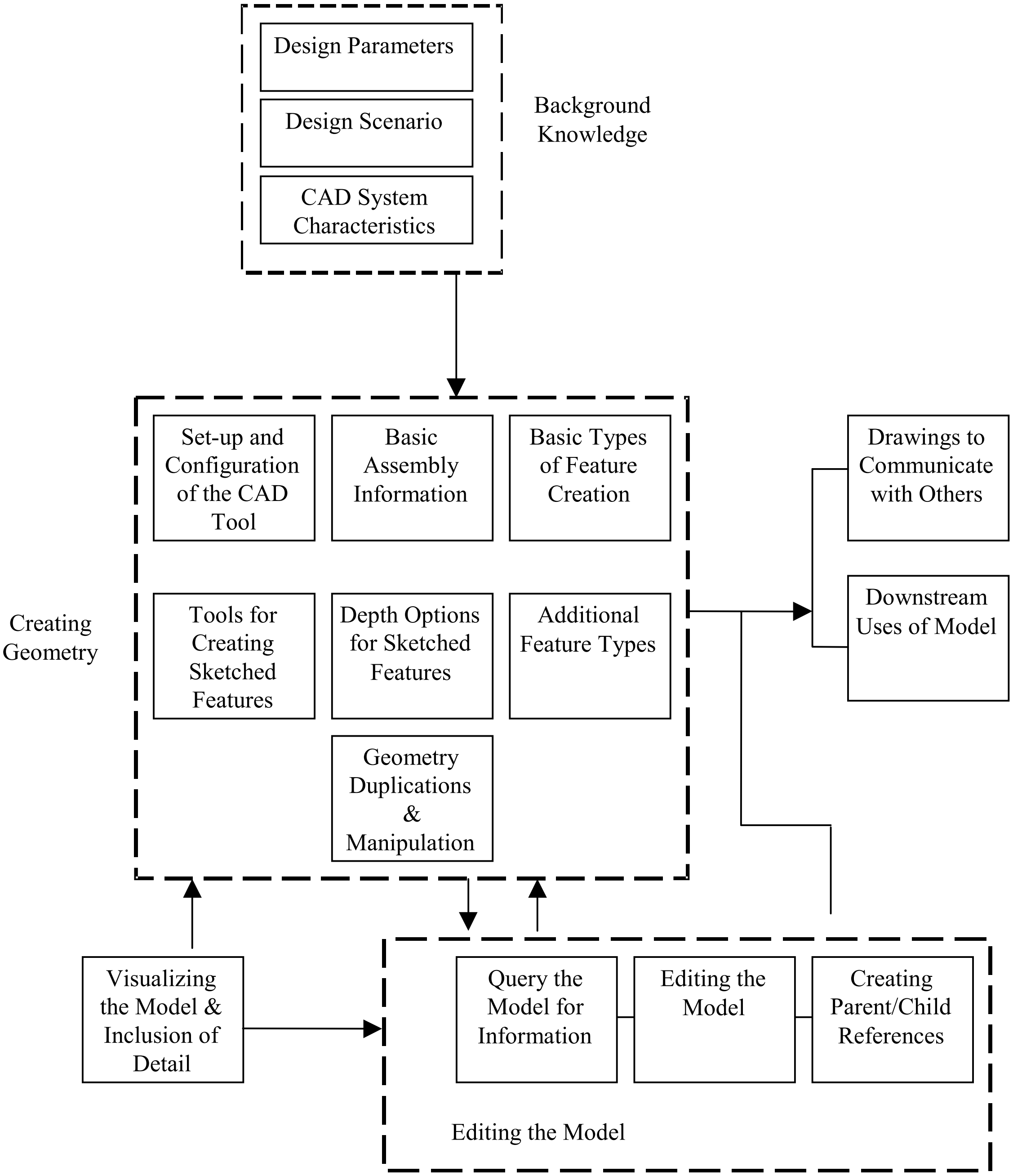


Figure 4.6: Graphical Representation of the Mental Model of the Use of Constraint-based CAD Tools for Participant 4

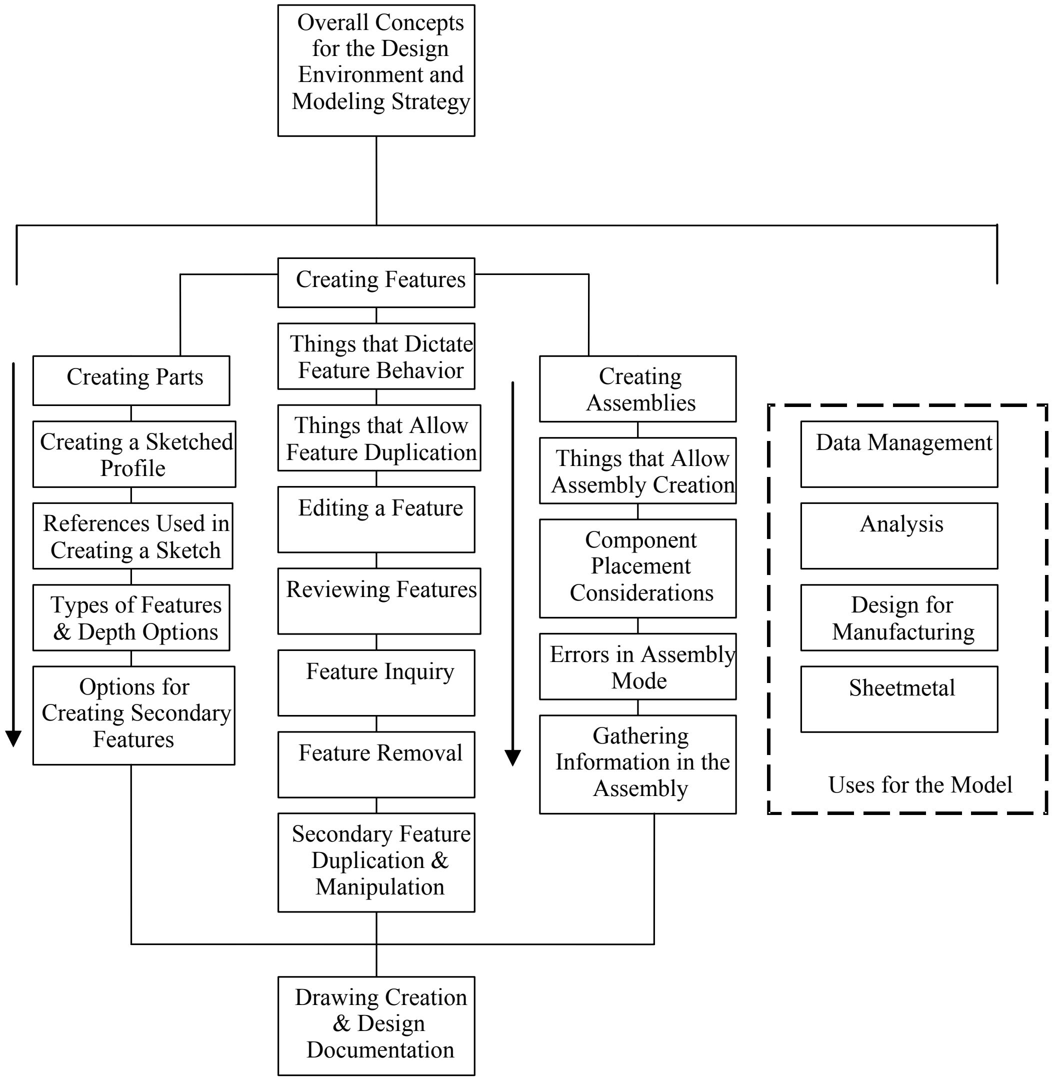


Figure 4.7: Graphical Representation of the Mental Model of the Use of Constraint-based CAD Tools for Participant 5

Description of Knowledge Map for Participant 1

When examining the knowledge map of Participant 1, it appears that it is divided into two large categories: background information coupled with modeling requirements and geometry creation and manipulation. Within each of these larger halves of the model are the groups into which he categorized the concepts and terms on the cards. The knowledge map also has a particular flow to it that is characteristic of the process that Participant 1 uses to create 3D models. In fact, during the follow-up session of the task, the researcher asked him to characterize the model, and his response centered on his procedure for modeling a part and all of the factors that he must consider while performing those operations. It should be noted that Participant 1 removed six cards from the task: modeling standards, primitive geometry, Boolean, origin, coordinate system, and Sheetmetal. It should also be noted that Participant 1 added six cards to the task: default datum planes, geometry creation, geometry editing, suppliers, objectives/part application, and material selection.

This knowledge map begins with his consideration of customer requirements and the application that the part is going into. Both of those factors often dictate what type of manufacturing process will be used to make the physical part, in addition to having some effect on the commands that Participant 1 uses in creating and editing geometry. The next step in the model is his visualization and conceptualization of the part in it environment, the finished geometry it will have, and possibly how it is made. Participant 1 must also visualize the component elements that define each feature and the potential manner in which they go together on the model.

As part of the processes of visualization and consideration of external factors, Participant 1 states that he subconsciously integrates his knowledge gained from past modeling experiences together with the potential downstream uses of the model to begin developing a solution to the design problem in the CAD tool. When beginning to create a part, Participant 1 then considers the assembly that the part will go into, including its interaction with adjacent parts. From there, he begins to define a part within the CAD system, as evidenced by these stages in his knowledge map. At this stage, Participant 1 moves from his consideration of background information and modeling requirements to the processes of creating geometry.

As Participant 1 determines how to create the first feature of the model, he considers the design intent to be captured in his model, and how this can be accomplished using the fundamental characteristics of the software: parametrics, dimension-driven design, and associativity. His knowledge map of the use of constraint-based CAD tools then moves to the various steps of geometry creation. He uses default geometry references and planes to begin he creation of his base feature. From there, he compares the visualization of his design and the requirements of the design intent to determine what type of feature he will create. In doing so, he knows that he can either add or remove material from the model. While the first solid feature in the model must add material, he knows that there are other types of features to be made eventually. Based on the type of feature to be created, he considers the form it will take. He elaborated on two particular feature types for this stage of his map: cuts and protrusions, which are the primary methods of adding and removing material from the model in Pro/ENGINEER. These features also involve the creation of a profile, which captures the requisite shape of the feature.

Participant 1 is next concerned with sketching the profile of his current feature. Selecting a sketching plane, creating the geometry of the profile, and applying constraints and dimensions to the geometry are all involved in this stage of the model. Upon completion of the profile, he moves to considerations of the depth options for the base feature. Each option can be evaluated in terms of its relevance to the current situation and the capture of design intent. In addition, certain depth options will establish particular parent/child reference between features that may or may not be beneficial at a later time. Another category that coincides with feature creation is feature duplication. While the process described previously is repeated throughout the creation of a model, duplicating geometry is a selective process. It only occurs when Participant 1 deems necessary based on his perception of the geometry within the part.

The adjacent stage in the model is one that Participant 1 labels as geometry editing. A user not only must create geometry within the CAD tool, but they must also edit it. In doing so, Participant 1 has categorized three additional groups into this section of his map: model interrogation, types of editing procedures, and potential errors that occur while editing the geometry. The nature of the engineering design environment is often one of cyclical change and revision, so it is likely that the CAD models will change from the way in which they were first created. Given the nature of the CAD tool, Participant 1 believes it to be critical to investigate the model prior to making changes so as not to disrupt any parent/child reference within the model. By using particular techniques to investigate the model prior to making changes, one can potentially avoid errors due to those changes.

The final stage of the model reflects the primary output of the process for Participant 1, which is a drawing. Drawings serve as a means to document the design as well as to communicate with other members of the design environment. Considering the terms in this category, Participant 1 not only communicates with coworkers locally, but also via file translation to other remote sites.

Description of Knowledge Map for Participant 2

When asked about the origination of this mental model, Participant 2 stated that he reflected on his current methods and techniques of use as if he were being asked to teach them to someone else. He examined his repertoire of skills and techniques and determined that much of his CAD usage is about being efficient. When comparing the columns and flow of the concepts in Figure 4.4, Participant 2 stated that these concepts are grouped as going from basic concepts to effective utilization of the tool. He sees it as the use of a tool within a given context to perform a specific function that allows him to address a particular problem.

When examining the terms that Participant 2 used in each group and category (see Appendix F), it is important to note that they are not listed next to each category in numerical order, but in decreasing order of importance going from left to right. It is also important to note that some columns have two groups or categories associated with them and the upper-most group is the one considered most important to Participant 2 in this case. He summarized this model as a linear thought process necessary to produce a 3D model that embodied his requirements at the time. Each column in the model provided input to the following column until the end was reached. Finally, Participant 2 excluded three cards from the list due to their irrelevance to his situation: primitive geometry, Boolean, and origin.

The model begins with what Participant 2 considers to be the basic guidelines of using the software and things that the user should know ahead of time, as well as a knowledge of how geometry is are created within the CAD tool. He characterized these things as the “core competencies” of using this tool. Basic guidelines for using the software include design intent, modeling standards, customer requirements, and downstream uses of the model. He spoke several times of "seeing the end of the process" in order to create the model right the first time. Participant 2 considers past experiences, a person's ability to visualize geometry, knowledge of drafting fundamentals, and a basic understanding of data management tools as part of that set of core competencies as well. The final portion of core competencies centers on how things are made within the CAD tool. Knowing that constraint-based CAD tools are used to create parts, which eventually become components of assemblies, is critical. Knowing that those parts are also used directly to make documentation drawings is also critical. Understanding these things then leads Participant 2 to begin the geometry creation process.

For Participant 2, geometry creation begins by having a firm understanding of reference geometry within the CAD tool, such as datum planes, axes, and coordinate systems and their relevance to creating geometry. They are often used to establish references within the CAD model from which to build subsequent features. From here, Participant 2 moves to an understanding of basic geometry creation in Pro/ENGINEER. Similar to Participant 1, Participant 2 considers the first feature of the model to be important, because it is here that the core competencies come to fruition. This first feature is the initial manifestation of all of the external design considerations as well as the user's basic understanding of the software and its processes. Participant 2 recognizes that one either adds or removes material from a model, so he listed the cut and protrusion features separate from the secondary feature types, such as rounds, drafts, and shells, due to what seems like their primacy within the CAD tool. Following this stage of his model was the ability to apply a form to the geometry based on the requisite shape that the user has visualized within the design. Participant 2 summarized many of the other choices that surround the process of adding and removing material from the model with his next category that contains the semantics of what happens before and after the actual addition or removal of material. He stated that the process of selecting a sketching plane and an orientation plane, dimensioning the profile, and choosing an appropriate depth option is fundamental to these basic geometry creation methods. He further summarized the first six columns of his knowledge map by stating that it is at this point that a user now has a basic knowledge of the software tool, which includes the core competencies mentioned previously.

The next stage of his knowledge map depicts the use of advanced functionality within the software to duplicate geometry that has already been created. Recall that this whole map moves along the continuum of basic concepts to increased efficiency, so it is at this point that Participant 2 begins to exhibit techniques that allow him to work faster and to maximize effort. In this case, it involves using existing geometry as references while sketching additional features, and using various duplication functions to capture design intent and corresponding model behavior. The next stage of is model involves making the model work for him. Understanding that the model is dimension-driven, parametric, and associative allows Participant 2 to manipulate the model a higher level to make it perform according to his design requirements. He mentioned that the ability to effectively use the duplication and editing tools, as well as manipulate model geometry according to the core processes of the software, lead to what he would call “efficiency” in the use of the CAD tool.

The next stage of his knowledge map moves into what he calls “effective utilization” of the software. He included as categories in this stage the functions that deal with more advanced levels of geometry editing, recognizing and correcting errors that occur during the modification process, and advanced outputs of the software.

More advanced geometry editing and manipulation includes a fundamental understanding of constraints and geometric relations, and knowledge of how to edit them. This appeared to be important when Participant 2 discussed using the Redefine, Reroute, and Modify commands to change the relationships between features to capture changes in design intent during the design process. Knowledge of these functions is critical, according to Participant 2, in recognizing and overcoming errors within the editing process. Using the model interrogation functions to gather information about the model and its inherent relationships is critical to performing effective design changes, due to the complexities of parent/child references within the model. Participant 2 also denoted in his map the ability to recognize when a model or feature is over-defined or under-defined within the context of the software. Participant 2 sees this as important not just for accurate models, but also to avoid expending effort unnecessarily.

The final stage of the knowledge map for Participant 2 focuses on the uses for the CAD model when it is complete. In many cases for Participant 2, this is the creation of a drawing, but there are also other things that can be gleaned from accurate geometry. One can measure various aspects of the geometry to use those values elsewhere, as well as the generation of mass properties to be used as inputs in other facets of the design process. In addition, accurate models also allow Participant 2 to use them as input for his analysis duties, which include structural and thermal verification of parts.

Description of Knowledge Map for Participant 3

The knowledge map of the use of constraint-based CAD tools appears to be shaped like a funnel, taking design visualization at its broadest sense coupled with fundamental knowledge of the design environment and its tools to produce a model that is useable for other things. Participant 3 described his knowledge map in a very conceptual way, as opposed to the procedural nature of Participants 1 and 2. While procedural information does exist in grouping that deals with product creation, this map is much more concerned with global details of the design process and how the CAD tools fits than it is about procedural usage. It should be noted that Participant 3 did not add or remove any cards while completing his model. He was able to incorporate into his model the cards that had been removed by the previous participants. In addition, Participant 3 did not place any significance on the order of the cards within each group. He only placed significance on the groups themselves and the relationships between them on a larger scale.

Participant 3 began his knowledge map by placing the concept of visualization at the top in what appeared to be an umbrella-like fashion. He considered it paramount to everything that he does as a designer. It allows him to operate the CAD system effectively, and it allows him to comprehend customer design specifications and create new and interesting solutions to current problems. It also allows him to create product offerings that are new to the market and patent-worthy. Visualization also acts as an intermediate stage, which allows Participant 3 to integrate the interrelated factors that comprise the next level of groups in his map: the characteristics of the CAD tool and his past experiences with factors inside and outside the CAD environment.

For Participant 3, the group that describes the characteristics of the CAD tool includes concepts such as parametric, feature-based, dimension-driven, and associativity. These are the core operating principles of constraint-based CAD tools. They control how geometry is created and edited, as well as how design intent is embedded into the model and the ease with which that is done. These factors coexist with the past experiences and preconceived notions of Participant 3 to dictate much of his behavior while using the CAD tool. His past experiences of success and failure influence the command choices that he makes and the combinations of commands that he uses. His knowledge of customer requirements and the manufacturing processes to be used dictate the kinds of geometry he creates and the manner in which he creates it, often times based on his anticipation of future changes. Participant 3 adheres to standards when he models; those that are particular to his company, and those that are particular to the industry of blow-molded plastics. In addition, his extensive use in the past of traditional drafting tools and techniques influences his choices for geometry creation and the way that he progresses through his modeling process.

In his knowledge map, participant 3 placed the previous groups of concepts in equal standing due to their interrelated nature. Each one affects the other at the level of decisions that happen, the information that gets passed on, and the nature of his modeling process. It is this last item, the nature of the modeling process, which represents the next level of his knowledge map. It includes the context of the assembly in which the part will be placed and the part creation process itself. The assembly context includes reference geometry such as skeletons and simplified part representations that allow Participant 3 to plan his part design in terms of the spatial envelope that it will occupy within the larger product. This spatial envelope is important given that it controls the interaction between a mating part in the physical world, but it also heavily influences the command choices Participant 3 will use to the constrain a particular part in three-dimensional space. Attention to the context of the assembly is critical, because, according to Participant 3, one would not know where to begin designing a part. He commented during this portion of the knowledge-mapping task that most companies do not make single piece-parts as a finished product, so understanding the context of the assembly is important to using the CAD tool.

On equal footing with the context of the assembly in the knowledge map of Participant 3 is the actual part creation process. As seen in Figure 4.5, the act of capturing the product information in the CAD tool is comprised of seven sub-groups. This stage of his knowledge map combines those seven sub-groups into two larger headings: geometry creation and geometry refinement and editing. While the majority of the knowledge map for Participant 3 is conceptual in nature, this section does take on a somewhat procedural tone.

The first sub-group in this stage of the map deals with reference entities. It consists of concepts such as datum planes, datum curves, and datum axes, which aid Participant 3 in the geometry creation process. In addition, the selection of the sketching and orientation planes is also in this category, which is a necessary step in the creation of a sketched feature in Pro/ENGINEER. Participant 3 also includes in this category sketching references that can be added to accommodate particular dimensioning and referencing schemes.

The next sub-group for Participant 3 consists of the various ways to create a feature. While the concepts that were provided for this task are not an exhaustive list of the possible ways to create geometry in the CAD tool, Participant 3 included in this section the two primary methods for him: creating a cut and protrusion and the various feature forms used with them. The other participants, in terms of basic geometry creation, made a similar distinction – those features that either add or remove material from the model. Given that both of the aforementioned features require a sketched profile, the next group created by Participant 3 dealt with the sketching process to create geometry. These concepts embodied his knowledge of the ways to create geometry within the Sketcher module of Pro/ENGINEER while simultaneously capturing the critical dimensions and design intent necessary for the creation of the model. This category also included the various depth options that could be applied to a feature once a particular feature form had been specified.

The next sub-group created by Participant 3 in his knowledge map dealt with what he called “tweaking the model.” This group included concepts that are often used in the finishing stages of a model, such as rounds, draft, and the shell command. His last sub-group for the geometry creation portion of this stage of his knowledge map included concepts that were based on the parametric nature of the CAD tool and the ability to create additional geometry quickly and easily. They involve the exact duplication of geometry based on the inherent geometric relations and dimensioning schemes in each feature.

The fourth stage of Participant 3’s knowledge map also included geometry duplication. These concepts required a firm understanding of parent/child references and the previously discussed methods of geometry creation in order to use them effectively, for example the creation of a pattern or a group, or the use of the mirror and copy functions. All of these would create additional geometry very quickly, but they typically create additional parent/child references as well. In addition to creating duplicate geometry, Participant 3 also included concepts in this group related to editing the model to reflect changes in design intent. Critical to this mission were the abilities to redefine the profile and other attributes of a feature, and to be able to gauge the impact of that change on the rest of the model and to deal with any errors that may arise as a result of the editing process. Concepts such as the interrogation of the model to examine the inherent parent/child references, the examination of the feature order, and the techniques used to review past changes in the model to overcome any errors were included in this sub-group.

The next level of the knowledge map details the context of the assembly and how crucial that is to the creation of the part model, as well as the procedural description of the concepts included in creating a 3D model. The final stage of the knowledge map for Participant 3 represents what he considers not only the culmination point of the first iteration of the design process, but also the first point of feedback into the visualization process that started the whole thing in the first place. While designing with the end in mind, the last stage of his knowledge map included the documentation and analysis processes that are contingent upon the accurate creation of a flexible 3D model. This includes such concepts as the creation of a drawing and the export of 3D data to other software tools and to other members of the design team.

Description of Knowledge Map for Participant 4

Similar to the other participants in this study, Participant 4 seemed to organize his knowledge map into large sections with smaller groups in each one. Three groups embodied the background knowledge that he said was critical for understanding the context and the use of these tools: design parameters, design scenario requirements, and different characteristics of the CAD tools. The next big section of Participant 4's map was geometry creation and the various aspects thereof. The groups in this section focused not only on part geometry creation, but they also focused on design visualization and the context of the assembly. The third large section of the model dealt with geometry editing, particularly with regard to gathering information from the model and editing techniques to be used to manage relationships within the model. All of these sections then lead to the final stage of using the model for other things within the design process, including the creation of drawings and the use of analysis tools. Participant 4 characterized his conceptual model as "combining background knowledge of engineering design to create and edit geometry that can be used later." In creating his knowledge map, Participant 4 removed five cards: surface geometry, Boolean, primitive geometry, PDM, and Sheetmetal. However, he did add one card dealing with feature creation: chamfer.

The first large group within the knowledge map of Participant 4 was related to background knowledge and basic knowledge of the CAD tools. The first subgroup here was design parameters. Participant 4 asks the internal question "What is the part used for?" He uses his past experiences with regard to this type of part and the current customer requirements to help him target a potential solution. The combination of these two factors contributes to his determination for the design intent for the part. His ability to recognize the inherent characteristics of the design contributes to his determination of feature order as well as his implementation of corporate design standards. Participant 4 also uses his knowledge of the spatial envelope of the design to couch his considerations of the design scenario requirements. These design scenario requirements included sharing of data between coworkers and outside groups as well as consideration of the manufacturing processes involved in producing this part. Particularly in the case of Participant 4, sharing of CAD data between himself and the tooling group was one of his primary considerations for how he would create geometry.

In addition to all of the aforementioned factors that account for potential changes in his design intent, Participant 4 also included in this section of his knowledge map the fundamental processes of the software. Keeping these in the back of his mind while he works influences his choices for feature creation, the establishment of references, and the choices he makes for editing his models. He included concepts such as dimension-driven and parametric in this group, because he said they were "at the very heart of the software." The CAD tool uses features as the building blocks of the mode, and they are modified by their inherent dimensions and geometric relations. To Participant 4, not understanding these concepts leaves the user in a very precarious position in terms of the decisions they make using the CAD tool. By combining the fundamental knowledge of the core software processes with an understanding of the design intent, the scope of the problem, and the intended use of the model, Participant 4 was able to define his background knowledge of the problem.

The next portion of his knowledge map dealt with geometry creation and the various aspects of it. Participant 4 actually began this portion of his knowledge map with a group that included concepts related to a basic understanding of the assembly environment and the basic references that could be used to build geometry. It centered on the idea that parts were actually components within a larger context: the assembly model. In working with parts at this level, they were in either one of two states: completely defined or under-defined. While the goal in the assembly is to have components that are fully defined, it is possible that during product creation, a part would be left under-defined. However, Participant 4 considered it important to recognize this situation and provide the necessary information to fully define the part as soon as it was feasible. In order to create a functional part, Participant 4 also included concepts in this group with respect to datum geometry particularly default datum planes. He viewed them as directly related to successful geometry creation.

The next group in this section of his knowledge map included concepts related to the basic types of feature creation. Similar to the other participants, Participant 4 developed this portion of his knowledge map in terms of the two basic ways to add or remove material from the mode: a cut or protrusion. He also included the concepts of feature forms that could be applied to the profile to obtain 3D geometry. These concepts appeared to provide the input for the next group of the map that included concepts related to the basic functions that were used to create sketched geometry. Included in this group was the concept of the sketch profile itself, which is central to the creation of most kinds of geometry in constraint-based CAD tools. In addition, the manner in which the sketch is created is strongly influenced by the anticipated feature type and form according to Participant 4. Also included in this group were the concepts of the sketching plane and the orientation references, which are elementary in the use of Pro/ENGINEER as a CAD tool. Without knowledge of these two concepts, Participant 4 commented that a user “would not get very far.” Finally, the concepts of geometric construction and constraints were included as the primary means of geometry creation Sketcher. The elements from these last three groups form the input for the concepts in the last section of the geometry creation portion of Participant 4’s knowledge map. This next group dealt with the various depth options applied to a feature to finalize its creation. The feature form is based on the inherent recognition by the user of the requisite geometry for each feature, and it serves as the culmination point of the creation process for sketched features.

The next group in the geometry creation portion of the model was comprised of concepts related to additional methods of geometry creation. The first five groups of this portion of the knowledge depict the sequential process of creating a sketched feature, but Participant 4 implied that this group was different. These were features that were typically added near the end of a model and they were children of the earlier features in the model. They were defined simply by picking references and the software created a pre-defined feature form. Feature types such as rounds, chamfers, and shell were included within this category. The last group included in the geometry creation section of the knowledge map for this participant was one that focused on geometry duplication and manipulation. It included such software functionality as patterns, mirroring, copying and grouping. It appeared that these were the driven by the dimensions and references that were established during the initial geometry creation stages, as well as an opportunistic exploitation of the fundamental processes of the software, including the dependent nature of certain parent/child reference conditions and the condition of associativity.

The next large section of the model included three groups that dealt with editing geometry. Participant 4, just like all of the other participants, worked in an environment where some aspects of the design seem to change on a daily basis. To accommodate those changes effectively, Participant 4 stressed the relationships between geometry creation and geometry editing through the ability to query the model for information, the actual editing commands in the software, and a fundamental understanding of the many ways in which parent/child references are created.

Interrogation of the model involved the concepts, specific to Pro/ENGINEER, that allowed Participant 4 to examine the relationships that existed in his model as well as the engineering data that resided there. Examining the regeneration order of the model, the parent/child references, and the assembly references were the concepts included with respect to references, while the ability to measure distances, mass properties, and the interference between parts in the assembly were included as examples of engineering data obtained from the model. The ability to find these various pieces of information and to use these various functions allowed Participant 4 to adapt to changing design intent and customer requirements. To respond to those changing factors, Participant 4 included in this group of his knowledge map the concepts surrounding the modification of the model either while it was being created or once it had been created and was now being modified. These concepts included the ability to modify, delete, and redefine features in the model, as well as a working knowledge of how to address errors in the geometry editing process. Participant 4 implied that while errors in the editing process did not occur every time he modified geometry, he said they were fairly frequent, and that “they were just a fact of life” when using these types of CAD tools. It should also be noted the position of visualization in the knowledge map of Participant 4. He included it in such a fashion to contribute both to the groups that dealt with geometry creation and geometry editing. In his opinion, it affected the level of detail that a person would use in creating a model as defined by the situational requirements and their ability to adequately foresee the impacts of some of their changes to a model.

In moving to the final portion of the knowledge map for Participant 4, it appeared that it was a culmination point of sorts. These participants use these CAD tools to make a model, which is not necessarily the end result of the engineering design process. While the major portions of his knowledge map contain conceptual elements of the “bigger picture”, it is still somewhat procedural in nature, similar to the other participants. For Participant 4, the effective creation and manipulation of geometry seemed to be based on the combination of fundamental knowledge of the core software processes, previous experiences, and a scope of the design problem at hand. The solution to that problem appeared to imply further uses of the CAD model, including the creation of drawings and other downstream engineering processes. By creating a model to include all of the critical dimensions and geometric constraint information necessary for the creation of the physical part, Participant 4 implied that this was critical to creating a usable detail drawing and to producing accurate tooling from the model.

Description of Knowledge Map for Participant 5

The knowledge map for Participant 5 can be characterized as a set of overall concepts that affect the modeling strategies he uses to arrive at the finished output of his process, which is a drawing. In an ancillary fashion, this process is also affected by other factors that impact creation of the model, including manufacturing, data management, and analysis. It appears that his overall approach to this exercise was to determine all of the things that he could do with the CAD system and to break those categories down into their constituent elements. The main body of his knowledge map is comprised of the things that he can do with the CAD tool: create features, parts, and assemblies and their eventual translation into a drawing to document the design. The portions of the map that relate to the creation of parts and assemblies are sequential in nature from top to bottom, while the portion relating to features has its own inherent relationships between the groups.

Participant 5 implied that the relationships pertaining to the creation of a feature was not necessarily hierarchical or sequential, but simply just related; “things that you can do to features." While Participant 5 primarily classified concepts related to features in terms of their creation in a part, he also implied that features could also be created and manipulated within the context of the assembly as well, hence the location of features between parts and assemblies in Figure 4.7. It should be noted that while Participant 5 did not add any cards to the original list, he did remove four concepts: surface geometry, skeleton models, Boolean, and primitive geometry.

The group in the knowledge map that contained overall concepts about the environment appeared to have two different types of concepts in it: those that were directly related to the CAD system and those that were not. It included the fundamental core processes of the CAD tool, such as dimension-driven, parametrics, and associativity, and it also included things determined by the engineering environment, such as design intent, modeling standards, and past experiences. He also included drafting experience and model interrogation in this group. When Participant 5 explained this arrangement, he commented that his understanding of the core processes of the software, and how they impact the creation and manipulation of the model geometry, interacted with his past experiences of success and failure in using the tool. This allowed him to capture the design intent in the model to accurately reflect the given design scenario. He stated that he also included model interrogation in this group because he often gathers information in the model to help determine the design intent of the situation, particularly if he is using model created by another person. These are the concepts that Participant 5 saw as impacting all that he did in using the tool.

As mentioned previously, the main body of the knowledge map for Participant 5 consisted of the concepts related to the creation of features, parts, and assemblies, with the concepts of feature creation also relevant not just in the part, but in the assembly as well. In the portion of the model related to part creation, Participant 5 included concepts related to creating a sketched profile, references used in creating a sketch, types of feature and depth options, specifying dimensional information for feature creation, and particular concepts related t the creation of secondary features. This particular portion of the knowledge map Participant 5 implied as being sequential in nature. Participant 5 first started with the concept necessary for initiating a sketched feature, such as the selection of a sketching plane and orientation reference and their importance on the finished geometry. In addition, he also specified that sketching references had a direct relationship on the creation of parent/child references and should be given some thought during the planning stages of model creation. Participant 5 also included concepts in this portion of the knowledge map related to the selection of datum planes and axes as sketching references and the importance of geometry construction in sketcher for capturing geometric relationships. Dimensioning and the concept of associativity were included in the process of sketching the feature as well. The next group in his feature creation section focused on concepts related to using cuts and boss features to add or remove material from the model. It also included various depth options available during feature creation. Participant 5 implied that these concepts embodied the final stage of feature creation. The last group in this portion of the model included concepts directly tied to the creation of secondary features once the base feature was finished, such as revolved, swept, and lofted geometry, as well as rounds, draft, and shells.

In the portion of his knowledge map that dealt specifically with feature creation, Participant 5 commented that feature order and geometric relationships directly affected the behavior of the features in a model. While he implied that this effect was unavoidable, he commented that the extent of this could be minimized through careful planning and consideration of the design intent of the problem. As mentioned previously, Participant 5 considered the creation and manipulation of features to exist at both the part and assembly levels of the design. As such, his next several groups in the feature creation portion of his map included concepts that were relevant to features at both levels. Participant 5 implied that features could be duplicated in a part as well as an assembly with such techniques as copy, mirror, pattern, and group. He also implied that editing a feature with the redefine or modify function could also happen in a part or an assembly. He emphasized this process in the assembly given the presence of all of the spatial information that would likely affect the reasons and outcomes for the changes. Participant 5 also included the ability to review and remove features within the part and assembly as well, using such concepts as delete, measure, and the feature tree. Participant 5 implied that these commands allow the user to determine the extent of their changes prior to making them, thereby reducing the potential for error within the model when changes are made.

The third portion of Participant 5's knowledge map includes the concepts related to creation of assembly models. According to his knowledge map, assembly creation begins by inserting a component. When placing a component in an assembly, Participant 5 includes the consideration of such concepts as parent/child references and the ability to interrogate these relationships. In addition, when creating assemblies, due consideration must be given to the interaction between mating parts in the establishment of assembly references. In the case of Participant 5, these assembly references are the specific Mates that he applies in SolidWorks to the surfaces and axes of the parts in the assembly. When creating the assembly, these Mates must be applied to position the component in space. The other concepts in this category dealt with this process and when it goes awry, such as the implications of components not being fully constrained in space and the user's ability to recognize this condition. In recognizing this condition, Participant 5 implied that the concepts of suppressing components, rebuilding the model, and rolling back the feature tree were essential.

All of the sections in the main body of Participant 5's knowledge map dealt with creating geometry in the model while the final section at the bottom dealt with the creation of the drawing. According to Participant 5, this documentation was the culmination of his design process. It also allowed him to communicate his design to others, but he did mention that, as opposed to viewing the model on screen, it did require some amount of visualization ability on the part of the viewer.

The ancillary portion of his knowledge map consisted of all of those concepts that Participant 5 felt were related to the use of constraint-based CAD tools, but that he did not feel were directly related to geometry creation. The concepts included here focused on downstream uses of the model, such as manufacturing processes, analysis, and data management. Participant 5 implied that while these might affect his usage of certain commands, they would not have a significant impact.

SUMMARY

The findings presented in this chapter are based on the data collected from five participants employed as practicing professionals in the engineering design domain. It was assumed that each of them had the requisite expert characteristics to provide meaningful data for this study. A mixture of methods was used to elicit knowledge from these experts in regard to their use of constraint-based CAD tools. Observations, interviews, a knowledge-mapping task, and a think-aloud modeling task were used to examine the development and definition of expertise in the use of constraint-based CAD tools.

The analysis of the observation data yielded fifteen constituent themes related to the development of expertise and the interrelationship between them. The data from the interviews with each participant further expanded on several of the previous fifteen themes, particularly in regard to past experiences that have aided in developing expertise and the participants' conceptions of expertise in general and as it relates to CAD tool usage. One of the elements that emerged from the developmental nature was the use of a particular problem solving or modeling strategy. The think-aloud modeling task examined the modeling procedure of each participant as it related to the creation of a 3D model within a contrived setting. This process exposed the major steps that each participant went through to create the model. Finally, each participant re-created the format of their mental model regarding the use of the CAD tools by performing a knowledge-mapping task. This process yielded the basic structure of their mental models as well as provided the information for the creation of a generic model for all of the participants.

CHAPTER 5: SUMMARY, DISCUSSION, AND RECOMMENDATIONS

This chapter contains summaries of the sections related to the research process used to study the development and definition of expertise in the use of constraint-based CAD tools. It begins with a review of the purpose and significance of this study and a restatement of the research questions, as well as summary of the methodology used to examine this phenomenon. A brief overview of the main areas of literature that supported this study is also given. This chapter also includes a summary of the research findings followed by discussion of those findings and recommendations for further research in this area.

INTRODUCTION

The call for the integration of constraint-based CAD tools into engineering graphics curricula has been made (Miller, 1999; Ault, 1999; Branoff et al., 2002), but there is no clear decision in regard to how to proceed. Many people within the academic setting consider constraint-based CAD as simply another tool with which to document the design process. While that is true to some degree, there is much more to it than that. Constraint-based CAD tools are complex pieces of CAD software that have a myriad of options within them (Bertoline & Wiebe, 2002; Greco, 2000 & 2001) for capturing the knowledge and insight of the individual or collective engineering group.

However, with all of the different options for creating geometry and using the CAD model afterwards, much of that knowledge becomes “proceduralized” and trapped within the context of professional performance. With all of the variation in possible techniques and solutions to problems, no consensus has been reached in terms of how these tools should be used, let alone how they should be taught. Understanding what expert users of these CAD tools know and how they develop that knowledge is instrumental in the development of next-generation engineering graphics curricula. Given the amount of money spent and the time invested in the training of engineers and designers to use these CAD tools, the understanding of these expert characteristics for the development of effective curricula is imperative. In order to uncover the inherent knowledge base behind the use of these tools, and the techniques and strategies associated with using them, an examination of professional expert usage was conducted in this research study to examine how these individuals experience expertise within this domain, as well as how they conceptualize it.

PURPOSE STATEMENT

The purpose of this exploratory research study was to explore the phenomenon of expertise in the use of constraint-based CAD tools by examining practicing professionals. In doing so, an initial description of the factors and experiences that contribute to the definition and development of expertise in this area was obtained. At this stage in the research, the social and cognitive theories of expertise in various disciplines, the knowledge of professions, and CAD tool information were used as a background for the development of expertise in the use of these tools. Using interviews, observations and cognitive knowledge elicitation methods, this research sought to examine the definition and development of expertise as determined by practicing professionals through their experiences and practical uses of the CAD tools.

CENTRAL RESEARCH QUESTION

How does one develop expertise in the use of constraint based CAD tools?

Subquestions

1. What are the critical concepts that comprise the mental model and the software techniques of expert, constraint-based CAD users?
2. How do professional and social factors and experiences within authentic design activities impact the development of expertise in the use of constraint-based CAD tools?

RELEVANT LITERATURE

To address the questions regarding the development and definition of expertise in the use of constraint-based CAD tools, a literature review was undertaken to examine the many facets of expertise, including perspectives from cognitive psychology, sociology, and technology. There are three kinds of observable things that can be defined in terms of practical performances: materials, tools, and processes. All of these are specific to a particular framework or context in which they are useful, and pure knowledge that lacks this framework cannot understand the impact that these things have on technology. Instruments and their associated entities cannot be removed from technical knowledge

(Polanyi, 1962). A knowledge domain can only survive if it is a coherent system of superior knowledge, which is upheld by people that recognize each other as practitioners within that domain. This framework is upheld by using the modern aspects of the knowledge domain as a guide. The superior knowledge will be held to be true by all of those people who are acknowledged by members of the domain as belonging to the domain. In addition, only small parts of the culture are available to the participants, and the rest is tacit in the forms of cultural norms, traditions, and customs that are not questioned, but merely accepted. The superior knowledge is a sum total of all of the classics of the domain and those that came before (Polanyi, 1962). This last statement alludes to the notion that some parts of knowledge are socially constructed (Cambrosio & Keating, 1995). A community-centered approach to technological knowledge focuses on longstanding traditions of practice that are evident in well-defined communities of technological practitioners. These communities are comprised of either individual followers of the particular tradition or of organizations. Specific commercial and industrial products are created and developed by collections of engineers and other specialists who, when taken together, define an identifiable community of practitioners. The extension, articulation, and incremental development of the particular tradition define the normal activities of this group (Constant, 1987). It is through this social construction of technological knowledge that certain portions of expertise within a knowledge domain are developed (Mieg, 2001).

The cognitive examination of expertise focused mainly on information processing, which examines the means by which humans process sensory information and encode it for storage into long-term memory. This affects their problem solving strategies, as well as their mental model of how a knowledge base is defined and implemented. Technology and science both involve processes as well as products. Technological growth is no longer just a linear accumulation of artifacts. Both scientific facts and technological artifacts are to be understood as social constructs (Woolgar, 1987).

Developing expertise is an ongoing process of the acquisition and refinement of skills and knowledge that are needed within a particular domain of life. From the standpoint of using a particular tool, this is often done within collaborative work settings or communities of practice (Wenger, 2000). In this case, it is the application and use of a particular design tool. In order to assess expertise, one must understand how it develops. Much research has been done in the way of analyzing expertise and its various properties (Ericsson & Smith, 1991; Chi, Glaser, & Farr, 1988; Feltovich, Ford, & Hoffman, 1997). Experts tend to excel within particular knowledge areas, and they perceive large and meaningful patterns to their domain knowledge. Experts also tend to solve problems quickly with fewer errors, and they have superior long- and short-term memory skills. Development of an extensive problem scope, the ability to see that problem at a deeper level, and the ability to monitor their path towards a solution are also characteristics of experts within a given field (Glaser & Chi, 1988). Expertise is also viewed not just as an attribute of a particular person, but also by the way a person is perceived by other people within their professional setting (Mieg, 2001). In this case, expertise is a labeling function applied to a person or group by another person or group.

All of the perspectives from which expertise was examined address the notion of practical intelligence and the fact that, in most cases, expertise is gauged within the specific context of a particular domain. Practical intelligence is also linked to the strategic use of tools, and constraint-based CAD is no exception. Several studies (Bhavnani, 1996, 1997, 1998, 1999) have examined the use of CAD from a 2D, architectural perspective, but the study of constraint-based CAD is lacking in this area. Thus, this study was an initial attempt at addressing some of these issues. To address the definition and development of expertise in the use of constraint-based CAD, this study used several methods taken from a variety of disciplines. While this may seem frivolous, the nature of research regarding expertise and its assessment is eclectic to say the least (Sternberg et al., 2000). Interviews and observations, based on the phenomenological tradition of qualitative inquiry (Moustakas, 1994; Creswell; 1998; Giorgi, 1985), were used to examine the development of expertise. Think-aloud protocols (Ericsson & Simon, 1993; Sternberg et al., 2000; Bainbridge & Sanderson, 1995) and knowledge mapping tasks (Jonassen, 1993; Olson & Biolsi, 1991), taken from the cognitive psychology domain were used to explore the characteristics that comprise the definition of expertise within this field.

PROCEDURES

Due to the fact that a localized concentration of experts within a domain is rarely if ever found, this research study used a smaller sample size than those used in experimental research designs. Experts were selected using a variety of criteria including their time in a particular job and their status as a practicing professional (Hoffman, Shadbolt, Burton, & Klein, 1995). In fact, Polkinghorne (1989) and Meyer and Booker (1991) recommended the analysis of between five and twenty participants for an exploratory phenomenological study. Potential companies to draw participants from were identified by the researcher based on suggestions made by the Engineering Design Graphics Division of the American Society for Engineering Education and by RAND Worldwide, a leading engineering consulting company. Contact was made with human resources and engineering management personal in order to have them nominate people within their respective companies as potential participants for the study. As a result, five experts were selected based on their experiences and their status as practicing professionals, years of experience in the engineering design field, years of experience using the CAD tool, and educational background.

The observations were conducted within the participants' places of employment to provide a naturalistic setting in which to observe the phenomenon (Creswell, 1998). The field notes for each participant were analyzed to look for common elements that signify their place within the social structure of the group and how their expertise is developed and used. Using the phenomenological research tradition as a guide, emphasis was placed on looking for the meanings of these experiences and how they relate to expertise development in the use of constraint-based CAD tools.

Interviews were also conducted with each participant that centered on the experiences in their academic and professional careers that have brought them to this point. Particular emphasis was placed on experience related to technological tools and processes. The focus of the interview analysis was the examination of experiences with the phenomenon of expertise and what that meant to each of the participants (Creswell, 1998; Moustakas, 1994). The researcher also discussed expertise in terms of his experiences as a means to bracket the information and guard it from any undue bias. Finally, a rich description of the development of expertise was made in terms of the descriptions given by the researcher, the participants, and the literature.

The think-aloud protocol was used as a means to examine the problem-solving process employed by the participants in the creation of constraint-based CAD models. In doing so, the researcher attempted to uncover the relationship between the expert's mental model and the actions they actually perform. A form of protocol analysis (McGraw & Harbison-Briggs, 1989) called a think-aloud protocol was used to analyze the transcripts for each problem solving session to determine common language and methods used in the process. The goal of this analysis was to examine the modeling procedures used by the expert participants to create geometry within the CAD tool.

Finally, the knowledge mapping tasks were conducted with each participant in an effort to create a view of their mental model with respect to the domain of constraint-based CAD. This was accomplished by labeling a series of cards with common terms and phrases, taken from constraint-based CAD literature, the experience of the researcher, and the observations of each participant, and asking each participant to arrange them based on their perception of the importance of and relationships between the concepts. The goal of this analysis was to determine the relationships and structure of the critical concepts within the higher-level knowledge domain surrounding constraint-based CAD tools (McGraw & Harbison-Briggs, 1989; Olson & Biolsi, 1991). A graphical representation of each participant's arrangement was created to form a knowledge map, which was compared and combined with those from the other participants to attempt to create a common mental model of constraint-based CAD.

ANALYSIS

The findings presented in this chapter are based on the data collected from five participants employed as practicing professionals in the engineering design domain. It was assumed that each of them had the requisite expert characteristics to provide meaningful data for this study. Observations, interviews, a knowledge-mapping task, and a think-aloud modeling task were used to examine the development and definition of expertise in the use of constraint-based CAD tools.

The observations and interviews yielded information relevant to the development of expertise that could be categorized into constituent themes of the phenomenon. Some of these themes are embodied in the results of actions that experts take, while others are the driving forces behind those actions. It appears that this phenomenon is the combination of knowing how and when to perform a particular action, and knowing what consequences that particular action will have on any related segments of the engineering design process, specifically the geometry creation process involved in the design of a product. Expertise in the use of constraint-based CAD tools appears to contain knowledge about the CAD tool and about factors which influence the use of that tool. While each of these makes its own contribution to expertise in the use of constraint-based CAD tools, they also appear to be dependent upon the personal characteristics of the user and the characteristics of the design environment in order to properly execute their plan.

The core themes of the phenomenon of expertise in the use of constraint-based CAD tools are strongly interrelated. They include fundamental knowledge of the software processes and the implications for their use. Domain knowledge of engineering sciences and technological knowledge serve as a guide for applying various strategies within the CAD tool. Past experiences also appear to affect not only on the way each expert defines and develops a scope for the problem at hand, but they also affect the way an expert implements a solution. By combining their knowledge of what actions have worked in the past and the tacit knowledge of the engineering and technological domains in which they exist, experts can frame a problem and develop a solution to their design problem.

The subordinate themes of expertise in the use of constraint-based CAD tools are similar to the core themes in that some of them are related to the actual use of the CAD tool and others are related to the actions of the participants within their professional community. Downstream usage of the model impacts the definition and development of expertise by affecting the user’s strategy and their design considerations. In addition to downstream uses of the CAD model facilitating the development of expertise, the actual commands and techniques used in the day-to-day creation of geometry form a large part of the definition of expertise. While these techniques are definitely impacted by several core themes, such as strategy and design considerations, they are also developed by the interaction of experts within their local community of practice. Through the collaboration and communication with colleagues, experts are able to develop techniques for using the model as a communication device.

Supporting the development of expertise and often embodying the results of choices concerning strategy and software usage are the transitional themes of expertise in the use of constraint-based CAD tools. By operating within a design community that contains reference materials, knowledgeable colleagues, and immediate feedback from the production environment, support is given to the development of this phenomenon. The ways in which the expert works with regard to specific command choices and combinations are in many cases determined by the strategies that they employ in the use of particular commands within the software package. In addition, any academic or professional training that the user might have will affect the design considerations that they attend to, the fundamental understanding of geometry they may have, and any preconceived expectations about how the software may function.

The interviews used in this study further narrowed the information regarding the experiences of the five participants and how they impacted the core themes of expertise, particularly with regard to past experiences, the participants' conception of expertise, and how this related to their usage of the CAD tools. In examining the experiences of these five participants, it appears that expertise in the use of constraint-based CAD tools contains knowledge about the operational processes of the CAD tool. It also contains other factors, while not directly related to the CAD tool, which influence the use of that tool. While each of these two areas of knowledge makes its own contribution to expertise in the use of constraint-based CAD tools, they are also dependent upon the personal characteristics of the user and the characteristics of the design environment in order to properly execute their plan.

Past and present experiences appear to have played a key role in the development of expertise of these five participants, not just in regard to professional experience, but in academic training as well. These past experiences include the progression from traditional drafting tools and methods to the use of constraint-based CAD tools in the case of the two older participants. The other three participants are younger, and they never experienced the use of traditional drafting techniques and tools in their professional careers. They completed internships where they have learned about the profession and its customary practices, as well as mentors to guide them in the use of their tools. Each of the participants has several years of experience within the engineering design profession, and that has enhanced their awareness of standard practices within the industry in regard to materials and processes, communications between design groups within and between various facilities, and their methods and techniques for using their tools. Interfacing with customers and other team members also creates an awareness of potential design considerations that must go into the creation of each model. They are communicating between themselves, suppliers, and customers via the CAD model. This means that they must model effectively with a sound strategy for geometry creation and modification.

Each participant works in an environment where they have to collaborate with coworkers in the design of their products. Common to those activities is the use of the CAD tool to develop and document the design of the product, typically with parts, drawings, and assemblies in an integrated fashion, because that is the nature of their job requirements. In most cases, marketing departments or a customer liaison will pass technical specifications to the engineering groups, and they will begin to develop a solution based on company or industry design standards. The participants' past experiences and model interrogation techniques give them a framework in which to develop a solution for the given problem through the use of the CAD tool.

However, when they encounter difficulty in using the CAD tool to address a design problem, they each have a different support structure upon which to rely. Some are extensive corporate support groups while others are simply left to heir own devices. In trying to overcome their particular design problems or problems in using the CAD tool, all of them appeared to have a tendency to confer with colleagues who they thought might be able to help, or they would simply begin to experiment. Through this process, they would learn what would work and what would not work in a given situation, and then they would incorporate that into their repertoire for the next time they encountered a similar situation. By adopting a hands-on, visual learning style, the participants have been able to recognize the presence of certain conditions that are causing them difficulties within the CAD tool, such as missing references and invalid profile geometry.

For each participant, the size of their engineering groups varies, but each of them is considered by their coworkers as having a high level of knowledge with respect to the CAD tools and the products with which they work. While each participant was reluctant to admit that he was an expert, each one of them was able to articulate their own conceptions of expertise and how it related to constraint-based CAD tools. Their conceptions of expertise are based on what their past experiences have told them. They considered experts to be all knowing and capable of perfect performance, capable of communicating with non-experts in an intelligible fashion, and capable of recognizing the critical characteristics of a problem situation and incorporate them into a solution. Experts will also be well practiced in the use of the tools and techniques of their respective discipline, and their strategies and rules of thumb evolve from past successes and failures in the use of tools and techniques within a specific context.

Based on these conceptions of expertise, the five participants were then able to express their conceptions of expertise relative to the use of constraint-based CAD tools. They expected that experts would emphasize the incorporation of design intent into their models by synthesizing the various design considerations that surround a problem. They also expected that experts would be able to model faster and better than other users due to their experience with the tools. By combining their tacit knowledge of geometry, the pertinent design considerations and their past experiences, expert constraint-based CAD users are able to create robust geometry that can be used in many places throughout the design process. Although the participants were quick to point out that while their knowledge of the CAD tools is important, it is but one part of the larger picture of the design process. It is only a tool by which to develop and document a design; it alone cannot conceive an idea or see it to fruition.

In examining the experiences of these five participants, it appears that expertise in the use of constraint-based CAD tools also contains knowledge about the operational processes of the CAD tool. An understanding of the purposes of particular software commands and the syntax involved in using them, downstream uses of the CAD model, and the strategies developed to execute the creation of specific model geometry seem to be important to the effective use of these tools. In addition, these five participants have also expressed other factors, while not directly related to the CAD tool, which influence the use of that tool. Past experiences, the internal technical and social support structure of the organization, various design factors and considerations, and knowledge of the engineering design domain are some of the external factors that appear to have affected the development of expertise in these participants.

Further examination of the usage of the software tool and its inherent processes was done through the use of the think-aloud modeling task to gain a level of insight into the modeling procedures used by these five participants. In examining the procedures used by each participant, it appears that the choices they made with regard to creating and editing geometry were a result of several factors. Each participant had a choice when creating the individual features in their model, which was based on the attributes, aspects and attractiveness of the contributing factors, such as function of the part and the inherent geometric forms contained within it. It appears that each one of them gave consideration to the inherent geometry of the part, as well as the function of the model. Each participant examined the accompanying parts in the assembly in addition to the one they were asked to model.

According to the participants' modeling procedures, feature order impacted the appearance of the finished geometry, as well as the ability to modify existing features. Some participants decided to create as much geometry as possible within that first feature operation, while others decided to create separate features. The references used for the creation of each feature impacted the ability to later modify and edit the geometry, as well as the ability to capture design intent during creation. While some participants were adamant about selecting default datum planes to serve as sketching planes for the features they created, others decided to select existing part surfaces to establish the position and orientation of their features. In doing so, each participant had to consider the aspects of selecting a particular sketching plane and the effects that would have on their model later.

Each feature contained attributes including aspects of sketching plane orientation, feature type, feature order, and sketched geometry. Each person selected one of the default vertical datum planes on which to sketch the first revolved profile due to the default vertical orientation of the part. The selections for sketching planes for subsequent features was based not only on future orientation, but also on the references to other features as mentioned previously. By being able to recognize inherent geometry within the model, each participant was able to effectively choose a feature type for each of the features in their model.

While this was relatively simple for them, their methods for creating certain features varied. Some participants decided to create various features on the model separately and copy them, while other decided to create the duplicate geometry as part of one complex feature. Feature order also played a role in the participants' choices for creating and duplicating geometry. Noticeable differences were seen here in terms of strategy for feature duplication regarding those participants who used Pro/ENGINEER and the participant who used SolidWorks. Each of the participants made some type of decision regarding their use of specific commands that would allow them to work at a particular speed, particularly in the areas of the model that afforded them the opportunity to use feature duplication techniques within the software. Given the procedural and relational nature of these software tools, each participant adopted a strategy for modeling the STOCK SUPPORT BASE in Appendix F that enabled them to maximize the attractiveness of certain choices the software and the modeling scenario presented to them. They considered the inherent geometry and default orientation of the part in deciding how to make the first feature. Once they decided on the revolved solid feature, they selected an appropriate sketching plane upon which to sketch a profile.

Based on their knowledge of the particular software sketching commands and how they interrelate with each other, each participant used a similar procedure to make the features in their model: selection of a sketching plane to establish feature position and orientation, sketching of a profile in some relative position on that plane, adding geometric relations and dimensions according to the design intent and the desired behavior of the model geometry, and finally the application of a feature form that coincides with the participant's visualization of the respective geometry. Each participant implemented this feature creation sequence in his own unique way, but one theme eventually emerged from these five participants. After the initial shape of the model was obtained in the base feature, they began to either add or remove material from the model using the procedure above to arrive at the finished solid geometry of the model. Their resulting modeling procedures focused on the critical nature of the description of the overall nature of the part geometry, and the embedded relationships of the subsequent features used to finish the full description of the part geometry.

Given the complexities of the modeling tool and the design environment, the knowledge-mapping task sought to examine the critical elements that the participants used to conceptualize the knowledge base behind the use of constraint-based CAD tools. Each of the participants accounted for concepts related to the direct usage of the CAD tool as well as the background or general information that impacted the use of those tools. User characteristics, software processes and design considerations combine to form a tacit knowledge base from which the participant could draw information to use in their strategic creation and modification of parts and assemblies to define the product to be made. Each participant also expressed his view of the use of the CAD tool as being goal oriented. While CAD tool commands and techniques were the manifestations of their relevant tacit knowledge bases, the ultimate goal was to produce a robust model that could be used throughout the design process.

DISCUSSION

Similar to the manner in which the data for this study was collected and analyzed, the discussion of the findings of this study will be done according to the results of the observations, interviews, think-aloud modeling tasks, and the knowledge-mapping tasks. In doing so, the researcher arrived at an increasingly narrow, yet summative view of expertise in the use of constraint-based CAD tools. This study sought to determine how one develops expertise in the use of constraint-based CAD tools, in terms of the experiential nature of the phenomenon, as well as the concepts embodied in its inherent knowledge base. Described below are the composite descriptions of the development and definition of expertise as derived from the five participants in this study.

A Composite Structural Description of Expertise

The definition and development of expertise in the use of constraint-based CAD tools were comprised of many interrelated factors and themes. Some of these themes were embodied in the results of actions that experts take, while others are the driving forces behind those actions. This phenomenon is the combination of knowing how and when to perform a particular action, and knowing what consequences that particular action will have on any related segments of the engineering design process, specifically the geometry creation process involved in the design of a product.

Expertise in the use of constraint-based CAD tools contains knowledge about the CAD tool: the purpose of particular software commands, the syntax involved in using it, downstream uses of the CAD model, and the strategy developed to execute the creation of specific model geometry. It also contains other factors, while not directly related to the CAD tool, which influence the use of that tool: past experiences, the internal technical support structure of the organization, various design factors and considerations, and knowledge of the engineering design domain. While each of these makes its own contribution to expertise in the use of constraint-based CAD tools, they were also dependent upon the personal characteristics of the user and the characteristics of the design environment in order to properly execute their plan.

The core elements of the phenomenon of expertise in the use of constraint-based CAD tools were strongly interrelated. They include fundamental knowledge of the software processes and the implications for their use. For example, the ability to edit a model and control the impact made on related models required a thorough recognition and interrogation of the parent/child references within the assembly in which the part resided, due to the associative properties of the assembly. It is not only important to know the many commands within the software tools, but also the differences between two command choices and the consequences for choosing any particular one of them (Bhavnani, 1999). Several participants expressed their reasoning throughout the study for their choices of using a Hole feature instead of a Cut feature in a given scenario. This typically involved their anticipation of changes that might be made later to the design. This is the case not just within the context of the current model being created or modified, but within the larger scope of the product assembly or the engineering database as a whole.

Domain knowledge of engineering sciences and technological knowledge serve as a guide for applying various strategies to overcome challenges through the use of tools. Fundamental tool knowledge is invaluable to the practicing professional (Ferguson, 1992; Bucciarelli, 1994), and the knowledge of constraint-based CAD tools is no different. Physical characteristics of the product, the designer's knowledge of the product environment, and propensity towards visualization and the use of tools will influence the manner in which the geometry is created or modified. In spite of all of this, there are also any number of design considerations that the experts must consider when developing a problem scope and definition. External factors, the part function, and the anticipation of design requirements and potential changes will all have an affect on the way the CAD models are created. Past experiences will not only have an affect on the way each expert defines and develops a scope for the problem at hand, but also an affect on the way an expert implements a solution. The ability to integrate a variety of factors guided by past experiences to develop an opportunistic solution is one of the basic tenets of expertise in any domain (Glaser & Chi, 1988). The combination of tacit knowledge of the engineering environment, coupled with the procedural and declarative knowledge of the software, allows the user to develop a strategic solution (Bhavnani, 1999). This solution is then implemented through their knowledge of the software processes used to create and modify geometry and the implications of their use. By providing designers with the opportunity to have similar experiences, the development of expertise in the use of these tools can be fostered.

The subordinate themes of expertise in the use of constraint-based CAD tools are similar to the core themes in that some of them are related to the actual use of the CAD tool and others are elated to the actions of the participants within their professional community. Downstream usage of the model impacts the definition and development of expertise by affecting the user's strategy and their design considerations. Users must consider the strategies they employ while creating the solid models, due to the possibility that another person might use their model in the future. If that model must be modified, it is imperative that the model behaves in the manner desired. As they accumulate time spent using the software, CAD users progress towards a state of being where they can accurately account for many of the specific factors that influence their design.

Also by sharing CAD data, designers are required to develop knowledge of those data sharing processes, as well as an understanding of what happens when their strategies for geometry creation do not work as expected. In addition to downstream uses of the CAD model facilitating the development of expertise, the actual commands and techniques used in the day-to-day creation of geometry form a large part of the definition of expertise. While these techniques are definitely impacted by several core themes, such as strategy and design considerations, they are also developed by the interaction of experts within their local community of practice. Through the collaboration and communication with colleagues inside and outside the organization, experts are able to develop techniques for using the model as a communication device (Henderson, 1999). Passing a model to another designer for use in their respective assembly, or using the model as part of a design review meeting where red-lining tools are available and decisions are to be made, were both manners in which the model becomes a collaboration device, similar to the conscription devices and boundary objects mentioned by Henderson (1999). The models carry in them the embodiment of the designer's ideas and requisite behavior for the model that can be used to promote discussion or to exclude particular individuals. Participants were also able to read and interpret engineering drawings as a means for constructing and editing geometry.

Supporting the development of expertise and exhibiting themselves as the manifestation of choices concerning strategy and software usage are the transitional themes of expertise in the use of constraint-based CAD tools. By operating within a design community that contains reference materials, knowledgeable colleagues, and immediate feedback from the production environment (Collins, 1987), support is given to the development of this phenomenon. Each of the participants worked in an environment that contained artifacts and tools that enabled them to develop their knowledge of the CAD tool. Reference materials, corporate modeling standards, knowledgeable colleagues, and an atmosphere that allowed them to experiment with their solutions to a particular design problem appeared to foster the development of their knowledge. Corporate culture and the enculturation of them into the engineering design profession accounted for much of their background knowledge in terms of the tacit information they applied to their choices in using the CAD tool (Collins, 1987).

The ways in which the expert works with regard to specific command choices and combinations are in many cases determined by the strategies employed in the use of particular commands within the software package. The choices of factors that receive his attention and are given priority ultimately affect the manner in which the CAD tool is used. In addition, any academic or professional training that the user might have will affect the design considerations that they attend to, the fundamental understanding of geometry they may have, and any preconceived expectations about how the software may function. All of which will impact what they consider to be important information to know and pertinent practices to follow with respect to using the CAD tools effectively. The following list summarizes the characteristic themes of expertise as exposed from the observation data.

1. *Problem Definition and Solution* – In each case, problem definition involved a great deal of time gathering information or simply testing a command to evaluate its results. The results would be compared to past experiences and knowledge and expectation of how the software operates.
2. *Strategies for using the tool* – The strategies used considered the extent to which their actions might influence related models and drawings within the engineering database. Their strategies for using the CAD tool were typically manifested within the resulting behavior of the 3D CAD files, which coincided with the situational design intent.
3. *Domain Knowledge* – This theme consisted of the core knowledge base which surround engineering design environments, including the accepted practices for the way work is done, cultural norms and practices, extensive knowledge of the products that they designed and how they were made, and “best practices” within the profession. The participants coupled with their past experiences and the design considerations to produce a particular strategy for using the CAD tool to create a model that embodied the design intent required for that particular project.

4. *Design considerations* – The participants considered many factors during the creation of a 3D model, including customer requirements, manufacturing process and how those would influence geometry creation, and potential changes to the product and how geometric characteristics would enable or disable that process.
5. *Past Experiences* –These past experiences, coupled with articulated modeling strategies and knowledge of the fundamental characteristics of the CAD tool, expose expertise in the use of these tools. These experiences included solid modeling within academic training, professional training and internships, and success or failure with respect to using the CAD tool.
6. *Downstream uses for the CAD model* – The participants used techniques that would create geometry that was easily modified and manipulated to support its use in other areas of the enterprise. These areas included manufacturing applications, analysis, documentation and archival, marketing literature, and inspection.
7. *Software usage* – Software usage was the embodiment of strategy and past experiences. This theme focused on the actual commands that participants selected, the order in which they were executed, and the subsequent selection of commands based on success or failure of the current operation.
8. *Technical Communications* – The participants often used the model as a vehicle for communication. They highlighted surfaces for discussion with coworkers, they sent screen captures to colleagues and customers for descriptive purposes, and they modified the model during design meetings to discuss its robustness with colleagues.
9. *Social Communication* – This theme encompassed the solicitation of information from each participant by his coworkers, the flow of information through the engineering environment, and how much each participant either directly or indirectly impacted that flow. It was common for the participants to discuss not only the creation of the models but also the circumstances that surrounded that creation process.
10. *Support Structure* – Each participant had his own support structure, which varied in complexity and availability, with those participants that worked for larger companies had more extensive support than those that worked for smaller companies. Typical

elements for a support structure included internal help desks, written reference materials, training guides, secure access to software vendors' web sites, or help from a coworker.

11. *Artifacts* – Each participant used artifacts from his design environment to gain feedback as to the success of his modeling approach, as well as to enable communication within the design environment. In some form or another, each participant's environment included model or drawing archives, sample parts and prototypes from vendors, and tooling that was generated as a result of using the solid model as a reference.
12. *The Design Environment* – Each participant's design environment was a dynamic and complex place full of many factors that affect the design and production of a product. It also gave structure to each participant's job duties, and in some cases, gave him access to his designs being manufactured and assembled.
13. *The Way He Works* – Each participant tended to work with a given set of design circumstances and use that information until it ran out. This manner was characterized by a very methodical procedure of gathering information, applying it to the situation, and assessing the results, all within the boundaries of company-specific processes and practices.
14. *Participant Characteristics* – Each participant possessed an engineering- or technology-related education and training, as well as a great deal of professional experience. In addition, each one had a high level of awareness of the CAD system functions that they knew well or those that they had problems with, which aided them in developing a feasible solution to a design problem that did not compromise their design strategy.

Examining Experiences and the Conceptions of Expertise

The previous description of expertise in the use of constraint-based CAD tools exposed the relevant themes that lead to the development of expertise and to experts' conceptions of expertise. The current description of expertise relates the elements of the participants' experiences listed in Table 4.2. It gives a combined description of the participants' past experiences, problem solving approaches, and their conceptions of expertise in an attempt to arrive at a more general view of the participants' experiences as they relate to the development of expertise in the use of constraint-based CAD tools.

In examining the experiences of these five participants, it appeared that expertise in the use of constraint-based CAD tools contains knowledge about the operational processes of the CAD tool. It also contained other factors, while not directly related to the CAD tool, which influence the use of that tool. While each of these two areas of knowledge made its own contribution to expertise in the use of constraint-based CAD tools, they were also dependent upon the personal characteristics of the user and the characteristics of the design environment in order for the participants to properly execute their plan.

Past and present experiences appear to have played a key role in the development of expertise of these five participants, not just in regard to professional experience, but in academic training as well (Glaser & Chi, 1988; Vincenti, 1990). These past experiences include the progression from traditional drafting tools and methods to the use of CAD tools in the case of the two older participants, which has given them the ability to effectively plan their design, as well as a firm understanding of geometry construction. They have made the transition through 2D CAD to 3D wireframe tools and eventually to constraint-based CAD tools. In doing so, they have gained an awareness of the levels of complexity inherent to each of those types of systems and an appreciation for the power and sophistication of their current techniques. This transition has forced them to develop a new thought process when using constraint-based CAD tools that is different from the thought processes they used before (Collins, 1987). It is affected by design considerations, geometry creation, and dynamic relationships between design components more so than in the past. This is due in large part to the fundamental processes upon which the CAD tools operate. The other three participants are younger, and they have never experienced the use of traditional drafting techniques and tools in their professional careers. They have had internships where they have learned about the profession and it customary practices, as well as mentors to guide them in the use of their tools. All of which has enculturated them into the domain of engineering design, making them aware of the typical problem solving processes used in these environments in regard to the use of CAD tools. It is a process embodied by experimentation and an attention to the ramifications of one's choices in terms of using the CAD tool.

Each of the participants has several years of experience within the engineering design profession, and that has enhanced their awareness of standard practices within the industry in regard to materials and processes, communications between design groups within and between various facilities, and their methods and techniques for using their tools. Spending time in the shop working with the products they design has given them an awareness of the effects that their decisions in using the CAD tool can have on the workings of the product (Vincenti, 1990). Experiences in machining operations and prototype design enables them to better capture critical information within the CAD tool. Interfacing with customers and other team members also creates an awareness of potential design considerations that must go into the creation of each model. At one time, drawings were used by the participants as the primary means of communication for the creation and inspection of parts. Now they are communicating between themselves, suppliers, and customers via the CAD model. This means that they must model effectively with a sound strategy for geometry creation and modification.

Each participant worked in an environment where they have to collaborate with coworkers in the design of their products. Common to those activities were the use of the CAD tool to develop and document the design of the product, typically with parts, drawings, and assemblies in an integrated fashion, because that is the nature of their job requirements (Henderson, 1999). In most cases, marketing departments or a customer liaison would pass technical specifications to the engineering groups, and they would begin to develop a solution based on company or industry design standards. Much of this communication came in the form of marked-up drawings or photographs, so they each have to develop the visual and graphical skills necessary for this type of communication (Ferguson, 1992). This process often required that they do a fair amount of research as well to determine the scope of the changes to be made and the impact that it will have on the engineering database. A common way that this was done was by interrogating the model using the functions inside the software to gather information about the model and its relationships to other models within the database. Through previous failures at the redefine and modification process, coupled with the knowledge of the fundamental software processes, each participant's past experiences gave them a framework in which to develop a solution for the given problem through the use of the CAD tool.

However, when they encountered difficulty in using the CAD tool to address a design problem, they each had a different support structure upon which to rely. Three of them had little or no support structure at all, while the other two participants had a rather extensive support structure. Those participants that were left to their own devices to develop a solution to the problems they had with the CAD tool appeared to have a much more thorough grasp of the command structures related to the geometry editing and manipulation functions and the various options therein. This was likely due to the frequency with which they encountered those particular menus. Those participants that had extensive support structures in the engineering environment, or who had a knowledgeable colleague within close reach, appeared to not have as deep of an understanding the editing and manipulation commands. Each of the participants had attended training courses specific to the use of the CAD tool, but those have only been good for learning basic functions of the tool and exposing them to the terminology involved with its use. When they returned to work, they often encountered situations where the geometry they needed to create was much more complex than the activities from the training course. In trying to overcome this problem, many of them would confer with colleagues who they thought might be able to help, or they would simply begin to experiment. In this experimentation process, they would integrate their understanding of the problem scope and its relevant factors with their knowledge of how the software worked. These factors often included materials and manufacturing processes, customer requirements, and the intended use of the CAD model when they were finished with it. All of these factors seemed to contribute to the commands they chose for geometry creation and the order in which features were created to accommodate potential future changes. The participants that had used constraint-based CAD tools in the past referenced the similarities between the tools as being helpful in learning a new one.

Through this process, they would learn what would work and what would not work in a given situation, and then they would incorporate that into their repertoire for the next time they encountered a similar situation. By adopting a hands-on, visual learning style (Vincenti, 1990), the participants were able to recognize the presence of certain conditions that are causing them difficulties within the CAD tool, such as missing references and invalid profile geometry. In addition, each of them has developed a particular method of working that has evolved from this problem solving approach. While they tend to use the same set of commands due to the nature of their products, they also appear to have a basic set of visualization skills that allow them to assess any modeling situation in order to create the most appropriate geometry. In terms of CAD tool usage, this includes several techniques: generating cosmetic cross-sections in complex parts to aid in the visualization of interior geometry, use of a template part to capture design data that is consistent within each model they build, and working in a shaded view of the model to accurately determine their position and orientation.

For each participant, the size of their engineering groups varies, but each of them was considered by their coworkers as having a high level of knowledge with respect to the CAD tools and the products with which they work. In fact, all of the participants expressed that the ability to collaborate with colleagues was essential to the development of a problem solution. They have all been approached by coworkers looking for the answer to a question about the software or for an opinion about how to perform a certain operation. While each participant was reluctant to admit that he was an expert, each one was able to articulate their own conceptions of expertise and how it related to constraint-based CAD tools. Their conceptions of expertise were based on what their past experiences have told them. They considered experts to be all knowing and capable of perfect performance. These participants also expected that experts would be capable of communicating with non-experts in an intelligible fashion, even at the level of the most basic detail. Experts would also have a firm grasp of their own knowledge base and its boundaries (Glaser & Chi, 1988). Based on their knowledge base and extensive experience, these participants felt that experts should be able to recognize the critical characteristics of a problem situation and incorporate them into a solution. Experts will also be well practiced in the use of the tools and techniques of their respective discipline, and their strategies and rules of thumb would evolve from past successes and failures in the use of tools and techniques within a specific context.

Based on these conceptions of expertise, the five participants were then able to express their conceptions of expertise relative to the use of constraint-based CAD tools. They expected that experts would emphasize the incorporation of design intent into their models by synthesizing the various design considerations that surround a problem. They also expected that experts would be able to model faster and better than other users due to their experience with the tools. They would develop macro programs, template model files, and libraries of CAD models that automate many of the more mundane aspects of geometry creation. In terms of expertise in general, this last conception of expertise corresponds to an expert's ability to automate many of the less-critical aspects of their task performance. Expert constraint-based CAD users would give consideration to the order in which they would create their features in anticipation of potential design changes. Experts would not create adverse parent/child references within the CAD model, and they would use appropriate geometry creation techniques to capture critical dimensional information in the model, which would enable the model to be edited easily.

By combining their tacit knowledge of geometry, the pertinent design considerations and their past experiences, the participants stated that expert constraint-based CAD users are able to create robust geometry that can be used in many places throughout the design process. Although the participants were quick to point out that while their knowledge of the CAD tools was important, it was but one part of the larger picture of the design process. It is only a tool by which to develop and document a design; it alone cannot conceive an idea or see it to fruition.

In examining the experiences of these five participants, it appeared that expertise in the use of constraint-based CAD tools contains knowledge about the operational processes of the CAD tool. An understanding of the purposes of particular software commands and the syntax involved in using them, downstream uses of the CAD model, and the strategies developed to execute the creation of specific model geometry seem to be important to the effective use of these tools. In addition, these five participants have also expressed other factors, while not directly related to the CAD tool, which influence the use of that tool. Past experiences, the internal technical and social support structure of the organization, various design factors and considerations, and knowledge of the engineering design domain are some of the external factors that appear to have affected the development of expertise in these participants. The following list summarizes the themes that emerged from the interview data.

1. *Professional and Academic Experiences* – Each participant had an extensive array of previous work and software usage experience, working professionally for at least five years, used a variety of CAD tools. These included professional experiences using both traditional drafting tools and different levels of CAD tools, internships and apprenticeships, and designing a variety of different products.
2. *Typical Domain Activities* – Each participant was required to perform several different roles within their group or organization, which engaged them in authentic practice in the engineering design environment. This also required communication with other people who needed the participants' skills and knowledge to accomplish their job functions and a need to perform reverse engineering activities to gather requisite information.

3. *Conceptions of Expertise* – Each participant assumed that an expert would possess extensive knowledge and varied experiences within their particular field. They also considered timeliness of information provided by an expert to be critical, and that most experts would be fast and all-knowing concerning their respective discipline.
4. *Problem Solving* – The participants have developed a hands-on, visual learning style with which to gather information and a mind set for what to do when all of the information is gathered. Their techniques also included sketching, trial and error approaches, and experimentation. Each one had a confidence level when developing a solution to a design problem that was based on knowledge of the software and how it operates.
5. *Factors Related to CAD Usage* – When using the CAD tool, each participant considered many factors, which typically were combinations of problem solving strategy, CAD tool usage, and design consideration. These factors included downstream uses of the model driving modeling decisions made by the user, communication and cultural issues within the design group, time constraints, and the stature of the CAD model in design process.
6. *CAD Model Characteristics* – Each participant described elements of CAD usage exhibited by experts as including the pros and cons of certain command choices, implications of modeling decisions and how that affects the design intent of the model, and what was acceptable for “good” and “bad” geometry creation and use.

The interrelated nature of the common themes of expertise that were discovered in this study is summarized below in Figure 5.1. The core themes combine to influence the subordinate themes, which eventually leads to the creation of a 3D CAD model. Past academic and professional experiences gave the participants a way of working and a knowledge base from which to draw. They used this information, coupled with their problem solving strategies and their knowledge of the CAD tool, to address their design situations. The arrows on the circle that encompasses the subordinate themes imply that this is an ongoing process in which ideas, experiences, and strategies all churn together to develop a solution.

All of these activities took place within engineering environments that were dynamic places to work and that forced the participants to perform varied roles within their organizations. However, there is some amount of feedback from the subordinate themes to the core themes, particularly in terms of successful and unsuccessful software usage techniques and downstream uses of the model, which will be stored as past experiences to be used in developing future strategies. This feedback allowed the participants to adjust their strategies and to integrate new information into their mental models. Surrounding the core and subordinate themes are the transitional themes, which enable and are often impacted by the interaction of the others. Included in these themes are the participants' conceptions of expertise, which influenced the ways that they worked and how they perceived themselves with respect to their coworkers and environment. Recognizing themselves as capable users of the tools gave them the confidence they needed to approach their modeling situations with the potential to be successful.

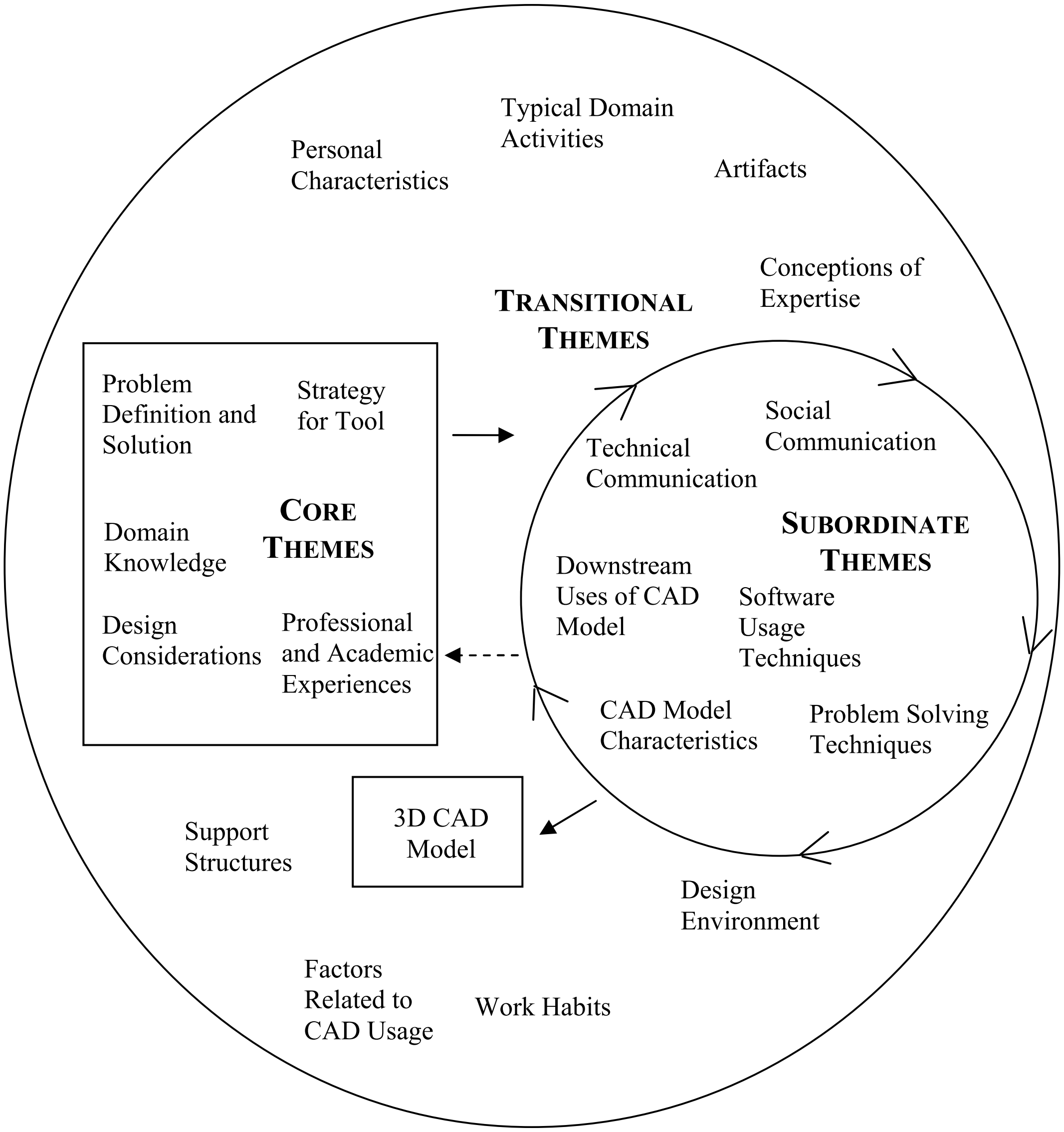


Figure 5.1: The Interrelated Themes of Expertise in the Use of Constraint-based CAD Tools

The observation and interview data discussed in the last two sections of this chapter have addressed the development of expertise in the use of constraint-based CAD tools. They have done so by looking at the experiences that have led the participants to their current status within their respective organizations and by looking at their actions within the context of their professional workplace. It is apparent that these actions within the workplace, particularly with respect to using the CAD tool, are impacted by past experiences, the current design environment, and the information gathered during the problem solving process. The next two sections of this chapter discuss the findings related to the definition of expertise in terms of tool usage and the structure of the knowledge base of the participants.

Examining Expert CAD Usage

In examining the procedures used by each participant, it appeared that the choices they made with regard to creating and editing geometry were a result of several factors. As mentioned in chapter three, alternatives are in essence a presentation of a situation that includes a particular choice. Attributes and aspects contribute to alternatives in an increasingly detailed fashion. The attractiveness of each mitigating factor is often the decisive element in making a choice. It embodies the potential cost or benefit to each participant in the given moment. The modeling procedures presented in chapter four exhibited similar elements.

Each participant had a choice when creating the individual features in their model, which was based on the attributes, aspects and attractiveness of the contributing factors. Each one of them gave consideration to the inherent geometry of the part, as well as the function of the model. Each participant examined the accompanying parts in the assembly in addition to the one that they were asked to model. They all chose to create a revolved first feature as opposed to an extruded first feature due to their recognition of the inherent geometry of the part, which was circular in nature and not rectilinear, and their knowledge of the options for various feature forms able to be created in the CAD tool.

According to the participants' modeling procedures, feature order impacted the appearance of the finished geometry, as well as the ability to modify existing features. Some participants decided to create as much geometry as possible within that first feature operation, while others decided to create separate features. For example, Participant 3 stated that "the smaller the number of features you have, the less chance you have for the model to blow up on you later when you try to modify it." Obviously, editing capabilities in the future were a concern at this point. While Participant 2 had similar considerations, his strategy was different. "It's easier to do something simple the first time, rather than try to do something complicated and fix it later." These participants found themselves repeatedly in this type of situation, not only in the modeling task, but also during the times when the researcher observed them in their daily work: the trade-off between complexity of the current feature and the capture of critical design intent in the model.

The references used for the creation of each feature impacted the ability to later modify and edit the geometry, as well as the ability to capture design intent during creation. While some participants were adamant about selecting default datum planes to serve as sketching planes for the features they created, others decided to select existing part surfaces to establish the position and orientation of their features. In doing so, each participant had to consider the aspects of selecting a particular sketching plane and the effects that would have on their model later. Due to the inherent nature of the software, parent/child references are established during the selection or creation of a sketching plane. The participants knew this, and they were able to deal with required design changes in the modeling task when necessary. Good examples of the results of selecting particular features as references came when certain participants had to edit the order of their geometry when they had made a mistake. Each one of them was able to accomplish this relatively easily given their due consideration to the selection of a sketching plane as well as their establishment of references in Sketcher.

Each feature contained attributes including aspects of sketching plane orientation, feature type, feature order, and sketched geometry. Each person selected one of the default vertical datum planes on which to sketch the first revolved profile due to the default vertical orientation of the part. The selections for sketching planes for subsequent features were based not only on future orientation of the model and its features, but also on the references to other features as mentioned previously. By being able to recognize inherent geometry within the model, each participant was able to effectively choose a feature type for each of the features in their model. Their ability to do this is related back to their visual nature, and the type of problem solving approach that they apply: attention to detail and a thorough understanding of the desired behavior of the model.

While modeling this object seemed relatively simple for them, their methods for creating certain features were varied. Some participants decided to create the Mounting Bosses as one extruded feature while others decided to create them as three separate features. Again, the participants weighed the cost of complex feature creation now versus complex geometry modification later and vice versa. The same scenario happened with the Mounting Holes and the Spotfaces. Based on past successful experiences, some participants decided to create one Mounting Boss, one Mounting Hole, and one Spotface and duplicate them in a circular fashion. In doing so, conscious thought had to be given to the various aspects of feature creation, such as sketching plane, orientation plane, dimensioning references, depth options, and sketched geometry. Feature order also played a role in the participants' choices for creating and duplicating geometry. The participants who used Pro/ENGINEER and chose to use the Pattern command to duplicate geometry created the Mounting Bosses, Mounting Holes, and Spotfaces, and then duplicated them prior to creating any of the associated Round features. Participant 5 however used SolidWorks, which allowed him to create the Mounting Boss, the Mounting Hole, the Spotfaces, and their associated Rounds, and then select them all for duplication at the same time. While this may seem like trivial syntactic differences between the software packages, it is important to note the placement of Rounds in the model of Participant 5 as opposed to the other four participants. Generally, fillets and rounds are features that are placed on the model at the end of geometry creation, due to their relative instability during the modification and manipulation processes. Software functionality and his use of it in the past, combined with his engineering knowledge of the function of the Rounds and the Spotfaces, made this feature order an attractive choice for Participant 5.

The previous example leads to another attractive quality of certain feature orders and types and that is speed. Each of the participants made some type of decision regarding their use of specific commands that would allow them to work at a particular speed. Those participants who decided to duplicate geometry deemed it faster than creating individual features and were willing to accept the consequences of such actions. Those participants who decided to create separate features did so because they were either comfortable with that procedure or deemed the risks of using duplication techniques outweighed the benefits. The issue of speed also arose in the scenarios of the participants using Pro/ENGINEER. Pro/ENGINEER requires the user to establish a sketching orientation before proceeding to create the profile. While these participants had the option to select a plane for orientation, all of the participants at some point chose to allow the software to determine an orientation for them. When asked about this, they commented that this saved them a few menu picks and made the process go faster. Again, this was an example of automation coupled with the use of heuristics to gain an edge in the modeling situation. They had also experienced in the past the orientations that the software would provide to them, so when presented with a similar scenario, they were able to recall past behavior of the CAD tool.

Given the procedural and relational nature of these software tools, each participant adopted a strategy for modeling the STOCK SUPPORT BASE that enabled them to maximize the attractiveness of certain choices that the software and the modeling scenario presented to them. They considered the inherent geometry and default orientation of the part in deciding how to make the first feature. Once they decided on the revolved solid feature, they selected an appropriate sketching plane upon which to sketch a profile. Based on their knowledge of the particular software sketching commands and how they interrelate with each other, each participant sketched a proportional profile representing the amount of geometry they decided to incorporate into the first feature. That choice was made in regard to their plan for creating subsequent features, the known behavior of certain features when certain commands are applied to them, and the function of the part itself. They dimensioned the sketch according to the given dimensions on the drawing, and they applied geometric constraints based on how they wanted the geometry to behave. The revolved feature form was then applied.

Each subsequent feature was created with a similar procedure: selection of a sketching plane, sketching of a profile in some relative position on that plane, adding geometric relations and dimensions according to the design intent and he desired behavior of the model geometry, and finally the application of a feature form that coincides with the participant's visualization of the respective geometry. Each participant implemented this feature creation sequence in his own unique way, but one theme eventually emerged from these five participants. Each one of them created the feature(s) that described the overall characteristic shape of the model first, which required adding geometry to the database. After that shape was obtained, they began to either add or remove material from the model using the procedure above to arrive at the finished solid geometry of the model. The participants then added the fillets and rounds to the model, as well as the cosmetic treatment of the Threaded Hole in the Port Boss to finish the geometry of the part.

It appeared that the modeling techniques employed by these five participants were similar in the creation of the given object. Each of them considered past experience with a particular command and how that impacted their ability to create geometry easily and accurately. The participants also considered potential changes to the model and how these could be accommodated given the functionality of the software. Feature order, parent/child references, and sketched geometry were all considerations at this point. They coupled this knowledge with the information presented in the given situation to develop a strategy for creating the STOCK SUPPORT BASE, which would capture the design intent of the model and the inherent characteristics of the geometry. Their resulting modeling procedures focused on the capture of critical dimensions included in the overall nature of the part geometry, and the embedded relationships of the subsequent features used to finish the full description of the part geometry.

Selection of the base feature was critical to the modeling process of each participant. It influenced the parent/child references established within the model as well as the orientation adopted by the finished model. This was the geometry from which all of the other features in the model were referenced. Once the decision had been made regarding what would become the first feature, subsequent features were created that either added or removed material from the model. Each sketched feature in the model was created using a similar procedure. The following modeling procedure emerged from the analysis of the data provided by these five participants:

1. Determine sketching plane
2. Sketch profile
3. Add constraints/relations
4. Add dimensions
5. Apply feature form

The Knowledge Base of Constraint-based CAD Tools

While the knowledge-mapping task produced its own discrete data to be analyzed and its own set of findings related to the structure of the five participants' knowledge of constraint-based CAD tools, it also provides a useful summation to the examination of this phenomenon. While analyzing the knowledge maps for each participant, it became apparent that their knowledge of their respective constraint-based CAD tools was both procedural and declarative, which closely follows the characteristics suggested by Bhavnani (1998, 1999) in his examination of the use of 2D CAD tools. While the functionality of the tools has certainly grown more complex, the basic use of the tool has not: geometry creation. While the nature of the use of the CAD tools has changed over time, the reasons for their use have not: speed, accuracy, and capture of design information.

The concepts used by the participants in the performance of this task came from several sources, including engineering graphics textbooks, CAD tutorials, the past experience of the researcher, and the observation meetings between the participant and the researcher. From these, the participants tended to classify items into groups that represented factual items or concrete elements of the geometry, such as Cut, Boss, or Round, and also the procedural nature of the software, such as Extrude, Revolve, and Pattern. As they sometimes struggled to place certain concepts within the map that they had developed, they could never break the bond between the procedural nature of the commands and the declarative result they would obtain. Even software operations that exhibited the use of strategy on the part of the participant were always described in terms of what was required from a procedural or declarative standpoint to make it function properly.

Heavily influencing the decision to place a concept in a particular group, especially related to geometry creation, was past experience and fundamental understanding of the core characteristics of the software itself. While each participant had his own manner in which he characterized his model, the beginning of that description typically started with a discussion of the broad explanation of these tools. The impact that associativity, constraint-based geometry, dimension-driven geometry, and parametric geometry had on the majority of their decisions in terms of how to capture design intent with the model typically pervaded any discussion of feature creation, duplication, and modification.

In examining the knowledge maps of these five participants related to the use of constraint-based CAD tools it appears that they have several common characteristics. Each of the participants accounted for concepts related to the direct usage of the CAD tool as well as the background or general information. While each participant accounted for the specific conceptual elements in these large categories in slightly different ways, it was apparent that many of the concepts were interrelated on a variety of levels. For example, the concepts of past experience, design intent, customer requirements combined with knowledge of the fundamental processes of the software to dictate the choices for geometry creation.

The notions of dimension-driven, parametric, associativity, and constraint-based directed the selection and creation of specific feature types, feature forms, depth options. Knowledge of parent/child references and geometric constraints also influenced the manner in which geometry was edited and duplicated. In order to investigate the ramifications of certain geometry creation ad editing strategies, each participant appeared to use some form of geometry interrogation tools to gather information within the CAD tool.

Each of the participants expressed their view of the use of the CAD tool as being goal oriented, to produce a model that could be used throughout the design process. Communications with team members, suppliers, and vendors through the use of drawings derived from the CAD model or by simply sharing CAD data back and forth were mentioned several times as downstream uses for the model. Several participants also mentioned using the CAD tool as the input for analysis of the design, as well as archiving the model for maintenance of the design database. Figure 5.2 represents a common knowledge map based on the major categories from the five participants in this study, which closely parallel the conception of engineering and design knowledge suggested by Vincenti (1990).

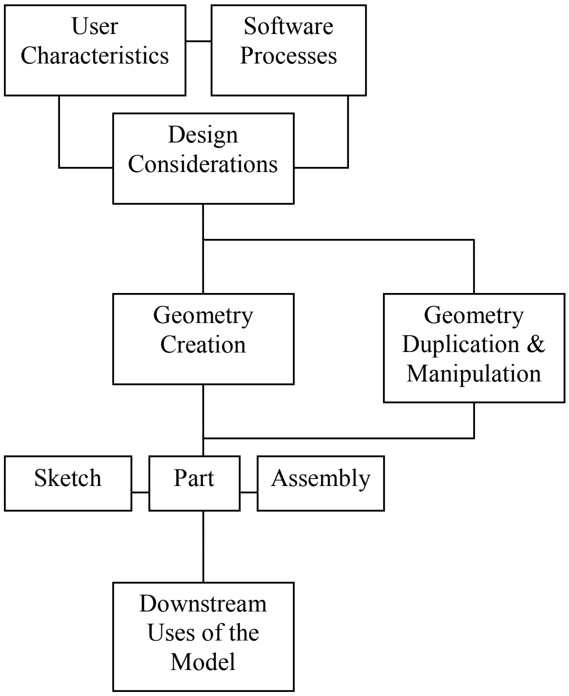


Figure 5.2: Common Knowledge Map for All Participants

Each of the common elements listed in the knowledge base for all participants further included all of the specific elements listed below.

User Characteristics

1. Past Experiences
2. Visualization

Software Processes

1. Parametric
2. Constraint-based
3. Dimension-driven
4. Modeling Procedure
5. Feature Order
6. Parent/Child References

Design Considerations

1. Design Intent
2. Customer Requirements

3. Manufacturing Processes
4. Modeling Standards

Geometry Creation

Sketch

1. Datum Geometry
2. Geometric Construction
3. Sketching Plane (and Orientation Reference)
4. Dimensions
5. Geometric Constraints/Relations

Part

1. Feature Orientation
2. Feature Types
3. Material Addition
4. Material Removal
5. Feature Form
6. Depth Options

Assembly

1. Component
2. Assembly References
3. Assembly Structure
4. Simplified Versions

Geometry Duplication and Manipulation

1. Modify
2. Redefine
3. Reorder
4. Copy
5. Pattern
6. Design Table/Family Table (and Instances)
7. Model Interrogation
8. Rebuild/Regenerate

Downstream Uses of the Model

1. Documentation
2. Analysis
3. Manufacturing Input
4. Archival

Based on the data collected for this study and the analysis methods used, specific elements exist that defined expertise in the use of constraint-based CAD tools for these participants. Past experiences, strategies for using the tool, design considerations, problem definition and solution, and domain knowledge are the core themes of expertise, which influence actual software techniques, social and technical communications between people in the design process, and downstream uses for the CAD model. Combining all of these core and subordinate themes of expertise are support structures, which contribute to as well as enable the particular strategies that are developed and the communication channels established within the engineering design environment. Engineering artifacts and the design environment itself also contribute to the development of expertise, but they also dictate many of the design considerations for which the user must account. Not only do all of these themes impact the way an expert works, but the way the expert works and their own personal characteristics also influence them. In this case, the constituent themes of expertise appear to be highly interrelated.

Upon further examination of past experiences related to these five participants, it appears that expertise is developed by authentic activities within the context of the engineering environment, as well as the opportunity to be immersed in the used of constraint-based CAD tools during their educational process. The characteristics described by these five participants appear to be similar to those of experts in other disciplines, particularly with respect to problem scope and definition, the ability to gather information to develop a problem-solving strategy, and the ability to recognize the boundaries of one's own knowledge base.

In addressing the issues of tool usage and strategy, the definition of expertise in the use of constraint-based CAD tools as evidenced by the modeling procedures of these five participants appears to be composed of "knowing how" and "knowing what." This includes knowledge of geometry creation, manipulation, and editing techniques coupled with information about the design considerations that surround the model creation. Not only did the participants exhibit knowledge of the engineering domain, but also fundamental knowledge of the software, which in most cases was impacted by past experiences and their own user characteristics. This becomes apparent when examining Figure 5.2. The combination of tacit engineering knowledge with declarative and procedural software leads to a strategic use of the tool to complete a goal-oriented design process.

IMPLICATIONS FOR THE ENGINEERING GRAPHICS PROFESSION

The purpose of this study was to examine practicing professionals within engineering design environments to attempt to describe the experiences that have led to the development of expertise in the use of constraint-based CAD tools. In addition, an attempt was made to describe the procedures and techniques they employ in the use of those tools, as well as the knowledge base that underlies the use of this software, to begin to define expertise in the use of these tools. A potential outcome of this research was that the findings generated from this study would be able to be applied to the future education and training of individuals in the use of complex, constraint-based CAD tools. While most engineering environments are similar in the tools and processes that they use, it is difficult to generalize too far past the scope of these five participants.

However, this study does contribute to the body of knowledge of the discipline that is engineering graphics and engineering design both in industry and in educational environments. It describes the experiences that have allowed these participants to reach their current levels of expertise. It gives a basic look at their problem solving processes and some of the factors that are taken into account in developing a solution to the problem. This study also provides a glimpse of the characteristics of an expert CAD user as conceived by the types of people most likely to be able to recognize such characteristics. In addition, the results of this study also shed light on a basic modeling procedure for creating geometry within the CAD tool based on the inherent characteristics of the geometry of the product to be designed and the strategy developed by the user to create such geometry. Finally, this study provides a very general, highly conceptual view of the knowledge base that underlies these tools. Its emphasis is on the fact that using these CAD tools combines tacit, procedural, and declarative knowledge to develop a means to address geometry creation and manipulation in the course of creating a model to be used throughout the engineering design process. Training of new employees within a company, or new users of a particular software package, should focus on establishing a problem context and definition that encompasses the factors surrounding the design. Situations that include geometry creation and redefinition, as well as geometry modification and manipulation, should be provided in this training to prepare new users for the complexity of the design situation. In addition, reverse engineering and redesign activities provide good exercises in developing and presenting these topics in a training environment.

In considering all of these factors, companies could promote more collaboration between their design employees. They could also develop more extensive support networks that give users the ability to access relevant training and help materials in a timely fashion so as to promote situated learning (Lave & Wenger, 1991). In addition, they could ensure that all design employees have at least a basic level of knowledge of the CAD tool to be able to communicate with their fellow coworkers, as well as other design counterparts outside of the immediate organization. With regard to the definitional aspects of expertise in the use of constraint-based CAD tools, corporate design environments could employ modeling standards that incorporate the basic processes suggested by the modeling procedures of the participants and the knowledge base evident in their mental models of this topic. Environments should be established that promote collaboration, interaction with customer requirements, and a mechanism for addressing updates and changes within the particular software package being used.

For educators the task is a bit different. In trying to overcome many of the traditional methods and techniques that have existed for many years, their task is about changing the body of knowledge that surrounds engineering graphics, just as other disciplines have changed their respective knowledge base with the advent of new tools (Keller & Keller, 1996). It is about incorporating these concepts and techniques into relevant instructional activities. Creating lessons that use authentic learning activities and promote collaboration between class members would be a good start. However, it is important to develop exercises that go beyond just creating the model.

Engineering graphics curricula developed based on this study should promote exploration of the design scenario using the CAD tool as an information gathering device. Learning activities should be project-based, and they should establish a context in which the design problem exists. These exercises would incorporate the characteristics of the knowledge base listed in the previous section of this report in an effort to establish common modeling strategies and standards for the students in the curriculum.

The participants in this study made no secret that creating the model was just one part of the design process, even though it bears a great deal of significance. Student activities should center on context-specific activities that force them to use their models for something other than display purposes. Moving CAD data between software packages, using models to create prototypes and drawings, and generating machine tool code from the surface data in the model would all be legitimate examples of authentic design activities. While it will take extra effort on the part of the instructor, educational activities should be developed that place the student into a context in which the model exists and that defines the model's acceptability and level of "correctness" based on its response to anticipated and unforeseen design changes.

In summary, learning activities within the engineering graphics curriculum that employ the use of constraint-based CAD tools should include the following elements:

1. Collaboration between students in the completion of the activities
2. Creation of a design scenario/context in which the activity takes place
3. Consideration of customer requirements
4. Assessment based on design intent of the model
5. Reverse engineering/redesign of complex parts
6. Extended modeling practice of a variety of different geometric forms
7. Design changes that fit within the context
8. Assessment of changes and updates to the software package being used

RECOMMENDATIONS FOR FURTHER RESEARCH

While the methods used for this study were sufficient for an initial exploration of expertise in the use of constraint-based CAD tools, any level of generalization past the realm of these five participants is precarious at best. This particular study only involved the use of two different software packages, while there are more than that number available and in commercial use within the engineering design community. In addition, the number of participants selected for this study and the characteristics of the environments where they worked should be expanded to include more possibilities. In addition, these same methods could be applied to other graphics tool applications, such as analysis, animation, and illustration software to name a few. Further research should be done in this area to explore these topics. The following list includes specific recommendations and suggestions for areas in interest in this discipline.

1. As mentioned above, these methods were sufficient for an exploratory study, but to obtain any kind of statistical significance, these methods should be applied to more participants. However, it should be noted that monetary and scheduling issues could be prohibitive.
2. Empirical verification of the themes and concepts found in this study should be done. While this could be partially addressed by the first point, a different methodology would also benefit in this case. A Delphi technique (Meyer & Booker, 1991) could be used to reach consensus on these topics, as well as to add others, now that a starting point has been identified.
3. Empirical verification of the strength of the relationships gleaned from the interview data, as well as that obtained from the knowledge mapping task, should be performed similar to the techniques suggested by Olson and Biolsi (1991).
4. While constraint-based CAD tools are similar, these five participants did exhibit differences based on the operation of the specific CAD tool. Including more software tools beside Pro/ENGINEER and SolidWorks would be beneficial.
5. Relative to the experiences of these five participants, two of them were substantially older than the others, which meant that they had used traditional drafting tools and techniques for a significant portion of their careers. A study to further examine this

unique experience would be worthwhile from the standpoint of job training and re-training.

6. This study was conducted in the state of North Carolina, which does not have as large of an industrial base as some other states where these tools would also be used. Expanding this study to include various geographic areas of the country may enlighten the differences in the engineering culture and the use of its tools between various regions of the country.
7. Similar to the previous two points, a wider range of products could be examined to expose the various modeling techniques and thought processes used to model castings, forgings, sheetmetal parts, and plastic purposes, with the sole purpose of the study as the examination of those techniques and their differences.
8. On a larger scale, these same methods, as well as the ones suggested in the aforementioned recommendations, could be used to address the larger issues of graphic science and its larger body of knowledge. While the different computer graphics tools are similar, there are certainly enough differences in terms of interfaces, techniques, and outputs to make a worthwhile study.

REFERENCES

Abbott, A. (1988). *The system of professions.* Chicago, IL: The University of Chicago Press.

Agnew, N.M., Ford, K.M., & Hayes, P.J. (1997). *Expertise in context: Personally constructed, socially selected and reality-relevant?* In P.J. Feltovich, K.M. Ford, & R.R.Hoffman (Eds.) Expertise in context: Human and machine (pp. 219-244). Cambridge, MA: AAAI Press/The MIT Press.

Alexander, P.A., Schallert, D.A., & Hare, V.C. (1991). Coming to terms: How researchers in learning and literacy talk about knowledge. *Review of Educational Research 61*(3)*,* 315-343.

Alexander, P.A. (1992). Domain knowledge: Evolving themes and emerging concerns. *Educational Psychologist, 27*(1), 25-77.

Anderson, J.R. (1990). *Cognitive psychology and its implications* (3rd ed.) New York, NY: Freeman.

Anderson, J.R. (1993). Problem solving and learning. *American Psychologist, 48*(1), 35-44.

Anderson, R. (1998). *Foreword.* In R. Valle (Ed.) Phenomenological inquiry in psychology: Existential and transpersonal dimensions (pp. ix-xi). New York: Plenum Press.

Annett, J. (2000). *Theoretical and pragmatic influences on task analysis methods.* In S.F. Chipman, J.M. Schraagen, & V.L. Shalin (Ed.) Cognitive task analysis (pp. 25-37). Mahwah, NJ: Lawrence Erlbaum Associates.

Ault, H. K. (1999). 3-D geometric modeling for the 21st century. *Engineering Design Graphics Journal, 63*(2), 33-42.

Bainbridge, L. & Sanderson, P. (1995). *Verbal protocol analysis.* In J. R. Wilson & E.N. Corlett (Eds.) Evaluation of human work: A practical ergonomics methodology (pp. 169-201). London: Taylor & Francis.

Barr, R. E. (1999). Planning the EDG curriculum for the 21st century: A proposed team effort. *Engineering Design Graphics Journal, 63*(2), 4-12.

Batra, D. & Davis, J.G. (1992). Conceptual data modeling in database design: Similarities and differences between expert and novice designers. *International Journal of Man-Machine Studies*, 37, 83-101.

Beach, L.R., Chi, M.T.H., Klein, G., Smith, P., & Vicente, K. (1997). *Naturalistic decision making and related research lines.* In C. E. Zsambok & G. Klein (Eds.) Naturalistic decision making (pp. 29-35). Mahwah, NJ: Lawrence Erlbaum Associates.

Bertoline, G. R., Wiebe, E. N., Miller, C.L. & Mohler, J.L. (1997). *Technical graphics communications* (2nd ed.) New York, NY: McGraw-Hill.

Bertoline, G. R. (1998). Visual science: An emerging discipline, *Journal for Geometry and Graphics, 2*(2), 181-187.

Bertoline, G.R. (2001). Historical development of graphics. http://www.tech.purdue.edu/cg/courses/tech519g/historic.html. Verified June 13, 2002.

Bertoline, G. R., & Wiebe, E. N. (2002). *Fundamentals of graphics communication* (3rd ed.) Burr Ridge, IL: Richard D. Irwin.

Bhavnani, S.K. & John, B.E. (1996). Exploring the unrealized potential of computer-aided drafting. *Proceedings of CHI '96*, 332-339.

Bhavnani, S.K. & John, B.E. (1997). From sufficient to efficient usage: An analysis of strategic knowledge. *Proceedings of CHI '97*, 91-98.

Bhavnani, S.K. & John, B.E. (1998). Delegation and circumvention: Two faces of efficiency. *Proceedings of CHI '98*, 273-280.

Bhavnani, S.K., John, B.E., & Flemming, U. (1999). The strategic use of CAD: An empirically inspired, theory-based course. *Proceedings of CHI '99*, 183-190.

Bigge, M.L. & Shermis, S.S. (1999). *Learning theories for teachers* (6th ed.). New York: Addison Wesley Longman, Inc.

Bogdan, R.C. & Biklen, S.K. (1998). *Qualitative research for education: An introduction to theory and methods* (3rd ed.). Needham Heights, MA: Allyn & Bacon.

Branoff, T. J. & Hartman, N. W. (2002). The 3D Model Centered Curriculum: Where Are We Now? *Proceedings of the 56th Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education*, San Francisco, California, January 6 - 9, 2002.

Branoff, T.J., Hartman, N.W., & Wiebe, E.N. (2002). Constraint-based, three-dimensional solid modeling in an introductory engineering graphics course: Re-examining the curriculum. *Engineering Design Graphics Journal*, 66 (1), 5 - 10.

Broadbent, D.E. (1958). *Perception and communication.* London: Pergamon.

Burgess, R.R. (2001). Northrop grumman rolls out pegasus UCAV demonstrator. *Sea Power*, 44 (9), 31-33.

Byrne, R.M.J. (1990). *Mental models.* In Eysenck, M. (Ed.) Dictionary of Cognitive Psychology. Oxford: Basil Blackwell.

Byrum, B.B. (2001). And the winner of the joint strike fighter is…. *Sea Power*, 44 (10), 42-46.

Camerer, C.F. & Johnson, E.J. (1991). *The process-performance paradox in expert judgement: How can experts know so much and predict so badly?* In K.A. Ericsson & J. Smith (Ed.) Toward a general theory of expertise (p. 195-218). Cambridge, MA: Cambridge University Press.

Charness, N. (1989). *Expertise in chess and bridge.* In D. Klahr & K. Kotovsky (Eds.) Complex information processing: The impact of Herbert A. Simon (pp. 183-208). Hillsdale, NJ: Erlbaum.

Chase, W.G. & Ericsson, K.A. (1982). *Skill and working memory.* In G.H. Bower (Ed.) The psychology of learning and motivation (Volume 16, pp. 1-58). New York: Academic Press.

Chi, M.T.H., Glaser, R. & Rees, E. (1982). *Expertise in problem solving.* In R.J. Sternberg (Ed.) Advances in the psychology of human intelligence. (Volume 1, pp. 7-75). Hillsdale, NJ: Lawrence Erlbaum Associates.

Chipman, S.F., Schraagen, J.M., & Shalin, V.L. (2000). *Introduction to cognitive task analysis.* In S.F. Chipman, J.M. Schraagen, & V.L. Shalin (Ed.) Cognitive task analysis (pp. 3-23). Mahwah, NJ: Lawrence Erlbaum Associates.

Christman, A. & Naysmith, J. (2001, April). Trends in CAD/CAM for mold makers. *Modern Machine Shop Online.* http://www.mmsonline.com/articles/040106.html

Churchill, S.D., Lowery, J.E., McNally, O., & Rao, A. (1998). *The question of reliability in interpretive qualitative research: A comparison of three phenomenologically based protocol analyses.* In R. Valle (Ed.) Phenomenological inquiry in psychology: Existential and transpersonal dimensions (pp. 63-85). New York: Plenum Press.

Churchland, P.M. (1989). *A neurocomputational perspective: The nature of the mind and the structureof science.* Cambridge, MA: MIT Press.

Clancey, W.J. (1997). *The conceptual nature of knowledge, situations and activity.* In P.J. Feltovich, K.M. Ford, & R.R.Hoffman (Eds.) Expertise in context: Human and machine (pp. 247-291). Cambridge, MA: AAAI Press/The MIT Press.

Clark, A. C. & Scales, A. Y. (1999). Taking the pulse of the profession. *Proceedings of the 53rd Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education*, Columbus, Ohio, January 15-17, 1999.

Colaizzi, P.F. (1973). *Reflection and research in psychology: A phenomenological study of learning.* Dubuque, IA: Kendall Hunt Publishing.

Collins, H.M. (1987). *Expert systems and the science of knowledge.* In W.E. Bijker, T.P. Hughes, & T.J. Pinch (eds.) The social construction of technological systems: New directions in the sociology and history of technology. Cambridge, MA: The MIT Press, p. 329 - 348.

Computer Aided Design Report. (1998, June). When bad things happen to good cad users (Vol. 18 No. 6). San Diego, CA.

Connolly, P. E., Ross, W. A. & Bannatyne, M. W. (1999). Applied 3D modeling technology instruction for freshman computer graphics majors: Developing a foundational knowledge. *Paper presented at the 54th Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education*, Biloxi, Mississippi, November 6-9, 1999.

Constant II, E.W. (1987). *The social locus of technological practice: community, system, or organization?* In W.E. Bijker, T.P. Hughes, & T.J. Pinch (eds.) The social construction of technological systems: New directions in the sociology and history of technology. Cambridge, MA: The MIT Press, p. 223 - 242.

Cordingley, E.S. (1989). *Knowledge elicitation techniques for knowledge-based systems.* In D. Diaper (Ed.) Knowlede elicitation: Principles, techniques and applications (pp. 89-178). New York: John Wiley and Sons/Halsted Press.

Courter, B. (1999). White paper: Conceptual engineering. Parametric Technology Corporation.

Cragg, P.B. & King, M. (1993). Spreadsheet modeling abuse: An opportunity for OR? *Journal of the Operational Research Society 44*, pp. 743-752.

Craik, K. (1943). *The Nature of Explanation*. Cambridge: Cambridge University Press.

Craik, F.I.M. & Lockhart, R.S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 13, 671-684.

Creswell, J.W. (1998). *Qualitative inquiry and research design: Choosing among five traditions.* Thousand Oaks, CA: Sage Publications.

Cumberland, R. R. (2001). *The foundation of a progressive engineering graphics curriculum*: A directed project report. Unpublished masters thesis, Purdue University, West Lafayette.

Davidson, J. & Sternberg, R.J. (1998). *Smart problem solving: How metacognition helps.* In D.J. Hacker, J. Dunlosky, & A.C. Graesser (Eds.) Metacognition in educational theory and prcatice (pp. 47-68). Mahwah, NJ: Lawrence Erlbaum Associates.

deGroot, A. (1966). *Perception and memory versus thought: Some old ideas and recent findings.* In B. Kleinmuntz (Ed.), Problem solving (pp. 19-50). New York: Wiley.

Dean, A. (2000, November). *Intelligent data translation: How close are we?* http://www.cadserver.co.uk/common/viewer/archive/2000/Nov/1/feature4.phtm

deKleer, J. & Brown, J.S. (1983). *Assumptions and ambiguities in mechanistic mental models.* In D. Gentner & A.L. Stevens (eds.) Mental Models. (p. 155-190).

DeVore, P. W. (1964). *Technology: An intellectual discipline*. Washington, DC: American Industrial Arts Association. (Bulletin Number 5).

DiBello, L. & Kindred, J. (1992). *Understanding MRPII systems: A comparison between two plants* (Technical Report for Cognitive Studies of Work). New York: City University Graduate School.

DiBello, L. (2001). *Solving the problem to employee resistance to technology by reframing the problem as one of experts and their tools.* In E. Salas & G. Klein (Eds.) Linking expertise and naturalistic decision making (pp. 71-93). Mahwah, NJ: Lawrence Erlbaum Associates.

Doane, S.M., Pellegrino, J.W., & Klatzky, R.L. (1990). Expertise in a computer operating system: Conceptualization and performance. *Human-Computer Interaction 5,* pp. 267-304.

Dominowski, R.L. & Bourne, L.E. (1994). *History of research on thinking and problem solving.* In R.J. Sternberg (Ed.) Thinking and problem solving (p. 1-33).

Driscoll, M. (2000). *Psychology of learning for instruction* (2 ed.). New York: Allyn & Bacon.

Duff, J.M. (1990). Teaching engineering graphics as a body of knowledge. *Proceedings of the 44th Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education*, Tempe, Arizona, 1990.

Edelman, G.M. (1987). *Neural Darwinism: The theory of neuronal group selection.* New York, NY: Basic Books.

Ericsson, K.A. & Smith, J. (1991). *Prospects and limits of the empirical study of expertise: An introduction.* In K.A. Ericsson & J. Smith (Ed.) Toward a general theory of expertise (p. 1-38). Cambridge: Cambridge University Press.

Ericsson, K.A. & Simon, H.A. (1993). *Protocol Analysis* (2nd ed.). Cambridge, MA: The MIT Press.

Ericsson, K.A. & Charness, N. (1997). *Cognitive and developmental factors in expert performance.* In P.J. Feltovich, K.M. Ford, & R.R.Hoffman (Eds.) Expertise in context: Human and machine (pp. 3-41). Cambridge, MA: AAAI Press/The MIT Press.

Glaser, R. & Chi, M.T.H. (1988). *Introduction.* In M.T.H. Chi, R. Glaser, & M.J. Farr (Eds.) The Nature of Expertise. Hillsdale, NJ: Lawrence Erlbaum Associates.

Feltovich, P.J., Ford, K.M., & Hoffman, R.R. (1997). *Introduction.* In P.J. Feltovich, K.M. Ford, & R.R.Hoffman (Eds.) Expertise in context: Human and machine (p. xiii-xviii). Cambridge, MA: AAAI Press/The MIT Press.

Ferguson, E.S. (1992). *Engineering and the mind's eye.* Cambridge, MA: The MIT Press.

Firlej, M. & Hellens, D. (1991). *Knowledge elicitation: A practical handbook.* New York: Prentice Hall.

Foster, P. N. (1997). Lessons from history: Industrial arts/technology education as a case. *Journal of Vocational and Technical Education,13* (2).

Gall, M., Borg, W., & Gall, J. (1996). *Educational research* (6th ed.). New York: Addison Wesley Longman.

Gardner, K.M., Rush, A., Crist, M.K., Konitzer, R., Teegarden, B. (1998). *Cognitive Patterns: Problem-solving frameworks for object technology.* Cambridge: Cambridge University Press.

Gentner, D. & Stevens, A.L. (1983). *Introduction.* In D. Gentner & A.L. Stevens (Eds.) Mental Models. (p. 1-3).

Giesecke, F.E., Mitchell, A., Spencer, H.C., Hill, I.L., Dygdon, J.T., & Novak, J.E. (1993). *Technical Drawing (9th ed.).* New York, NY: Macmillan Publishing Company.

Giorgi, A. (1985). *Phenomenology and psychological research.* Atlantic Highlands, NJ: Humanities Press.

Glaser, R. & Chi, M.T.H. (1988). *Introduction.* In M.T.H. Chi, R. Glaser, & M.J. Farr (Eds.) The Nature of Expertise. Hillsdale, NJ: Lawrence Erlbaum Associates.

Glesne, C. (1999). *Becoming qualitative researchers: An introduction* (2nd ed.). New York: Addison Wesley Longman.

Gray, W.D. & Kirschenbaum, S.S. (2000). *Analyzing a novel expertise: An unmarked road.* In S.F. Chipman, J.M. Schraagen, & V.L. Shalin (Ed.) Cognitive task analysis (pp. 275-290). Mahwah, NJ: Lawrence Erlbaum Associates.

Greco, J. (2000, September). Thinking tools. *Computer Graphics World*, 23 (9). pp. 49 – 52.

Greco, J. (2001, November). Getting smart. *Computer Graphics World*, 24 (11). pp. 38 - 43.

Gredler, M. E. (2001). *Information Processing Theories.* In Learning and instruction: Theory in to practice (4th ed.). Upper Saddle River, NJ: Merrill Prentice-Hall.

Greeno, J.G. (1978). *Nature of problem-solving abilities.* In W. Estes (Eds.) Handbook of learning and cognitive processes. (pp. 239-270). Hillsdale, NJ: Erlbaum.

Greeno, J.G. (1983). *Conceptual entities.* In D. Gentner & A.L. Stevens (Eds.) Mental Models. (pp. 227-252). Hillsdale, NJ: Lawrence Erlbaum Associates.

Hanratty, P.J. (1995). Parametric/relational solid modeling. In D.E. Lacourse (Ed.) *Handbook of solid modeling,* (pp. 8.1-8.25) New York: McGraw-Hill.

Heider, F. (1958). *The psychology of interpersonal relations.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Henderson, K. (1999). *On line and on paper: Visual representations, visual culture, and computer graphics in engineering design.* Cambridge, MA: The MIT Press.

Herschbach, D. R. (1995). Technology as knowledge: Implications for instruction. *Journal of Technology Education, 7*(1), 31-42.

Hinton, G. (1993). *Connectionist symbol processing* (Ed.). Cambridge, MA: MIT/Elsevier Books.

Hoffman, R.R., Shadbolt, N. R., Burton, A.M., & Klein, G. (1995). Eliciting knowledge from experts: A methodological analysis. *Organizational Behavior and Human Decision Processes, 62(2),* 129-158.

Hoffman, R.R., Feltovich, P.J., & Ford, K.M. (1997). *A general framework for conceiving of expertise and expert systems in context.* In P.J. Feltovich, K.M. Ford, & R.R.Hoffman (Eds.) Expertise in context: Human and machine (pp. 543-580). Cambridge, MA: AAAI Press/The MIT Press.

Holding, D.H. (1985). *The psychology of chess skill.* Hillsdale, NJ: Erlbaum.

Hollnagel, E., Cacciabue, P.C., & Hoc, J.M. (1995a). *Work with technology.* In J.M. Hoc, P.C. Cacciabue, & E. Hollnagel (Eds.) Expertise and technology: Cognition and human-computer cooperation (pp. 1-15). Hillsdale, NJ: Lawrence Erlbaum Associates.

Hollnagel, E., Cacciabue, P.C., & Hoc, J.M. (1995b). *Expertise and technology: I have a feeling we are not in Kansas anymore.* In J.M. Hoc, P.C. Cacciabue, & E. Hollnagel (Eds.) Expertise and technology: Cognition and human-computer cooperation (pp. 279-286). Hillsdale, NJ: Lawrence Erlbaum Associates.

Ihde, D. (1997). The structure of technology knowledge. *International Journal of technology and Design Education,7,* 73-79.

ITEA. (2000). *Standards for technological literacy: Content for the study of technology.* NSF Grant No. ESI-9626809. Technology for All Americans Project.

Jonassen, D.H. & Wang, S. (1992). Acquiring Structural Knowledge from Semantically Structured Hypertext. *Proceedings of research and Theory Division of the Association for Educational Communications and technology.* February 1992.

Jonassen, D.H., Beissner, K., & Yacci, M. (1993). *Structural knowledge: Techniques for conveying, representing, and acquiring structural knowledge.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Johnson-Laird, P.N. (1983). *Mental models: Towards a cognitive science of language, inference and consciousness.* Cambridge, MA: Harvard University Press.

Johnson-Laird, P.N. (2000) *The current state of the mental model theory.* In García-Madruga, J., Carriedo, M, and Gonsález-Labra, M.J. (Eds.) Mental Models in Reasoning. Madrid: UNED. p. 17-40.

Keller, C.M. & Keller, J.D. (1996). *Cognition and tools use: The blacksmith at work.* Cambridge, UK: Cambridge University Press.

Kruger, K., & Dunning, D. (1999). Unskilled and unaware of it: How difficulties in recognizing one's own incompetence lead to inflated self-assessments. *Journal of Personality and Social Psychology, 77(6),* 1121-1134.

Lave, J.& Wenger, E. (1991). *Situated learning: Legitimate peripheral participation.* Cambridge, UK: Cambridge University Press.

Lincoln, Y.S. & Guba, E.G. (1985). *Naturalistic inquiry.* Beverly Hills, CA: Sage Publications.

Linstone, H.A. & Turoff, M. (1975). *The delphi method: Techniques and applications.* Reading, MA: Addison-Wesley Publishing.

LoPiccolo, P. (2002, February). 25 year retrospective, part 2: CAD/CAM/CAE. *Computer Graphics World, 25*(2). pp. 15-18.

Luce, R. & Raiffa, H. (1957). *Games and decisions.* New York: Wiley.

Macdonald, K.M. (1995). *The sociology of the professions.* Thousand Oaks, CA: Sage Publications.

Maddix, F. (1990). *Human-computer interaction: Theory and practice.* New York, NY: Ellis Horwood.

Majchrzak, A., Chang, T., Barfield, W., Eberts, R., & Salvendy, G. (1987). *Human aspects of computer-aided design.* Philadelphia: Taylor & Francis.

Margolis, H. (1996). *Dealing with risk.* Chicago, IL: The University of Chicago Press.

Marshall, C. & Rossman, G.B. (1995). *Designing qualitative research.* (2nd ed.). Thousand Oaks, CA: Sage Publications.

McCracken, G. D. (1988). *The long interview.* Newbury Park, CA: Sage Publications.

McGraw, K.L. & Harbison-Briggs, K. (1989). *Knowledge acquisition: Principles and guidelines.* Englewood Cliffs, NJ: Prentice Hall.

McNamara, T.P. (1994). *Knowledge Representation.* In R.J. Sternberg (ed.) Thinking and Problem Solving (p. 83-113).

Mead, G.H. (1925). The genesis of the self and social control. *International Journal of Ethics, 35,* 251-277.

Merrill, M. D. (1999). *Instructional transaction theory (ITT): instructional design based on knowledge objects.* In C. M. Reigeluth (Ed.). Instructional Design Theories and Models:Volume II A New Paradigm of Instructional Design. Mahwah, NJ: Lawrence Erlbaum Associates.

Meyer, M.A. & Booker, J.M. (1991). *Eliciting and analyzing expert judgement: A practical guide* (Volume 5). San Diego, CA: Academic Press.

Mieg, H.A. (2001). *The social psychology of expertise: Case studies in research, professional domains, and expert roles.* Mahwah, NJ: Lawrence Earlbaum and Associates.

Miller, C. L. (1999). New technologies for engineering graphics. *Proceedings of the 53rd Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education*, Columbus, Ohio, January 15-17, 1999.

Moore, W. (1970). *The professions.* New York: Russell Sage Foundation. p. 56.

Moss, D.M. (1981). *Phenomenology and neuropsychology: Two approaches to consciousness.* In R.S. Valle & R. von Eckartsberg (Eds.) The metaphors of consciousness (pp. 153-166). New York: Plenum Press.

Moss, D.M. & Keen, E. (1981). *The nature of consciousness: The existential-phenomenological approach.* In R.S. Valle & R. von Eckartsberg (Eds.) The metaphors of consciousness (pp. 107-120). New York: Plenum Press.

Moustakas, C. (1994). *Phenomenological research methods.* Thousand Oaks, CA: Sage Publications.

Nasman, L. O. (1999). 3D modeling and the future of CAD. *Proceedings of the 53rd Midyear Conference of the Engineering Design Graphics Division of the American Society for Engineering Education*, Columbus, Ohio, January 15-17, 1999.

_________. (2001). Navy Explains Delays in the LPD 17 Program. *Sea Power,* 44 (7), 22-23.

Neath, I. (1998). *Human memory.* Pacific Grove, CA: Brooks-Cole.

Newel, A. & Simon, H.A. (1972). *Human problem solving.* Upper Saddle River, NJ: Prentice-Hall.

Nilsen, E., Jong, H., Olson, J., Biolsi, I., & Mutter, S. (1993). The growth of software skill: A longitudinal look at learning and performance. *Proceedings of INTERCHI'93,* pp. 149-156.

Norman, D.A. (1983). *Some observations on mental models.* In D. Gentner & A.L. Stevens (eds.) Mental Models. p. 7-14.

Olson, J. R. & Biolsi, K.J. (1991). *Techniques for representing expert knowledge.* In K.A. Ericsson & J. Smith (Ed.) Toward a general theory of expertise (p. 240-285). Cambridge: Cambridge University Press.

Otway, H. & von Winterfeldt, D. (1992). Expert judgement in risk analysis and management: Process, context, and pitfalls. *Risk Analysis, 12*(1), 83-93.

Panel on Engineering Infrastructure Diagramming and Modeling, Committee on the Education and Utilization of the Engineer, Commission on Engineering and Technical Systems, National Research Council. Published by National Academy Press, Washington, D.C. 1986. ISBN 0-309-03639-9. Page 74-75.

Paivio, A. (1986). *Mental representations: A dual code approach.* New York, NY: Oxford University Press.

Patton, M. (1990). *Qualitative evaluation and research methods* (2nd ed.). Newbury Park, CA: Sage Publications.

Polanyi, M. (1962). Personal knowledge: Towards a post-critical philosophy. Chicago, IL: University of Chicago Press.

Polkinghorne, D.E. (1989). Phenomenological research methods. In R.S. Valle & S. Halling (Eds.), *Existential-phenomenological perspectives in psychology* (pp. 41-60). New York: Plenum.

Proctor, R.W. & Dutta, A. (1995). *Skill acquisition and human performance.* Thousand Oaks, CA: Sage.

Ricoeur, P. (1979). The human experience of time and narrative. *Research in Phenomenology, 9,* 17-34.

Rohrer, W.D. & Thomas, J.W. (1989). *Domain-specific knowledge, metacognition, and the promise of instructional reform.* In E.L Bjork, & R.A. Bjork (Eds.) Cognitive strategy research (pp. 104-132). New York: Springer-Verlag.

Romanyshyn, R. (1981). *Science and reality: Metaphors of experience and experience as metaphorical.* In R.S. Valle & R. von Eckartsberg (Eds.) The metaphors of consciousness (pp. 3-19). New York: Plenum Press.

Rosenfeld, L.W. (1995). *Solid modeling and knowledge-based engineering.* In D.E. Lacourse (Ed.) Handbook of solid modeling. New York: McGraw-Hill.

Samurcay, R.. (1995). *Conceptual models for training.* In J.M. Hoc, P.C. Cacciabue, & E. Hollnagel (Eds.) Expertise and technology: Cognition and human-computer cooperation (pp. 107-124). Hillsdale, NJ: Lawrence Erlbaum Associates.

Schoenfeld, A.H. (1999). Looking toward the 21st century: Challenges of educational theory and practice. *Educational Researcher,28* (7)*,* 4-14.

Schein, E. (1973). *Professional education.* New York: McGraw-Hill. p. 43.

Schon, D.A. (1983). *The reflective practitioner.* New York: Basic Books.

Scribner, S. (1984). *Studying working intelligence.* In B. Rogoff & J. Lave (Eds.) Everyday cognition: Its development in social context (pp. 9-40). Cambridge, MA: Harvard University Press.

Simon, H.A. (1959). Theories of decision making in economics and behavioral science. *American Economic Review, 49,* 253-283.

Simmel, G. (1971). *On individuality and social forms* (K.H. Wolf, Trans., D.N. Levine, Ed.). Chicago, IL: The University of Chicago Press.

Simon, H.A. & Chase, W.G. (1973). Skill in chess. *American Scientist, 61,* 394-403.

Skolimowski, H. (1972). *The structure of thinking in technology.* In C. Mitcham & R. Mackey (Eds.) Philosophy and technology: Readins in the philosophical problems of technology (pp. 42-49). New York: Free Press.

Stein, M.K., Baxter, J.A., & Leinhardt, G. (1990). Subject matter knowledge and elementary instruction: A case from functions and graphing. *American Educational research Journal, 27,* 639-663.

Stein, N.L., & Trabasso, T. (1982). *Children's understanding of stories: A basis for moral judgment and dilemma resolution.* In C. J. Brainerd & M. Pressley (Eds.) Verbal processes in children. Vol. **2**. (pp. 161-188). New York: Springer-Verlag.

Sternberg, R.J., Forsythe, G.B., Hedlund, J., Horvath, J.A., Wagner, R.K., Williams, W.M., Snook, S.A., & Grogorenko, E.L. (2000). *Practical intelligence in everyday life.* Cambridge, UK: Cambridge University Press.

Sutcliffe, A.G. & Maiden, N.A.M. (1992). Analysing the novice analyst: Cognitive models in software engineering. *International Journal of Man-Machine Studies*, 36, 719-740.

Tennant, M & Pogson, P. (1995). *Learning and change in the adult years.* New York: Jossey-Bass.

Trimble, G. (1989). *Knowledge elicitation – some practical issues.* In D. Diaper (Ed.) Knowledge elicitation: Principles, techniques and applications (pp. 223-234). New York: John Wiley and Sons/Halsted Press.

Tulving, E. (1985). How many memory systems are there? *American Psychologist*, *40*, 385-398.

Unigraphics Solutions. (2000). White paper: Addressing the CAD/CAM/CAE interoperability issue.

Vincenti, W.G. (1990). *What engineers know and how they know it: Analytical studies from aeronautical history.* Baltimore, MD: The Johns Hopkins University Press.

von Eckartsberg, R. (1981). *Maps of the mind: The cartography of consciousness..* In R.S. Valle & R. von Eckartsberg (Eds.) The metaphors of consciousness (pp. 21-93). New York: Plenum Press.

von Eckartsberg, R. (1998). *Introducing existential-phenomenonological psychology.* In R. Valle (Ed.) Phenomenological inquiry in psychology: Existential and transpersonal dimensions (pp. 3-20). New York: Plenum Press.

__________. (2000). White paper: Behavioral modeling. Parametric Technology Corporation.

Weber, M. (1978). *Economy and society.* London: University of California Press.

Wenger, E. (2000). *Communities of practice: The key to knowledge strategy.* In E.L. Lesser, M.A. Fontaine, & J.A. Slusher (Eds.) Knowledge and Communities pp. 3-20. Boston, MA: Butterworth - Heinemann.

Wickens, C.D. & Hollands, J.G. (2000). Engineering psychology and human performance. (3 ed.). Upper Saddle River, NJ: Prentice-Hall.

Wiebe, E.N. (1999). 3-D constraint-based modeling: Finding common themes. *Engineering Design Graphics Journal, 63*(3), 15 - 31.

Williams, R., Faulkner, W., & Fleck, J. (Eds.). (1998). *Exploring expertise.* Houndmills, UK: Macmillan Press.

Woolgar, S. (1987). *Reconstructing man and machine: A note on sociological critiques of cognitivism.* In W.E. Bijker, T.P. Hughes, & T.J. Pinch (eds.) The social construction of technological systems: New directions in the sociology and history of technology. Cambridge, MA: The MIT Press, p. 311 - 328.

Wu, T.F., Custer, R.L., & Dyrenfurth, M.J. (1996). Technological and personal problem solving styles: Is there a difference? *Journal of Technology Education, 7*(2), 55-71.

Young, R.M. (1983). *Surrogates and mappings: Two kinds of conceptual models for interactive devices.* In D. Gentner & A.L. Stevens (eds.) Mental Models. pp. 35-52. Hillsdale, NJ: Lawrence Erlbaum Associates.

Yule, R. (2002, January). How CAD training pays for itself. *Machine Design, 74*(1). pp. 96.

Zimmerman, B.J. (1995). Self-regulation involves more than metacognition: A social cognitive perspective. *Educational Psychologist, 30* (3), 217-221.

Zsambok, C. E. (1997). *Naturalistic decision making: Where are we now?* In C. E.

Zsambok & G. Klein (Eds.) Naturalistic decision making (pp. 3-16). Mahwah, NJ: Lawrence Erlbaum Associates.

APPENDIX A

Contact and Consent Forms for Participants

August 1, 2002

Dear ___________,

Thank you for your interest in my dissertation project. I believe that it will yield results that will be beneficial for academic institutions and industry alike. For several years now, companies have struggled with how best to train their employees in the use of constraint-based CAD. Likewise, academic institutions have been slow to adopt the technology, and are now faced with similar problems - not just with regard to teaching students, but also in bringing faculty up to speed with the CAD tools. It is my goal that my dissertation will shed some light on the subject by providing information with regard to how experts use constrain-based CAD tools (i.e., create and edit parts and assemblies).

In order to accomplish this, I am going to need access to people in industry who have experience, and likely expertise, in the use of constraint-based CAD. Not just from the standpoint of being able to run the software, but I will need access to people that understand the fundamental characteristics and relationships that underlie constraint-based CAD and give these tools their power. This will require that I spend time at companies to develop relationships with the people there, to observe them as they work, and to interview them individually to get personal accounts of their strategies and the methods they employ within the CAD tool. I realize the sensitivity of entering an industrial setting, and it is my intent to keep my level of intrusion to a minimum. While I will certainly be engaged with people at these companies, I will not ask any more of them than they are willing to share. Since I will likely be observing participants at more than one company, any information revealed to me will be held in the strictest confidence so as not to compromise any of the parties involved. In addition, all participants in the study will be kept anonymous, unless they specify otherwise.

Data collection for this dissertation will consist of four elements: observations, interviews, protocol analysis, and a card-sorting task. The observations and interviews will serve as a means to gather information concerning the development process of expertise from both an educational and social perspective. Protocol analysis and card-sorting tasks are both cognitive measures designed to elicit a person’s knowledge and thought structure regarding a particular topic, in this case, constraint-based CAD. The interviews and observations will be analyzed to reveal emergent themes within the dialogue, and the cognitive measures will be analyzed to reveal the relationships between various concepts within this field. Given that this data collection process will occur over the period of several months, it is unlikely that I will need large amounts of exclusive access to a participant in the course of any given day. Other than the ongoing observations of the participants, the remaining data collection procedures will be scheduled in advance with the participant so as not to adversely impact their daily schedule.

Thanks again for your attention and help in this manner. If you have any further questions, please contact me, and I would be happy to discuss these items in greater detail. I can be reached at (919) 515-1740 (office/receptionist), (919) 414-9203 (cell), (919) 466-0655 (home), or nate_hartman@ncsu.edu. I am looking forward to working with you during the course of this project, and together we may be able to uncover information to aid academic and professional education in the use of constraint-based CAD tools.

Professionally yours,	Professionally yours,
Nathan W. Hartman Researcher	Theodore J. Branoff Co-Chairman of Graduate Research Committee

North Carolina State University
INFORMED CONSENT FORM

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

Principal Investigator: Nathan W. Hartman   Faculty Sponsors: Theodore J. Branoff

You are invited to participate in a research study. The purpose of this study is to examine the development and definition of expert usage of constraint-based computer-aided design (CAD) tools. The application of expert knowledge in the creation of three-dimensional representations (electronic models) of an object is central to the effective use of these tools in academic and industrial situations. The electronic models of interest are Part and Assembly files created within the CAD tools, because these files contain significant amounts of information about the design of the product and the thought process of the designer.

INFORMATION

The methods by which data will be gathered for this research project include observations, interviews, problem-solving tasks, and semantic mapping tasks. The observations and interviews will be recorded, through hand notation, audio recording, and potentially video recording. They will be analyzed in an effort to determine common themes that exist in the participants' responses regarding their past and present experiences and how those experiences have affected their development of expertise in the use of these types of CAD tools. The participants will also be involved in think-aloud protocol tasks, which ask them to verbalize their thought process as they solve a problem. In doing so, the researcher can gain access to the strategies used by each participant. In addition, the participants will conduct semantic mapping tasks, which require them to group related concepts that have been written on cards. The grouping is based on the participants' perceived relationship between these terms in accordance with their own personal experiences.

The observations will occur first with the researcher visiting each participant in order to observe the setting and the participant in that setting. The observations will vary in duration, but it is the goal of the researcher to be a frequent visitor within the participant's work environment. After using the information gathered in the observation to aid in finalizing an interview guide, the researcher will arrange an interview with the participant. This interview will consist of the researcher asking the participant a series of questions. The participant will be allowed to respond with as much or as little information as they choose. The interview session will last approximately two (2) to three (3) hours. The researcher will make an audio recording of the session for future transcription and reference. These transcripts will serve as the source of the common themes used to compose the preliminary model of the development of expertise related to the use of constraint-based CAD tools. Next, the researcher will ask the participant to perform a problem-solving task as described above. The transcript from this task will be used to form the basis for the definition of expertise related to the use of constraint-based CAD tools. Finally, the researcher will ask the participant to perform the semantic mapping task. Results from the individual participants will be compared to their problem-solving task transcripts to uncover any common elements between the two sets of information. In addition, the semantic maps from the individual participants will be synthesized into a common graphical representation that can be used as the second part of the foundation of the definition of expertise in the use of constraint-based CAD tools.

RISKS

No risk should be involved in participating in the study. Responses and the identity of each participant will remain confidential even though the results will be reported relative to each participant. Only the researcher will have access to the data. The researcher will attempt to maintain a casual rapport with the participant, and make a concerted effort to minimize the intrusiveness of each visit. The researcher is also sensitive to the fact that these sessions will be conducted typically within the participants' places of employment, and confidentiality will be maintained at all times.

BENEFITS

The benefits to be gained from this study include:

- Expert strategy to be used in the composition of teaching materials for engineering/technical graphics courses in an academic setting
- Specific information with which to create curricula for corporate training courses in the use of constraint-based CAD tools
- The insight gained by the participants into their own problem-solving and knowledge-structuring processes

CONFIDENTIALITY

The information in the study records will be kept strictly confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwise. No reference will be made in oral or written reports that could link you to the study.

COMPENSATION

No monetary compensation will be given for participation in this study. The researcher will share any findings related to the study with the participants in an effort to establish a good working relationship and as a manner of reciprocation for the participants' time invested in the project. If any participant should withdraw, the researcher will share any findings with the participant at the time of withdrawal.

CONTACT

If you have questions at any time about the study or the procedures, you may contact the researcher at

Nathan W. Hartman
Box 7801
502H Poe Hall
NC State University
Raleigh, NC 27695-7801
(919) 515-1740
nate_hartman@ncsu.edu , or

Theodore J. Branoff, Assistant Professor
Box 7801
510C Poe Hall
NC State University
Raleigh, NC 27695-7801
(919) 515-1747

If you feel you have not been treated according to the descriptions in this form, or if you feel that your rights as a participant in research have been violated during the course of this project, you may contact:

Dr. Matthew Zingraff
Chair of the NCSU IRB for the Use of Human Subjects in Research Committee
Box 7514, NCSU Campus
(919/513-1834), or

Mr. Matthew Ronning
Assistant Vice Chancellor, Research Administration
Box 7514
NCSU Campus
(919/513-2148)

PARTICIPATION

Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Subject's signature____ **Date** _________________

Investigator's signature___________________________________ **Date** _________________

APPENDIX B

Participant Personal Information Form

Participant Information

Name: ___________________________________

Prefer to go by: ___________________________

Age: __________________

Contact Address:

____

____

____

Phone Number: _____________________________

E-mail address: _____________________________

What is your educational background? ____________________________________
____
____
____

What is your current job title? ____

Which CAD tool do you use most? ______________________ **For how many years?** _____________

Have you ever had formal training (academic or professional) in the use of a CAD tool? __________ **What levels of training have you received?** ____________
____
____

Any additional information you would like to provide to describe yourself?
____
____
____
____

APPENDIX C

Observation Guide

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

OBSERVATION GUIDE

What does the participant's work environment look like? What kinds of resources are available in the participant's personal space and what do they have to go look for?

Does the participant tend to help others in their group?

What information does the participant gather to solve a problem?

From what direction does information primarily flow to the participant? Is it from a superior or a colleague?

Who does the participant talk to during the course of the day? Is it professional or personal? What do they talk about?

Do other colleagues approach the participant to solicit help or information related to the use of the CAD tool?

What are the participant's mannerisms as they complete their daily work? Do they seem at ease, frustrated, confident, content, etc? How does this affect their ability to complete their work?

Does the participant seem to solve their problem right away or does it take a while?

How does the participant approach the use of the CAD tool when working with a design? Do they have a particular procedure or routine that they follow when using the CAD tool or are they random in their choices?

How do the participants use past experiences to influence what they are working on currently?

What resources are available to the participant to help them use the CAD tools (model libraries, lessons learned, databases, consultants, etc.)

APPENDIX D

Interview Guide

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD: Examining Practicing Professionals

Interview Guide

Prior Work Experience

1. How would you describe your describe your past work experiences with respect to CAD use?
2. How was CAD involved in those experiences?
3. Do you work mostly with parts, assemblies, or drawings? Why?
4. Describe any formal software training that you have received. Was it beneficial?

Current Work Experience

5. How would you describe your current work experiences with respect to CAD use?
6. Do you work mostly with parts, assemblies, or drawings? Why?
7. Describe a typical day at your job.
8. Describe a typical project that you work on.
9. How is CAD involved in those experiences?
10. What is your level of involvement in a new design?
11. Describe the current project you are working on, and how does CAD fit into that project.

Personal Work and Learning Style

12. How would you describe your personal learning style?
13. If you have to learn something new, how do you go about it?
14. How do you address any challenges that you face in doing your job?
15. In the use of the CAD tool, if you must use a function that you have never used before, how do you proceed?
16. What factors must you consider when using the CAD tool on a particular design? How do you address those factors? **(look at prompts)**
17. Are there any specific characteristics of the CAD tool that you must consider when working with a particular design? How do you address those considerations? **(look at prompts)**

CAD Tool Information

18. How would you describe the CAD tools that you have liked using?
19. How would you describe the CAD tools that have posed you any challenges?
20. Describe an operation that you find easy to perform using the CAD tool. Why is that?
21. How do you overcome any challenges you face in using the CAD tool? Why do you use those techniques?
22. Do you employ any techniques in the use of the CAD system that allow you to work faster? How would you describe them? Why did you select those in particular?
23. How do you know that you have modeled something “correctly” (i.e., according to your intentions or the requirements of the project)?

24. If you encounter a model that was not modeled in an optimal fashion, how do you deal with that?
25. How would *you* describe an expert constraint-based CAD user?

Prompts

Can you be more specific?

Why is that?

Did I understand you to say…?

What about…
- P/C refs
- Associativity
- Critical dims
- Geometry or feature-creation tools
- Interface
- Duplication vs. individual features

APPENDIX E

Think Aloud Modeling Task Description

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

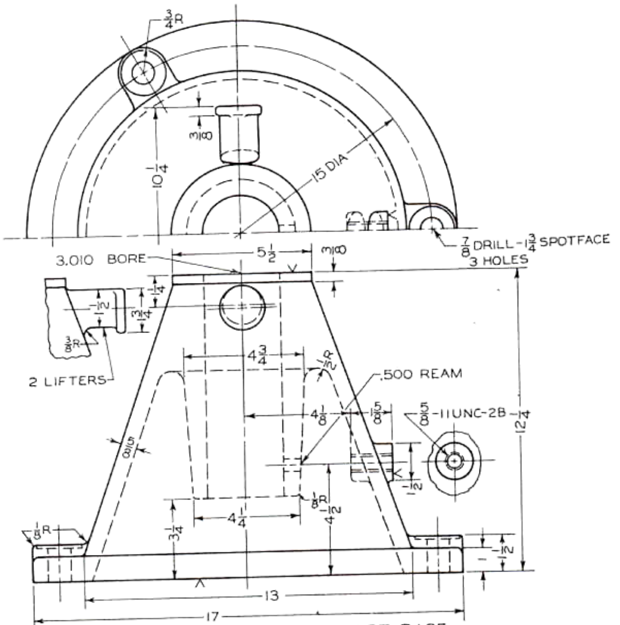
THINK ALOUD MODELING TASK DESCRIPTION

This think aloud modeling task is designed to elicit an applied example of the thought process and modeling strategy employed by experienced users of constraint-based CAD tools. Before you begin creating the 3D model, please discuss the overall plan or strategy that you will be using to create the model, including potential software command choices, modeling references, feature creation order, feature type, etc.

Throughout the course of modeling the specified object, talk aloud concerning what it is you are thinking and how you are going to approach the creation of this geometry. As you model the object, discuss your decision-making and reasoning processes that you are using regarding things like command choices, reference choices, choice of feature type, order of feature creation, consideration of other parts in the assembly, manufacturing processes, etc. This is not a comprehensive list. If there are other contributing factors that affect the way you create this model, please discuss those as well.

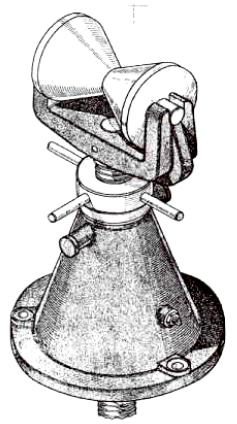
The accompanying illustration contains the given information for the modeling of this object. For this task, please create a 3D solid model of Part 1 (STOCK SUPPORT BASE) using the information provided as well as knowledge from your own personal experiences. It may not seem that this object is the most complicated part in the assembly, but it has been selected because it provides you with the opportunity to make choices that are of interest to the researcher concerning the creation of the geometry. While this modeling scenario has been deemed complete for the purposes of this research project, if you encounter a situation where you believe information is missing, please make an appropriate substitution for that information based on your own personal experience. In addition, please include that decision in the discussion of your modeling strategies.

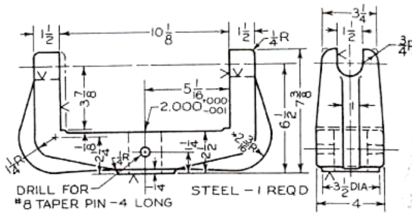
After you are finished modeling the object, there will be a short debriefing session with the researcher to examine in more detail some of the more critical passages involved in this task. Again, thank you for your time and participation in this research project.



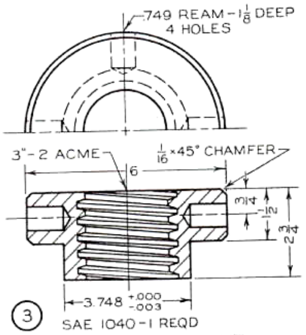
① STOCK SUPPORT BASE

CAST IRON-1 REQD





② SUPPORT ROLLER BRACKET



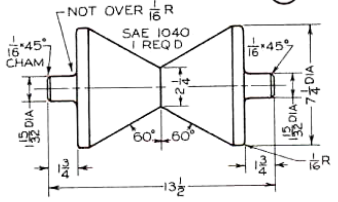
③ SAE 1040-1 REQD

ADJUSTING SCREW NUT

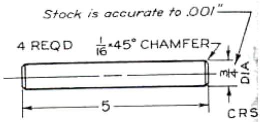
STOCK ITEMS

⑨ 1-#8 TAPER PIN 4" LENGTH

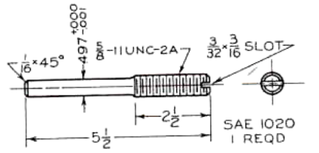
⑩ 1-5/8" FIN. HEX JAM NUT



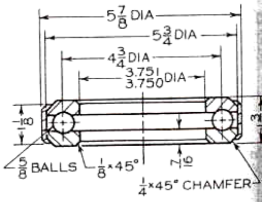
④ STOCK SUPPORT ROLLER



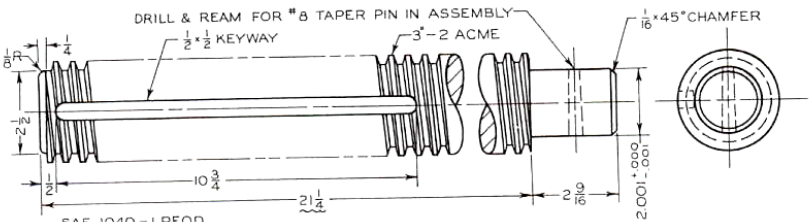
⑦ ADJUSTING NUT HANDLE



⑥ ADJUSTING SCREW GUIDE



⑧ THRUST BEARING



SAE 1040-1 REQD ⑤ SUPPORT ADJUSTING SCREW

Adapted from:Giesecke, F.E., Mitchell, A., Spencer, H.C., Hill, I.L., Dygdon, J.T., & Novak, J.E. (1993). *Technical Drawing (9th ed.).* New York, NY: Macmillan Publishing Company.

APPENDIX F

Knowledge Mapping Task Description

Towards the Definition and Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

KNOWLEDGE MAPPING TASK DESCRIPTION

This knowledge-mapping task is designed to elicit an applied example of the mental model employed by experienced users of constraint-based CAD tools. This task is intended to gather information about the relationships between the major concepts involved in the use of constraint-based CAD tools. For the purposes of this research project, this information will be used to define the initial boundary of the knowledge base regarding constraint-based solid modeling. Interaction with the researcher will be kept to a minimum during the task so as not to influence the placement of a particular concept in a specific location. After the task is complete, a short question and answer session will be conducted to follow up on any questions the researcher may have regarding the finished layout of the cards.

The accompanying collection of cards will be used for this task. Printed on each card is a word or phrase that represents a concept that is in some way related to the topic of constraint-based CAD tools. These concepts were derived from the researcher's observations, interviews, and modeling tasks with the participants of this study and from relevant commercial and academic literature. It is up to each participant to arrange the cards into whatever relationship they deem necessary based on their *own* personal experience with the topic of using constraint-based CAD tools. The following list includes key activities to be completed by each participant during the course of this exercise:

- Review the concept on each card. This will allow you to familiarize yourself with each term and to ask the researcher for any clarification as to what the term might mean. However, each word or phrase should be thought of in terms of using a constraint-based CAD tool to create a solid model of a part.

- Begin to arrange the cards based or *your* perception and experiences of the relationships between the concepts. These arrangements may take the form of clusters, hierarchies, linear sequences, or random locations; however, the final arrangement(s) should be based on *your* experiences alone with respect to solid modeling.

- Feel free to arrange and re-arrange the cards as many times as necessary. Also feel free to verbalize your thought process as it may help you think about the relationships that you are trying to portray.

- While the researcher has attempted to make this list of concepts as complete as possible, you may find that some concepts are missing *or* that some concepts should be removed based on your experiences. In either case, feel free to add and remove concepts as you see fit. However, please give your reasons for doing such so that the researcher may record them for further review and discussion.

- Once you have finished your arrangement, including any cards added or removed, notify the researcher that you are finished. Your arrangement will be recorded based on code numbers in the upper right corner of each card. These numbers have no other significance than for archival purposes.

After you are finished arranging the concepts according to your experiences with the topic, there will be a debriefing session with the researcher to examine the placement of concepts and their relationships to each other, as well as the reasons for removal or addition of any cards. This will also serve as a means for clarification of any of the thoughts that were brought out during the knowledge-mapping task. Again, thank you for your time and participation in this research project.

List of Terms for Knowledge Mapping Task

Each of the terms in the table corresponds to the numbered card used in the knowledge mapping task.

1. Feature
2. Part
3. Assembly
4. Drawing
5. Protrusion (Boss/Base)
6. Cut
7. Round (Fillet)
8. Draft
9. Shell
10. Datum Plane
11. Datum Axis
12. Parent/Child Reference
13. Design Intent
14. Modify
15. Redefine (Edit Sketch)
16. Reorder
17. Failure Mode/Error
18. Inset Mode
19. Roll Back Model
20. Use Edge (Convert Entities)
21. Offset Edge
22. Extrude
23. Revolve
24. Sweep
25. Blend (Loft)
26. Model Interrogation
27. Regen Info (Roll Back
28. Model Tree (Feature Tree)
29. Parent/Child Ref. Info
30. Surface Geometry
31. Skeleton
32. Modeling Standards
33. Manufacturing Proc.
34. IGES
35. Simplified Rep
36. Customer Requirements
37. Assembly References
38. Datum Curves
39. Past Experiences
40. Geometric Construction
41. Drafting
42. Constraints (Relations)
43. Sketching References
44. Sketching Orientation
45. Blind
46. Through All
47. Up to Surface
48. Primitive Geometry
49. Boolean
50. Downstream Use Model
51. Relations (Equations)
52. Sketch (Profile)
53. Sketching Plane
54. Origin
55. Pattern(s)
56. Associativity
57. Component
58. PDM
59. Base Feature
60. Family Table
61. Instance(s)
62. Moldflow Analysis
63.FEA
64. CFD
65. Sheetmetal
66. Over-constrained
67. Under-constrained
68. Coordinate System
69. Group
70. Copy
71. Mirror
72. Suppress
73. Mass Properties
74. Measure (Command)
75. Spatial Envelope
76. Interaction b/w Parts
77. Dimensioning
78. Parametric
79. Constraint-based
80. Feature-based
81. Threads (Cosmetic)
82. Parameter
83. Dimension-driven
84. Feature Order
85. Modeling Procedure
86. Centerline
87. Regenerate (Rebuild)
88. Delete
89. Visualization
90. Default Datum Pln.*
91. Geometry Creation*
92. Geometry Editing*
93. Suppliers*
94. Application of Part*
95. Material Selection*
96. Chamfer**

* Added by Participant 1
** Added by Participant 4

Included Concepts in the Major Groupings of Concepts for Each Participant
Each participant's major groups contained in the knowledge map and the constituent concepts of each group are listed below. The order of the numbers in each group is significant to each participant.

Participant 1

Customer Requirements: 36
Part Application: 94
Manufacturing Processes: 93, 33, 95
Visualization: 89
Past Experiences: 39
Downstream Usage of the Model: 50, 62, 63, 64, 58
Consideration of the Assembly: 3, 76, 31
Component: 57
Part: 2
CAD Tool Characteristics: 78, 79, 13, 56, 83, 80
Geometry Construction: 40
Feature: 1, 28
Default Datum Planes: 90
Base Feature: 59
    Geometry Creation: 91
        Surfaces: 30
        Types of Features: 5, 6, 7, 8, 10, 11, 58, 81, 9
            Feature Forms: 25, 22, 23, 24, 86
            Aspects of Using Sketcher: 67, 44, 66, 43, 82, 42, 77, 51, 20, 21, 52, 53
            Depth Options: 45, 46, 47
            Feature Duplication: 55, 60, 71, 70, 61, 69
    Geometry Editing:92
        Model Interrogation: 26, 29, 37, 27
        Editing Functions: 14, 15, 16, 18, 71
        Errors: 17, 19, 88, 87, 12, 84, 72
Information Gathering Functions:73, 74, 75
Drawing: 4
Drawing Output: 34, 41

Participant 2

Basic Design Guideleines:36, 33, 13, 32,
Things to Know Ahead of Time: 39, 41, 56, 58, 89
The Way Things are Built:52, 31, 1, 2, 57, 3, 4
Reference Geometry: 59, 5, 6
Additional Reference Geometry: 9, 30, 7, 8, 65, 81
Ways to Add or Remove Material: 22, 23, 24, 25
Feature Creation Sequence: 53, 44, 43, 77, 47, 45, 46
Advanced Geometry Manipulation: 70, 88, 71, 55, 69

Using Existing Geometry: 20, 21
Making the Model Work for You: 78, 12, 83, 80, 79
More Advanced Geometry Manipulation: 14, 15, 76, 84, 51, 42, 37, 87, 18, 82, 16, 19, 72, 60, 61
The Basic Pitfalls: 67, 66
How to Get Around the Pitfalls: 26, 29, 17, 27, 28, 35
Basic Outputs from the Model: 74, 73
Advanced Output to Other Software: 63, 62, 64, 75, 34

Participant 3
Characteristics of CAD Systems: 78, 79, 80, 56, 48, 49, 40, 83, 82, 65
Downstream Uses of the Model: 39, 41, 36, 58, 85, 32, 33
Assemblies: The Context in Which the Part is Created: 3, 76, 57, 59, 35, 37, 31
The Meat: Creating the Product in the CAD Tool: 4
    Datums and References: 86, 68, 11, 54, 53, 44, 43, 38, 10
    Various Ways to Create a Feature: 1, 5, 6, 25, 24, 23, 22
    Sketching and the Sketching Process: 52, 21, 20, 77, 45, 46, 47, 67, 66
    Tweaking the Initial Sketch: 8, 7, 9
    Parametric Creation of Geometry Based on the Initial Part: 14, 88, 87, 72, 69, 70, 71, 55, 18, 16, 15
    Geometry Manipulation: 60, 51, 61, 42
    Gathering Information from the Model: 26, 28, 75, 13, 74, 73, 29, 27, 19, 12, 17, 30
Visualization of the Design: 89
Existing Parameters that Control How You Do Things: 50, 64, 63, 62, 4, 81, 34

Participant 4
Design Parameters: 13, 36, 85, 84, 32, 75, 39
Design Scenario Requirements: 50, 34, 33
Different Types of CAD Systems and Their Uses: 56, 83, 82, 79, 78, 80
Basic Set-up of Constraint-based CAD Tools: 68, 54, 10, 11
Basic Assembly Information: 3, 31, 2, 57, 67, 66
Basic Types of Feature Construction: 1, 59, 5, 22, 6, 23, 24, 25
Basic Tools Used to Create a Sketched Feature: 53, 44, 43, 52, 40, 77, 86
Depth Options for Sketched Features: 45, 46, 47
Additional Feature Types: 8, 7, 96, 9, 9, 38
Geometry Duplication and Manipulation: 71, 70, 69, 55
Drawing Information to Communicate with Others: 4, 41
Visualizing the Model: 89, 60, 61, 35, 81, 28, 72
Gathering Information from the Model: 26, 29, 27, 74, 73, 76, 37
Using the Model Elsewhere: 62, 63, 64
Editing the Model: 14, 15, 16, 18, 87, 17, 19, 88
Creating Parent/Child References: 12, 20, 21, 51, 42
Participant 5
Overall concepts that Affect Modeling Environment: 79, 80, 85, 75, 32, 78, 39, 41, 13, 26

- Creation of Parts: 2
    - Creating a Sketched Profile: 54, 68, 53, 52, 44, 43
    - References Used to Create a Sketch: 40, 86, 10, 11
    - Types of Primary Feature and Depth Options: 47, 45, 46, 22, 5, 6
    - Options for Creating Secondary Features: 81, 38, 25, 24, 23, 7, 8, 9
    - Specifying Dimensional references for Feature Creation: 77, 83, 56
- Creation of Features: 1
    - Things that Dictate feature Behavior: 59, 84, 16, 42
    - Common Operations to Parts and Assemblies
        - Things that Allow feature Creation: 70, 71, 55, 21, 69, 20
        - Editing a Feature: 14, 15
        - Ways to Review Features: 28
        - Feature Inquiry: 74
        - Feature Removal: 88
        - Secondary Feature Duplication and Manipulation: 35, 60
- Creation of Assemblies: 3
    - Things that Allow Assembly Creation: 18, 57
    - Considerations for Placing a Component: 82, 61, 76, 51, 37, 29, 12
    - Errors in Assembly Mode: 66, 17
    - Missing Information in the Assembly: 67
    - Operations to Gather Information: 87, 27, 19, 72
- Creation of Drawings: 4, 89
- Uses for the Model
    - Data Management: 58
    - Design for Manufacturing: 33, 36
    - Sheetmetal Part: 65
    - Downstream Use of the Model: 50, 63, 64, 62, 73, 34