Defining Expertise in the Use of Constraint-based CAD Tools by Examining Practicing Professionals

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Abstract

Academic engineering graphics curricula are facing a rapidly changing knowledge base and current teaching and assessment methods are struggling to keep pace. This paper is the second in a two-part series which examines practicing engineering graphics professionals to discover their experiences in developing expertise in the use of constraint-based CAD tools. It presents the results of a knowledge-mapping task and think-aloud modeling task used with five practicing product designers to examine their solid modeling strategies used when creating a 3D model and their organization of the concepts surrounding the knowledge domain of constraint-based CAD tools. The results of the think-aloud modeling task yielded five specific modeling procedures which were distilled into one common modeling procedure for the given object. The results of the knowledge mapping task revealed five separate knowledge maps, and the common elements from each one were combined to form a generic knowledge map related to the use of constraint-based CAD tools. These two sets of results comprised the initial elements used to define expertise in the use of constraint-based CAD tools based on these five participants. This article provides an initial look at an approach to creating geometry with constraint-based CAD tools, as well as specific topics to be included in a curriculum that includes constraint-based CAD tools. These conclusions also suggest potential teaching and assessment methodologies.

Introduction

The engineering design graphics curriculum is at a crossroads. Computer technology is enabling engineers and technologists to design and manufacture parts without relying on two-dimensional drawings. However, the curricula at many universities, community colleges, and high schools still dedicate a great deal of time to covering 2D documentation drawings. There are several possible reasons why some programs have not changed to a curriculum that focuses on constraint-based, three-dimensional solids modeling, including cost (Miller, 1999), pedagogical issues (Clark & Scales, 1999), and traditional dogma (Branoff & Hartman, 2002). Where in the past drawings were critical components of the design process, today they tend to be ancillary documents. CAD technology is now being used to capture and store information that is critical to the definition of the product (Greco, 2000; 2001), not just its geometry. No longer are Boolean-based primitive CAD systems prevalent in the engineering design process (Dean, 2000).

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; Miller, 1999; Ault, 1999; Connolly, Ross, & Bannatyne, 1999). Three-dimensional constraint-based solid modeling is now being given due attention. In addition, applied and theoretical knowledge of engineering graphics are also being emphasized. 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. The tools that existed within the traditional 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.

Companies have adopted 3D CAD tools due to their advantages over 2D drafting: enhanced communication, visualization, accuracy, etc. (Dean, 2000). But at the beginning of the transition phase to 3D CAD, many CAD users still carried the mindset of using drawings as the basis of their work. 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 encouraging 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 while using this approach, the vast majority of them have not. Some of them do not need to be experts, but most of them should be more proficient (Cumberland, 2001). So it is imperative that the contemporary CAD tool user develop effective problem-solving strategies to accommodate the fluctuation in design variables which typically affect their design environment. The purpose of this exploratory research study was to explore the definition and development of expertise in the use of constraint-based CAD tools by examining practicing professionals. In addition, what are 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 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. The cognitive examination of expertise focused mainly on information processing theory, which examines the means by which humans process sensory information and encode it for storage into long-term memory (Gredler, 2001). This affects problem solving strategies, as well as mental models of how a knowledge base is defined and implemented (Johnson-Laird, 1983). This assimilation of past knowledge and present information forms the basis of mental model development. Developing expertise is an ongoing process of the acquisition and refinement of skills and knowledge that are needed within a particular domain of life (Keller & Keller, 1996).

From mental models and their inherent structures, experts are able to solve problems more quickly and accurately than novices. 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. This domain is what gives the individual the framework by which to assimilate new information to existing knowledge. Practical intelligence is also linked to the strategic use of tools, and constraint-based CAD is no exception. Several studies have examined the use of CAD from a two-dimensional, architectural point of view, but the study of constraint-based CAD is lacking in this area (Bhavnani, 1996, 1997, 1998; Bhavnani, John, & Flemming, 1999). Thus, this study was an initial attempt at addressing some of these issues.

Procedures

To address the development of expertise in the use of constraint-based CAD, this study used two methods of data collection with each participant: a think-aloud modeling task and a knowledge-mapping task. 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 performed when

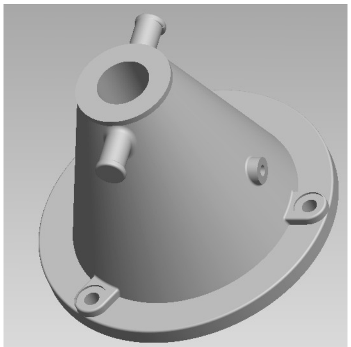
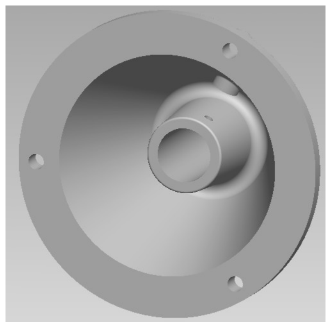


Figure 1 Think Aloud Modeling Task Figure -- STOCK SUPPORT BASE

Figure 1 Think Aloud Modeling Task Figure -- STOCK SUPPORT BASE (alternate view)



modeling an object. 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. Each participant was given the same written modeling scenario with an accompanying figure, and they were asked to create a 3D solid model of the STOCK SUPPORT BASE shown in Figures 1 and 2. This object was adapted from a common engineering design graphics textbook (Geisecke, Mitchell, Spencer, Hill, Dygdon, & Novak, 1993, p. 566). They were to use the additional given parts and the problem scenario for reference as necessary. The transcripts of these sessions were then analyzed to determine a common modeling procedure for the creation of the given object.

The knowledge mapping tasks were conducted with each participant in an effort to create a representation of their mental model regarding expertise in the use of constraint-based CAD tools. This was accomplished by labeling a series of note 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 conceptions of the importance of each item and the relationships between them. Participants were allowed to add or remove items from the list as desired. 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 then compared and combined with those from the other participants to create a common mental model of constraint-based CAD tools. Table 1 includes a list of the terms that were used.

Localized concentrations of experts within a domain are rarely found, hence the small number of participants in this study. 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 personnel 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 status as practicing professionals, years of experience in the engineering design field, years of experience using the CAD tool, frequency of CAD tool usage, complexity and applicability of geometry created, and educational background. Following is a brief description of each of the five participants:

- Participant 1 was 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 in mechanical engineering from a foreign institute of technology, and he is considered the resident constraint-based CAD expert in his group. Pro/ENGINEER was used at this company.

List of Terms for Knowledge Mapping Task			
1. Feature	25. Blend (Loft)	49. Boolean	73. Mass Properties
2. Part	26. Model Interrogation	50. Downstream Use Model	74. Measure (Command)
3. Assembly	27. Regen Info (Roll Back	51. Relations (Equations)	75. Spatial Envelope
4. Drawing	28. Model Tree (Feature Tree)	52. Sketch (Profile)	76. Interaction b/w Parts
5. Protrusion (Boss/Base)	29. Parent/Child Ref. Info	53. Sketching Plane	77. Dimensioning
6. Cut	30. Surface Geometry	54. Origin	78. Parametric
7. Round (Fillet)	31. Skeleton	55. Pattern(s)	79. Constraint-based
8. Draft	32. Modeling Standards	56. Associativity	80. Feature-based
9. Shell	33. Manufacturing Proc.	57. Component	81. Threads (Cosmetic)
10. Datum Plane	34. IGES	58. PDM	82. Parameter
11. Datum Axis	35. Simplified Rep	59. Base Feature	83. Dimension-driven
12. Parent/Child Reference	36. Customer Requirements	60. Family Table	84. Feature Order
13. Design Intent	37. Assembly References	61. Instance(s)	85. Modeling Procedure
14. Modify	38. Datum Curves	62. Moldflow Analysis	86. Centerline
15. Redefine (Edit Sketch)	39. Past Experiences	63.FEA	87. Regenerate (Rebuild)
16. Reorder	40. Geometric Construction	64. CFD	88. Delete
17. Failure Mode/Error	41. Drafting	65. Sheetmetal	89. Visualization
18. Inset Mode	42. Constraints (Relations)	66. Over-constrained	90. Default Datum Pln.*
19. Roll Back Model	43. Sketching References	67. Under-constrained	91. Geometry Creation*
20. Use Edge (Convert Entities)	44. Sketching Orientation	68. Coordinate System	92. Geometry Editing*
21. Offset Edge	45. Blind	69. Group	93. Suppliers*
22. Extrude	46. Through All	70. Copy	94. Application of Part*
23. Revolve	47. Up to Surface	71. Mirror	95. Material Selection*
24. Sweep	48. Primitive Geometry	72. Suppress	96. Chamfer**

* Added by Participant 1
** Added by Participant 4

Table 1

•Participant 2 was 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. Pro/ENGINEER was used at this company.

•Participant 3 was 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 in technology, and he works in a small group including his boss and one coworker. Pro/ENGINEER was used at this company.

•Participant 4 was 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 he uses them on a daily basis. It is a multi-national corporation that designs and manufactures electrical components for residential and commercial applications. Pro/ENGINEER was used at this company.

•Participant 5 was a twenty-eight year old designer for a company that designs and manufactures inoculation equipment for the poultry industry. He works in a group with four other designers, and they 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. SolidWorks was used at this company.

Findings

Think Aloud Modeling Task

Examination of the participants' modeling procedures and their 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 part functionality and inherent geometry, as well as the perceived efficiency of their modeling procedures. Participants were given the accompanying parts in the assembly for spatial and functional reference.

According to the participants' modeling procedures, feature order impacted the appearance of the finished geometry and the ability to modify existing features. Some participants decided to create as much geometry as possible within the 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 and their ability to capture design intent during geometry 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 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 the desired future orientation of that feature, but also on the references to other features. By being able to recognize inherent geometry within the model, each participant was able to effectively choose a feature type and appropriate orientation 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 shown in Figure 1 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.

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

Common Modeling Procedure	
1. Determine sketching plane	5. Apply feature form
2. Sketch profile	6. Repeat steps 1 through 5 to add major features
3. Add constraints/relations	7. Add material-removal features (holes, cuts, etc.)
4. Add dimensions	8. Add finishing features (rounds, fillets, etc.)

Table 2

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. Participants coupled this knowledge with the information presented in the given problem description 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, feature orientation, and the embedded relationships of the subsequent features used to finish the full description of the part geometry. The part modeling strategy of each participant generally focused on the creation of features which added material to the model first. Those features which removed material from the model tended to be created in a "secondary" fashion after much of the aforementioned geometry was in place.

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 common steps that emerged from the analysis of the participants' protocols gave some basic confirmation that the geometry creation process between constraint-based CAD tool brands (in this case, Pro/ENGINEER and SolidWorks) is similar. This commonality between tools from different vendors provides a basis for teaching fundamental concepts and strategies for creating geometry without promoting a focus on memorization of commands. It also provides basic confirmatory evidence of previously suggested techniques (Wiebe, 1999). In doing so, the body of engineering design graphics knowledge is enhanced during the use of a particular class of tools, and not simply one from a single vendor. Table 2 details the modeling procedure that emerged from the analysis of data provided by the five participants.

Knowledge Mapping Tasks

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 provided 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 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

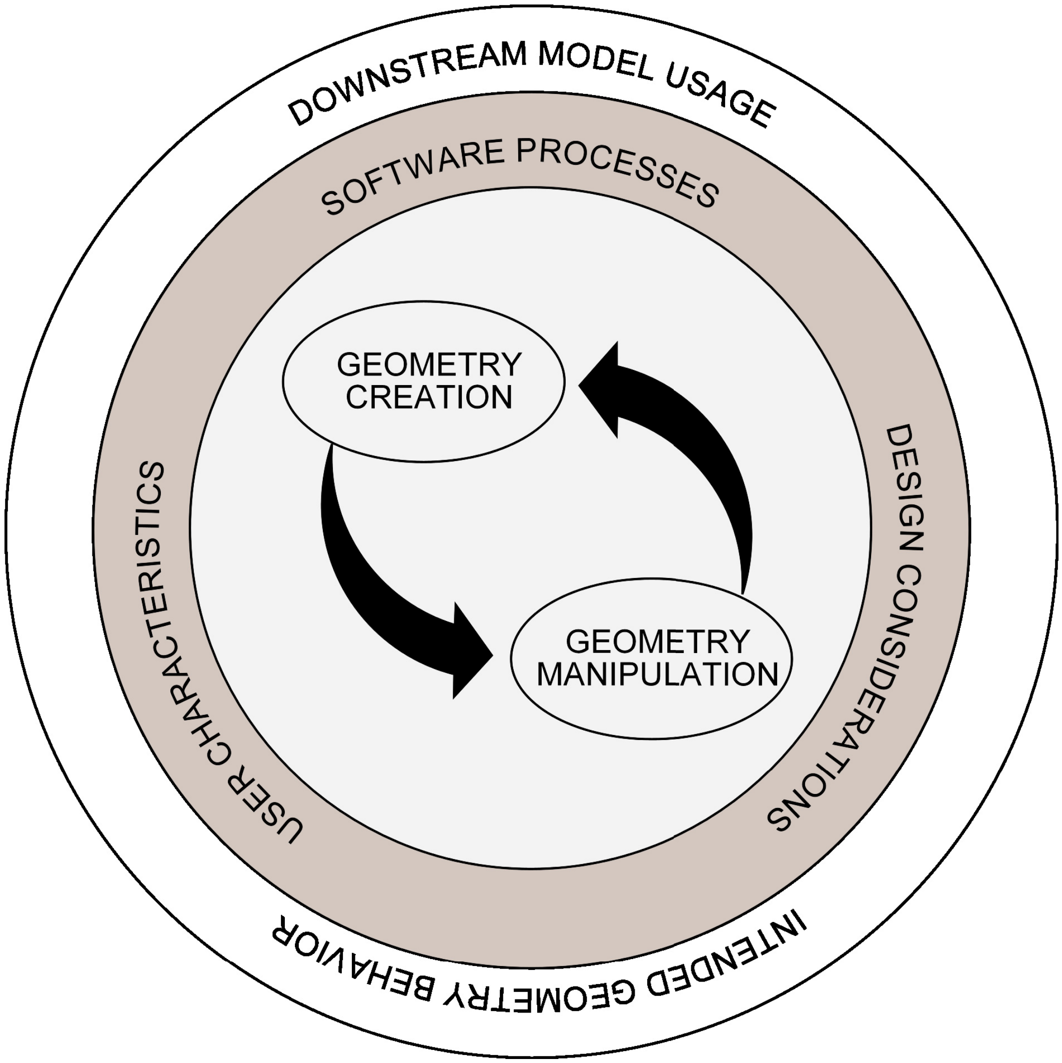


Figure 3 Common Map for Participants

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. This is shown in Figure 3 by a shaded ring that encompasses geometry creation and manipulation. The items in the shaded ring form a base for the decisions made during geometry creation and manipulation.

The notions of dimension-driven, parametric, associativity, and constraint-based directed the selection and creation of specific feature types, feature forms, and 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 and editing strategies, each participant appeared to use some form of geometry interrogation tool to gather information within the CAD tool. In Figure 2, this is summarized by the cyclical relationship between geometry creation and manipulation. Through trial and error, as well as strategic software usage, the experts were able to create and edit geometry effectively.

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 3 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).

Implications for Engineering Graphics Education

Upon examination of past experiences related to these five participants, it appears that expertise is developed by performing 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 possessed 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.

This study provides a glimpse of the basic modeling procedures 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 knowledge about the CAD tool, as well as engineering 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. This knowledge of tools and processes based on declarative knowledge was emphasized by Keller and Keller (1996).

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." It includes knowledge of geometry creation, manipulation, and editing techniques coupled with information about the design considerations that surround the model creation process, software processes, and past experiences. This knowledge combination forms the basis of strategic use of the tools to complete a goal-oriented design process. This becomes apparent when examining Figure 2.

Educational activities that involve the creation of CAD models to fulfill a specific purpose, as well as the modification of those models according to specified criteria, would coincide with these specific findings. Assessing the model according to its desired behavior and the relationships between its inherent features would be critical. Educational activities might include asking students to sketch (paper-and-pencil based) a modeling procedure for a given object based on geometric primitives or feature profiles, to create a model that must later be modified, without feature failure, in order to accommodate variations in the geometry and requisite behavior of the model, or to ask student to make changes to each other's models thereby making critical the use of geometry interrogation functions within the CAD tool. While these examples are but a few of the many options for educators, a primary focus of any modeling assignment should be the complete geometric and dimensional constraint of the features in a model and the assessment of the model according to relevant criteria.

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 to prepare new users for the complexity of the design situation. As educators, we should provide our students with a written problem scenario which describes the basic "ground rules" for the assignment, but leaves open other variables that would force students to contemplate the development of a modeling strategy based on the desired behavior of the model. Establishing common modeling procedures for creating similar types of geometry would also be beneficial. 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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