The Development of Expertise in the Use of Constraint-based CAD Tools: Examining Practicing Professionals

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Abstract

This paper presents a portion of a research study which examined practicing engineering graphics professionals to discover their experiences in developing expertise in the use of constraint-based CAD tools. Using methods adapted from phenomenological inquiry and cognitive psychology, five practicing engineering design professionals were assessed in an effort to gauge the experiences that contributed to their development of expertise. Interviews and observations were conducted throughout the fall of 2002 to gather data relevant to the experiences of the participants. The thematic elements distilled from the interview and observation data comprised the initial developmental factors of expertise. The conclusions drawn from this study provide an initial look at the development of expertise in the use of constraint-based CAD tools as affected by social and environmental conditions. These conclusions also suggest specific potential teaching and assessment methodologies.

Introduction

The call for the integration of constraint-based CAD tools into engineering graphics curricula has been made (Miller, 1999; Ault, 1999; Branoff, Hartman, & Wiebe, 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, there is potential for greater usage of the solid model within the design enterprise. 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, due to varying 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 an assortment of 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 how expert users of constraint-based CAD tools acquire and develop knowledge is instrumental in the development of next-generation engineering graphics curricula given resources typically invested in the training of engineers and designers to use these CAD tools. 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 practicing designers experience expertise within this domain, as well as how they conceptualize it. 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. Specifically, how does one develop expertise in the use of constraint-based CAD tools? Of additional interest were the critical concepts that comprise the mental model and the software techniques of expert, constraint-based CAD users.

Relevant Literature

To address the questions regarding the development 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 observations that can be defined in terms of practical performances: materials, tools, and processes. All are specific to a particular framework or context in which they are useful, and 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 knowledge 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, to be held true by all people who are acknowledged as belonging to the profession. In addition, participants are only conscious of a small portion of the professional culture in which they reside. The remainder is tacit in the forms of cultural norms, traditions that are merely accepted. The domain knowledge is a summary total of all of the classical norms and traditions of the domain and those individuals that came before (Polanyi, 1962).

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.

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).

Developing expertise is an ongoing process of the acquisition and refinement of skills and knowledge that are needed within a particular professional domain. From the standpoint of using a particular tool, this is often done within collaborative work settings (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 a chosen 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 is also 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 entity.

All perspectives from which expertise was examined address the notion of practical intelligence and the fact that expertise should be gauged within the specific context of a particular domain. Practical intelligence is also linked to the strategic use of tools, such as constraint-based CAD. Several studies (Bhavnani, 1996, 1997, 1998, 1999) have examined the use of CAD from a 2D, architectural point of view, but the study of constraint-based CAD tools is lacking. Thus, this study was an initial attempt at addressing these issues.

Procedures

To address the development of expertise in the use of constraint-based CAD, this study used two methods: observations and interviews based on the phenomenological tradition of qualitative inquiry (Moustakas, 1994; Creswell; 1998; Giorgi, 1985). The nature of research regarding expertise and its assessment provides no clearly established procedures for all cases (Sternberg Forsythe, Hedlund, Horvath, Wagner, Williams, Snook, & Grogorenko, 2000). Since a localized concentration of experts within a domain is rarely found, 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). Polkinghorne (1989) and Meyer and Booker (1991) recommended the analysis of between five and twenty participants for an exploratory phenomenological study.

Potential companies 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. Human resources and engineering management personnel in these companies nominated people as potential participants for the study. Due to time and budgetary constraints imposed on this study, as well as reluctance on the part of companies to allow their designers to participate, five people were selected for participation 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.

Following is a brief description of each of the five participants:

• 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 holds a bachelor's degree and a master's degree from a foreign institute of technology, both of which are in mechanical engineering, and he is considered the resident constraint-based CAD expert in his group.

• Participant 2 is a twenty-four year old design engineer with a bachelor's degree in mechanical engineering, and he works for a multi-national corporation that designs and manufactures heavy equipment for the construction and transportation industries. He works in a large group with several other resident experts.

• Participant 3 is a fifty year old design engineer for a company that designs and manufactures custom packaging and cases for consumer products. He holds a bachelor's degree and a master's degree, both of which are in technology, and he works in a group with two other people—his boss and one coworker.

• 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 constraint-based CAD tools and uses it on a daily basis. It is a multi-national corporation that designs and manufactures electrical components for residential and commercial applications.

• 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. Participant 5 has a bachelor's degree in industrial technology and mechanical drafting and design.

The observations and interviews were conducted within the participants' places of employment to provide a naturalistic setting in which to observe the phenomenon (Creswell, 1998). The researcher's field notes and each participant's interview transcript were analyzed to look for common elements that signified their place within the social structure of the group and how their expertise was 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 related to expertise development in the use of constraint-based CAD tools.

The focus of the data analysis was the examination of experiences with the phenomenon of expertise and what that meant to each of the participants (Creswell, 1998; Moustakas, 1994). First, the researcher engaged in the epoche process in an effort to bracket his own experiences and biases towards the topic. Next, the transcript data was 'horizonalized' (Moustakas, 1994) to assign equal value to all critical statements. From these horizons, the significant 'meaning units' were listed and all duplicates were removed. Each significant phrase was noted and duplicates were eliminated. Based on their apparent similarities, these units were then clustered into themes (Moustakas, 1994) to describe the phenomenon of expertise. From these clusters, a description of the development of expertise was made in terms of the descriptions given by the researcher, the participants, and the literature.

It was assumed that each participant had the following requisite expert characteristics to provide meaningful data for this study:

- 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.

Analysis and Findings

The observations and interviews yielded information relevant to the development of expertise that could be categorized into constituent themes of the phenomenon. Certain 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 of expertise in the use of constraint-based CAD tools 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 makes its own contribution to expertise in this domain, 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 served as a guide for applying various strategies to overcome challenges through the use of constraint-based CAD 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. 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.

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, allowed the participants to develop a strategic solution (Bhavnani, 1999). 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: some of them are related to actual use of the CAD tool and others are related to 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, 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 were 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 was given to the development of this phenomenon. The ways in which the experts worked with regard to specific command choices and combinations were in many cases determined by the strategies that they employed in the use of particular commands within the software package. In addition, any academic or professional training that the user might have had affected the design considerations that they attended to, the fundamental understanding of geometry they may have had, and any preconceived expectations about how the software may function. Corporate culture and the indoctrination 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 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 appeared that expertise in the use of constraint-based CAD tools contained knowledge about the operational processes of the CAD tool. It also contained other factors, while not directly related to the CAD tool, which influenced the use of that tool. While 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 to properly execute their plan.

Past and present experiences appeared 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. 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 had developed a particular method of working that has evolved from this problem solving approach.

Other past experiences included the progression from traditional drafting tools and methods to the use of constraint-based CAD tools in the case of the two older participants. This transition forced them to develop a new thought process when using constraint-based CAD tools that was different from the thought processes they used before (Collins, 1987). It was affected by design considerations, geometry creation, and dynamic relationships between design components more so than in the past. This was due in large part to the fundamental processes upon which the CAD tools operate. However, three participants were younger, and they never experienced the use of traditional drafting techniques and tools in their professional careers. They completed internships where they learned about the profession and its customary practices from mentors that guided them in the use of their tools.

Each of the participants had several years of experience within the engineering design profession, which 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 created an awareness of potential design considerations that must go into the creation of each model. They were communicating between themselves, suppliers, and customers via the CAD model (Henderson, 1999). This meant that they must model effectively with a sound strategy for geometry creation and modification.

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 became a collaboration device, similar to the conscription devices and boundary objects mentioned by Henderson (1999). The models carried in them the embodiment of the designer's ideas and requisite behavior for the model that could 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.

Each participant worked in an environment where they had 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 would pass technical specifications to the engineering groups, and they would begin to develop a solution based on company or industry design standards. The participants' past experiences and model interrogation techniques 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, each participant had a different support structure upon which to rely. Some participants used extensive corporate support groups while others were 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 were able to recognize the presence of certain conditions that were causing them difficulties within the CAD tool, such as missing references and invalid profile geometry.

For each participant, the size of their engineering groups varied, 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. 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 manner and capable of recognizing the critical characteristics of a problem situation and incorporate them into a solution. Experts would 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 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 would be able to create robust geometry that could 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 was only a tool by which to develop and document a design; it alone could not 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 contained 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 seemed to be important to the effective use of these tools.

In addition, these five participants expressed other factors, while not directly related to the CAD tool, which influenced 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 were some of the external factors that appear to have affected the development of expertise in these participants. Spending time in the shop working with the products they design gave them an awareness of the effects that their decisions in using the CAD tool had on the workings of the product (Vincenti, 1990). Experiences in machining operations and prototype design enabled them to better capture critical information within the CAD tool.

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. Again, however, they referenced the limited scope of the CAD tool it cannot develop an innovative or creative solution to a problem independent of the user.

A Description of the Constituent Themes of Expert Constraint-based CAD Usage

The development of expertise in the use of constraint-based CAD tools was comprised of many interrelated factors and themes. Certain themes were embodied in the results of actions that experts take, while others are the driving forces behind those actions. This phenomenon was the combination of knowing how and when to perform a particular action, and knowing what consequences that particular action would 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 'knowing how and knowing what': 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 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 to properly execute their plan. The following list contains a description of each of the constituent themes which embody expertise in the use of constraint-based CAD tools for the five participants, and their placement within each category is summarized in Table 1.

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 were 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 surrounds 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 their past experiences with 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. Professional and Academic Experiences — These 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. These experiences also included using both

Constituent Themes of Constraint-based CAD Tool Expertise		
Core Themes	**Subordinate Themes**	**Transitional Themes**
Strategy for Tool Use	Software Usage Techniques	Design Environment
Problem Definition and Solution	Downstream Uses of CAD Model	The Way the Expert Worked
Design Considerations	Technical Communication	Support Structures
Domain Knowledge	Social Communication	Artifacts
Professional and Academic Experiences	Requisite CAD Model Characteristics	Personal Characteristics
	Problem Solving Techniques	Typical Domain Activities
		Conceptions of Expertise
		Factors Related to CAD Usage

Table 1

traditional drafting tools and different levels of CAD tools, internships and apprenticeships, and designing a variety of different products

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 the Expert Worked — 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 with which they had problems. This awareness aided them in developing a feasible solution to a design problem that did not compromise their design strategy.

15. 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.

16. 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.

17. Problem Solving Techniques — 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

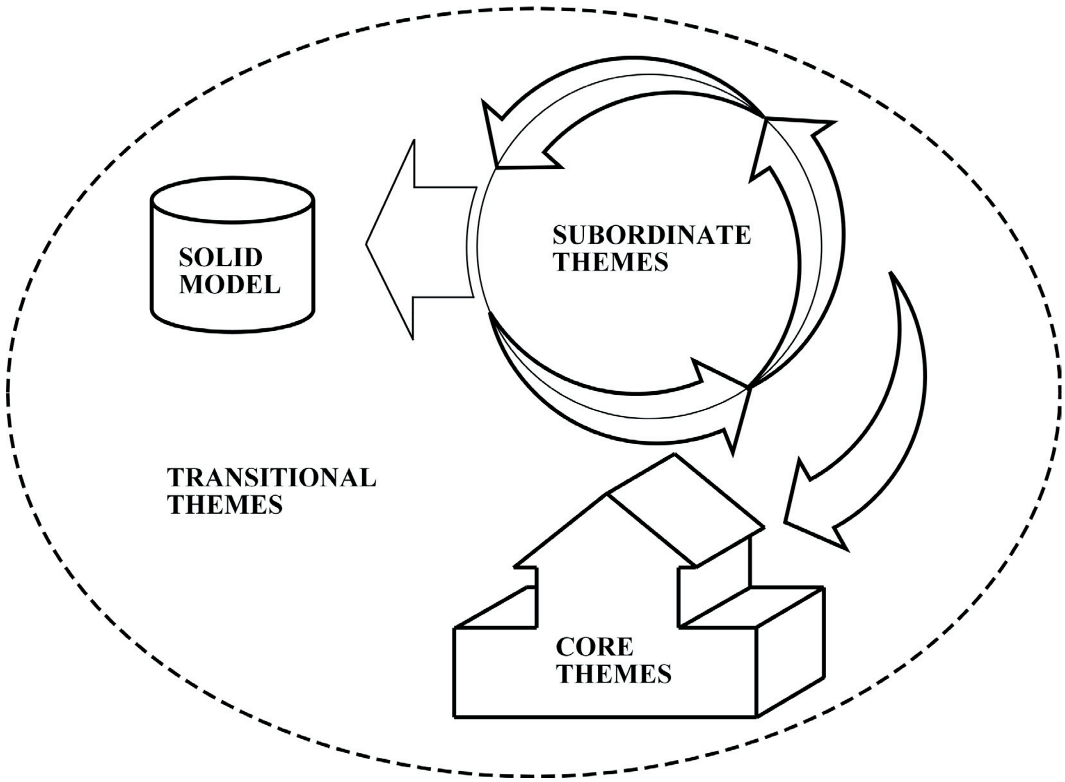

Figure 1 Process Diagram of Expertise in the Use of Constraint-based CAD Tools

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.

18. 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.

19. Requisite 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 'model' of the development of expertise in the use of constraint-based CAD tools is a combination of structural and procedural knowledge as indicated by the circular, process-oriented nature of Figure 1. The core themes combine to influence, as well as create the foundation for, the subordinate themes. They consist of the fundamental knowledge base of the engineering design discipline as it is expressed through the use of the CAD tool. In essence, these themes make up the "knowing what" portion of expertise in this area.

The core set of themes also receives feedback form the subordinate themes as a means of adapting and modifying problem solving style and the assimilation of newly acquired information. The subordinate themes are similar in their content with one important difference: they are process-oriented. The subordinate themes constitute "knowing how."

Both sets of factual and procedural knowledge both exist within the framework of the transitional themes, which embody choices made in using the software within the context of a professional design environment and its related artifacts. The content of these three groups of constituent themes taken together 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 interact 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. The observation and interview data discussed in the previous two sections of this paper 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.

Implications for Engineering Graphics Education

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. 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. Its emphasis is on the notion that knowledge couched in experience is a driving force behind the use of constraint-based CAD tools as a means for geometry creation and manipulation in the course of the engineering design process.

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.

For educators 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

Potential Curriculum Enhancements for Developing Constraint-based CAD Tool Expertise	
- Collaboration between students in the completion of the activities - Creation of a design scenario/context in which the activity takes place - Consideration of potential customer requirements - Assessment of student modeling activities based on design intent of the model	- Reverse engineering/redesign of complex parts - Extended modeling practice of a variety of different geometric forms - Assessment of changes and updates to the software package being used - Design changes that fit within the context

Table 2

collaboration between class members would be a good start. However, it is important to develop exercises that go beyond just creating the model. Table 2 provides a summary of potential techniques that could be incorporated into engineering design graphics curricula which embody the spirit if expert constraint-based CAD usage.

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.

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.

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