COGNITIVE MODELING STRATEGIES FOR OPTIMUM DESIGN INTENT IN PARAMETRIC MODELING (PM)

Anthony Rynne, William Gaughran
Department of Manufacturing and Operations Engineering
University of Limerick

Abstract

It is generally agreed that despite today's computers and CAD software having become extremely powerful, they are of limited use to engineers and technologists who do not fully understand fundamental graphics principles and 3-D modeling strategies. Increasingly technological education in our second level schools (high schools) is becoming more aligned to the real-world needs of business so as to better prepare students for entry into a more skilled and technically oriented workplace. In this context there is a real need to develop a coherent and systematic taxonomy for parametric modeling within a coherent and sound pedagogical framework.

The research entails developing a coherent theoretical framework and problem-solving heuristic for best practice in CAD pedagogy for the effective use of Parametric Modeling systems. The work encompasses cognitive psychology, instructional systems design, cognitive modeling and identifying and developing essential prerequisite skills tutorials. A pedagogic framework to define cognitive part modeling tasks and their co-ordination and sequencing is developed as an essential requirement for optimum PM productivity. Training in the efficiency of thought required to drive efficiency of action for effective PM underpins the developed strategic approach.

The findings indicate that more efficient use of PM systems are achieved if users have the capacity to generate cognitive models and the ability to decompose geometric elements, and cognitively assemble these in the context of achieving design intent. The findings will inform a final tutorial intervention package in establishing a best practice, strategic approach and in developing on-line tutorial interventions for all aspects of PM. The paper discusses an area of research that is directly relevant to the pedagogical needs of today's engineers and designers. In this regard 3D CAD users need to develop a mental model of PM systems in which the syntactic knowledge of the specifics of a system is supported by semantic knowledge of the tools available for creating and manipulating geometry in any system. The preparedness and capability of students to accomplish meaningful design using PM systems is directly related to their ability to visualize and deconstruct objects and to cognitively assemble them.

Introduction

In an increasingly technological society, engineering education has a pivotal role to play in shaping current and future students to meet the challenges of the global economy. Within engineering education an area that has experienced dramatic changes over the past 20 years is the way product designs are generated and communicated with a gradual transition first from 2D CAD to 3D boolean-based primitive CAD systems and then onto hybrid parametric solid and surface modeling systems. Increasingly, each annual upgrade of these PM systems is capable of using smarter and more intelligent techniques for designing products. Productivity has been and always will be a cornerstone in the profitability and viability of any enterprise that creates and manages design information. However such productivity measures typically relate to reducing the number of keystrokes and mouse clicks, reducing file size and automated testing and measurement of computer processing time.

As long as engineering drawings have been used to communicate design information, strategic approaches have been developed, used and employed to make manual drafting efficient. Similarly efficient drawing strategies were developed for 2D CAD drafting [1, 2, 3]. However there is a dearth of strategies for efficient use of PM systems. It is particularly important to focus on strategic pedagogical approaches to PM not only to ensure learners are being taught correctly so as to be productive, but because PM systems have a central and much more mission critical role to play across the entire product design process. Research at defining what constitutes expertise in using PM systems [4] confirms that expert modelers adopt a generic sequential modeling procedure beginning with determining the correct sketch plane, then sketching the best profile before adding relations/constraints followed by dimensions before finally creating the feature. This generic approach for sketched features applies to all PM systems.

Parametric modeling

In addition to the term parametric, feature-based, constraint-based and variable-driven have all been used to describe modern 3D solid and surface modeling systems. Parametric modeling (PM) systems have become the design tool of choice for engineers, technologists, designers and educators. As well as the obvious advantage of speed, more complex and flexible designs with more intricate detail can be achieved with 3D PM systems. While each new release of PM software allows more sophisticated and complex geometry to be created the basic focus of the tools is essentially on quicker and accurate geometry creation and modification. Essentially, a parametric model is an intelligent part that uses dimensions to drive the geometry. When design changes are necessary, it is easy to adjust dimensions and constraints, thereby causing the parametric model to update automatically. Parametric models add intelligence to the design database in that part features know how they relate to one another. A recent survey of Engineering Design Graphics (EDG) educators in the USA highlights as a major concern the excessive emphasis on software to the detriment of basic graphical concepts, problem solving and visualization skills [5]. This is an integral part of the cognitive part modeling framework proposed in this research. In order to be able to decode an engineering drawing the learner must develop their ability to visualize 3D spatial relationships. This has been identified as the key skill required for engineering design [6].

Current and future engineering, technology and product design graduates will need to understand complex modeling techniques and strategies for both solid and surface models to meet the needs of industry to be competitive in the global marketplace. In a survey of design and manufacturing companies who had a requirement for employees skilled in PM, the highest ranked skills were deemed to be assembly modeling, constraint-based modeling, modeling strategies and orthographic projection [7]. Wiebe suggests that the objects and actions of the parametric modeling interface should serve as metaphors for the objects and actions required of the actual task and that the more closely the task and the interface are aligned the more effectively the software can be used [8]. The parametric modelers used were Mechanical Desktop, Pro/Engineer, Solid Edge and SolidWorks. At a semantic level he found that there were clear common themes between all the modelers, while at a syntactic level interface details differed markedly between systems. Generally the activities that occur in a PM system can be classified as object creation, object modification and object review.

Declarative and procedural knowledge for PM

For many skilled tasks and activities such as 3D computer-aided design (CAD), the task knowledge of the user or learner may be considered to be of two types: declarative knowledge (DK) and procedural knowledge (PK). The distinction between these different types of knowledge has been noticed in other skilled tasks and has been labelled as the declarative-procedural knowledge distinction. Declarative knowledge is knowledge of facts (knowing that or knowing what) and procedural knowledge is knowledge of how to do things (knowing how). For instance in the same way that a pilot has the know-how to fly an aeroplane, an expert user of a 3D CAD system has the know-how to use it productively and efficiently. To design or model an object in a 3D CAD system the user must have different kinds of knowledge or information: information on the object being designed, knowledge of the commands which can be used to design the object, and strategies or tactical procedures for creating or building the object model using the PM system.

GOMS, which stands for goals, operators, methods and selection rules, is a theory of the cognitive skills involved in human-computer tasks [9]. It is based upon an information processing framework that assumes a number of different stages or types of memory (e.g. sensory store, working memory, LTM) with separate perceptual, motor, and cognitive processing. One of the few experiments in which this procedural knowledge extraction has been carried out for CAD tasks is an experiment by Lang et al. [10] in which they looked at extracting and using procedural knowledge in a CAD task that required participants to create a wireframe model of the bracket shown in Figure 1 using the Computervison CADD4X CAD system. This analysis of keystrokes was loosely based on the hierarchical GOMS structure and used pause analysis of keystrokes for procedural knowledge extraction. Lang et al. also showed that there are differences between the abilities of novices and experts to complete CAD tasks [11] given similar training in the appropriate commands required for the task. These differences occur at the micro-level of the problem solving structures users bring to bear on the task. Overall extracting procedural knowledge has been viewed as a difficult and time-consuming process.

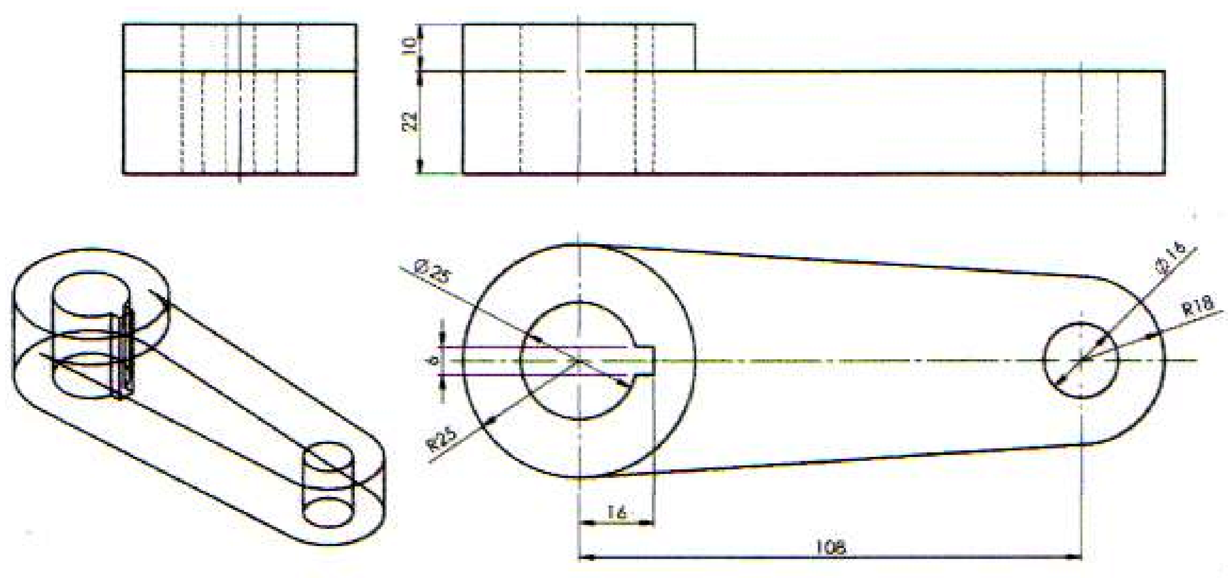

Figure 1. Part subjects had to model in Lang study.

With 2D or a traditional 3D wireframe system videoing or recording users is the only way of ascertaining the exact sequence of procedures used in carrying out a task as one cannot establish by looking at a 2D drawing on screen whether or not it was created efficiently. Lang et al. looked at this and concluded that PK could be extracted from keystrokes analysis, that such PK is transferable between CAD systems and that a highly developed DK of a system could compensate for inefficient strategies due to speed on the particular system.

This study however pre-dates the development of desktop computer based solid modeling that began in the early 1990s. Therefore there are some important differences between approaches used in wireframe which are more akin to 2D CAD skills in that they involve drawing lines, arcs and circles and trimming them, as opposed to the use of parametric sketches and features inherent in PM. Importantly extracting procedural knowledge is easier for parametric 3D systems than for 2D and traditional 3D systems, because the design tree in parametric systems captures the history of the part. While the design tree gives the final modeling sequence, which is very informative about the design intent and built in model intelligence, it may not necessarily convey the exact sequence in which the features were created as these can be reordered to achieve better design intent but only in a manner consistent with the parent-child feature relationships of the model. Observation is necessary then to establish the actual chronological modeling sequence, as corrected errors, the efficiency of the way sketch geometry is created to fully define a sketch, or subsequent changes to the feature sequence are not captured in the design tree. However such reordering of the design tree is only likely to be undertaken by more competent users of the system and is therefore considered of secondary importance to the overall modeling strategies adopted by users. Nevertheless poor sketching procedures will adversely impact on the overall modeling time and so can be indirectly measured by calculating the modeling time.

Cognitive Modeling for Parametric modeling

Research in cognitive psychology can provide guidance and structure for our decision making processes in PM. One of the most influential approaches to deductive reasoning is the mental model theory where each mental model represents a possibility, and its structure and content capture what is common to the different ways in which the possibility might occur [12]. A mental model is defined as a representation of a possible state-of-affairs in the world. The application of a cognitive visual model to comprehend PM tasks is analogous to the application of mental models by cognitive psychologists to comprehend verbal reasoning problems. Successful modeling results from the use of appropriate mental models and unsuccessful modeling occurs when we use inappropriate mental models.

However, while creating a mental model in sentence reasoning depends on working memory, constructing and encoding a cognitive visual model of an object will depend on the visualization skill of the user together with their knowledge of projection systems, their ability to create paper sketches and read drawings and their dimensioning and design knowledge. Building on the Lang et al. [10] approach for extracting procedural knowledge, and drawing from cognitive psychology and from pedagogic experience in PM the cognitive taxonomy for parametric part modeling shown in Figure 2 has been developed. Quite simply users must first be able to create a mental or cognitive model of a part prior to commencing building it in parametric modeling system. Incidentally at the assembly level similar principles apply.

A cognitive visual model may be said to be a representation in the minds eye of the object to be modeled. For basic part modeling from an orthographic drawing an expert user will be instantly able to create a cognitive visual model from the given views, deconstruct the object into its constituent elements, and cognitively assemble and sequence these to achieve the required design intent. Such cognitive modeling strategies apply to any user who wants to be productive in using PM systems. A novice user may have practiced the various modeling tools required to complete a task but still not be able to apply these appropriately to complete the new task.

Cognitive part modeling will determine the quality of the modeling strategies employed by the user and in conjunction with CAD system knowledge of the fundamentals of the modeling tools is required for productive use of parametric modeling systems. Speed and accuracy of modeling task performance provide indirect evidence about the internal processes involved in cognition and about their relationship to each other. While modern enhanced PM user interfaces give user feedback and make information available at the location of the cursor or screen pointer extensive training and experience are still required to use them efficiently. This training needs to be targeted at developing the user's ability to extract and use procedural knowledge as well as declarative CAD knowledge by improving the mental modeling ability of users. Current commercial online training systems tend to focus on the modeling attributes, features and tools of the particular software to the neglect of being able to strategically use the software to model products. In essence they tend to focus on declarative system knowledge but lack the pedagogic approach required for an integrated coherent framework, one that incorporates strategic procedural task knowledge as in the developed part modeling taxonomy shown in Figure 2.

The proposed cognitive taxonomy implies that knowing and understanding correct part modeling procedure and having the relevant knowledge of the software tools is not sufficient for efficient part modeling. Users simply will not be able to efficiently model any part without being able to first create a cognitive visual model of it. Without a cognitive or mental model users are unable to proceed at all in the case of more organic shapes, and invariably incorrectly in the case of more geometric shapes as they cannot mentally decompose the geometry correctly to know where to begin with the base feature and how to add subsequent features. Practice and prior experience with a solid modeler can speed up the modeling process but it will invariably be inefficient unless a sound cognitive model of the part to be modeled is first developed in the user's intellect that will then subsequently direct the procedural task knowledge. The goal state in the developed part modeling taxonomy is a robust efficient model, which is one that meets the required design intent and can be modified without feature failure. Design intent is the term used to describe how the model should be created and how it should behave when it is changed. It is not just about the size and shape of features, but includes tolerances, consideration of manufacturing processes, relationship between features, dimensions, and the use of equations.

The design function for a product encompasses engineering and industrial design and is the main factor in defining the physical from of a product to best meet the needs of customers [13]. Using parametric modeling, the designer roughly sketches initial shapes and then applies dimensions and constraints to create models that have intelligence in the form of design intent. The dimensions and constraints can be changed at any time, as the design is refined. Intelligent CAD models can thereby be created using parametric or constraint based modeling systems. Just as cognitive scientists have developed a grammar of vision, a set of rules that direct our perception of line, color, form, depth, and motion so too there is a need to develop a coherent grammar of design intent for parametric modeling. The sense of vision has fantastic ability to actively construct every aspect of our visual experience. Vision is not simply a matter of passive perception; it is an intelligent process of active construction. Similarly creating intelligent parametric models requires thought and careful planning and involves a well-developed 3D mindset to actively and intelligently deconstruct and reconstruct part and assembly models.

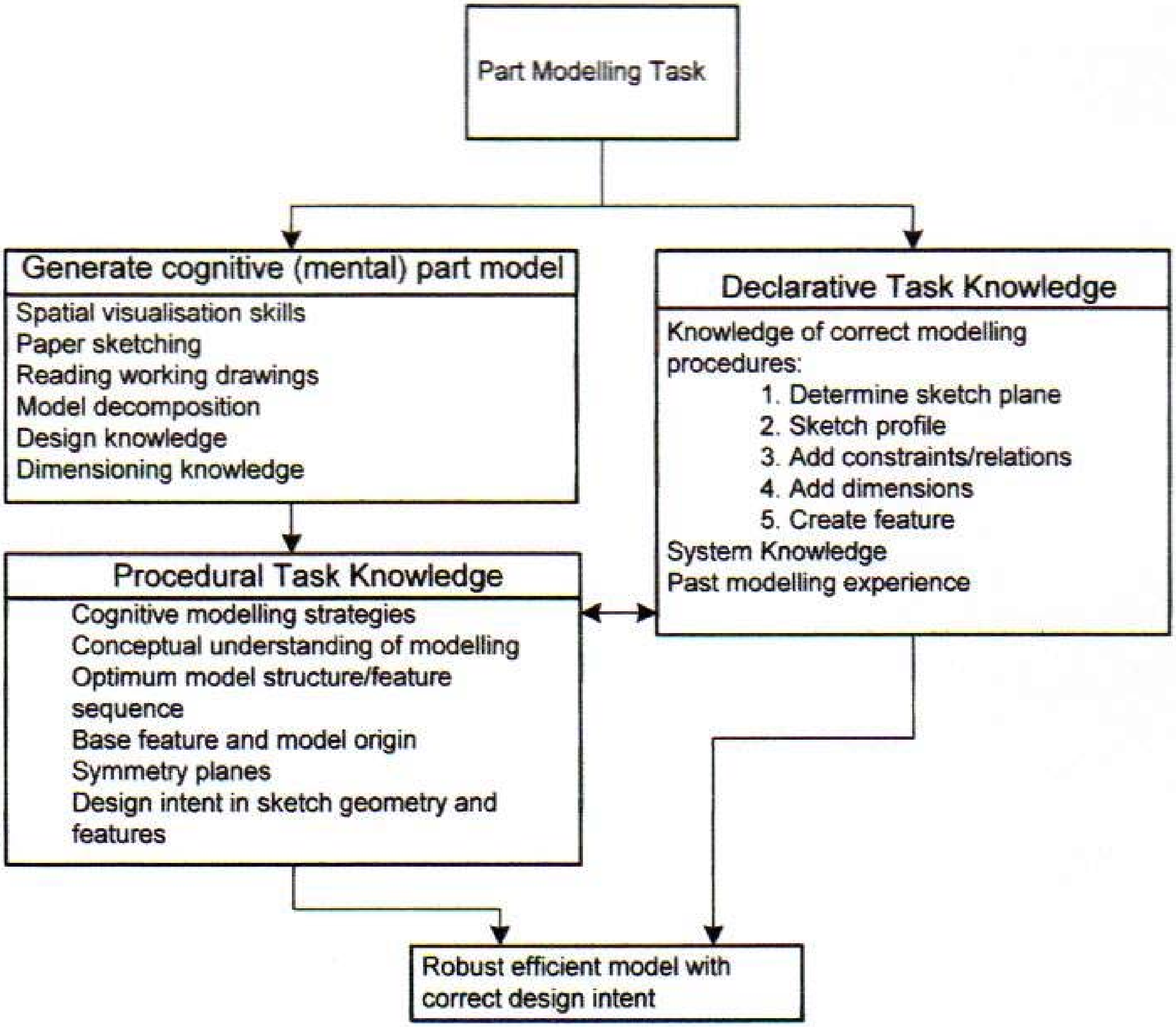

Figure 2. Cognitive taxonomy for Parametric Part Modeling.

Best Practice Strategies for Design Intent

Using PM CAD systems productively is not about pressing buttons, menu picking or software tool selection. There is a need to draw a distinction between being able to use particular parametric modeling tools and being able to model products in parametric modeling systems by applying these tools appropriately. This is to do with design intent. With a parametric modeler it is very important to plan out the design before modeling. Design intent is built into the model according to how dimensions and relations are established. Changes to a model will yield a different result for each different design intent. Sketches should be dimensioned in a way that defines the design intent. It is quite easy to build a parametric model of a part that is fully constrained and looks correct, but from a practical viewpoint is useless. This is because the design intent for the part has not been adequately considered.

Creating robust sketch geometry is the most critical user issue in capturing design intent and therefore in ultimately being productive with parametric solid modeling systems. The user must be able to visualize and extract the correct sketching requirements for a part so as to build it intelligently in the correct orientation and with the correct features in the correct sequence. Defining the sketch geometry for the base feature is the most critical of all the sketches, as this will determine where the part model origin is, what profile is used to create the base feature and which plane to create this profile sketch all of which will make the addition of subsequent features easier if done properly.

At the important sketching stage, the practices and strategies used in a PM solid modeling system differ substantially from those used for drawing in a 2D CAD system and users have to unlearn some of the skills and approaches used in 2D when making the transition to a 3D PM system. For instance in a 2D system where the geometry drives the dimensions, geometry is drawn accurately from the outset with maximum use made of snap and grid settings to ensure accuracy, whereas in a PM solid modeling system where dimensions drive the geometry, geometry is best drawn approximately to the size required without any need for snap and grid settings to be turned on, and then dimensions and relationships are added to define the geometry. While a parametric solid model is an intelligent representation of a part, it is important to analyse and plan every part before modeling to determine the most efficient sequence for creating the features. Poor modeling strategies will result in parts that take longer to create and that are difficult to edit. Features should be created to allow for maximum part flexibility and variation.

PM Decision-Making

Before starting to sketch, the model should be studied to identify the best profile to use for creating the base feature. The best profile is that which best describes the overall shape of the part, and will minimize the number of remaining features needed to complete the model. Each new part contains three infinite reference planes, which represent the front, top and right planes in space, each of which passes through the origin, which is the zero point in space. The general procedure for parametric modeling is to decide on the best or most descriptive profile for the first sketch for the base (first) feature of the model. You then select the most appropriate sketch plane on which to create this first sketch so that the final model will have the correct orientation when viewed pictorially. The sketch geometry should be created by capturing constraints as you sketch, and then dimensioned to fully define the geometry. Although sketches do not have to be fully defined to create features, normally it is better to do so to avoid possible later model distortion. The 2D sketch is then turned into a 3D solid usually by an extrusion or a revolve process. As noted previously, sketches can also be turned into solid features through a sweep or loft process. Extrusions pull the sketch normal to the sketch plane, while a revolved feature rotates the sketch around an axis. Sweeping moves the sketch along a path made up of straight or curved geometry, while lofting uses multiple sketches to transition from one shape to another. Each sketch is linked to its resulting feature. If the user goes and edits the sketch, the feature will update to reflect the change. Normally each sketched feature will require its own sketch.

When designing, a part always begins with a base feature. This is usually a basic shape such as a block or cylinder that approximates the shape of the part. Features are then used to add and remove material to the 3D base part. A feature manager design tree keeps all the features organized and displays them in a list in the order in which they were created. Control of the features is very important, and they can be reordered, renamed and edited. Features can be divided into two groups: sketched features and applied features. Sketched features require a sketch whereas applied features do not. Features should be created to allow for the maximum part flexibility and variation. Rather than perceiving the finished solid model as a large solid mass, it needs to be viewed as a composition of features

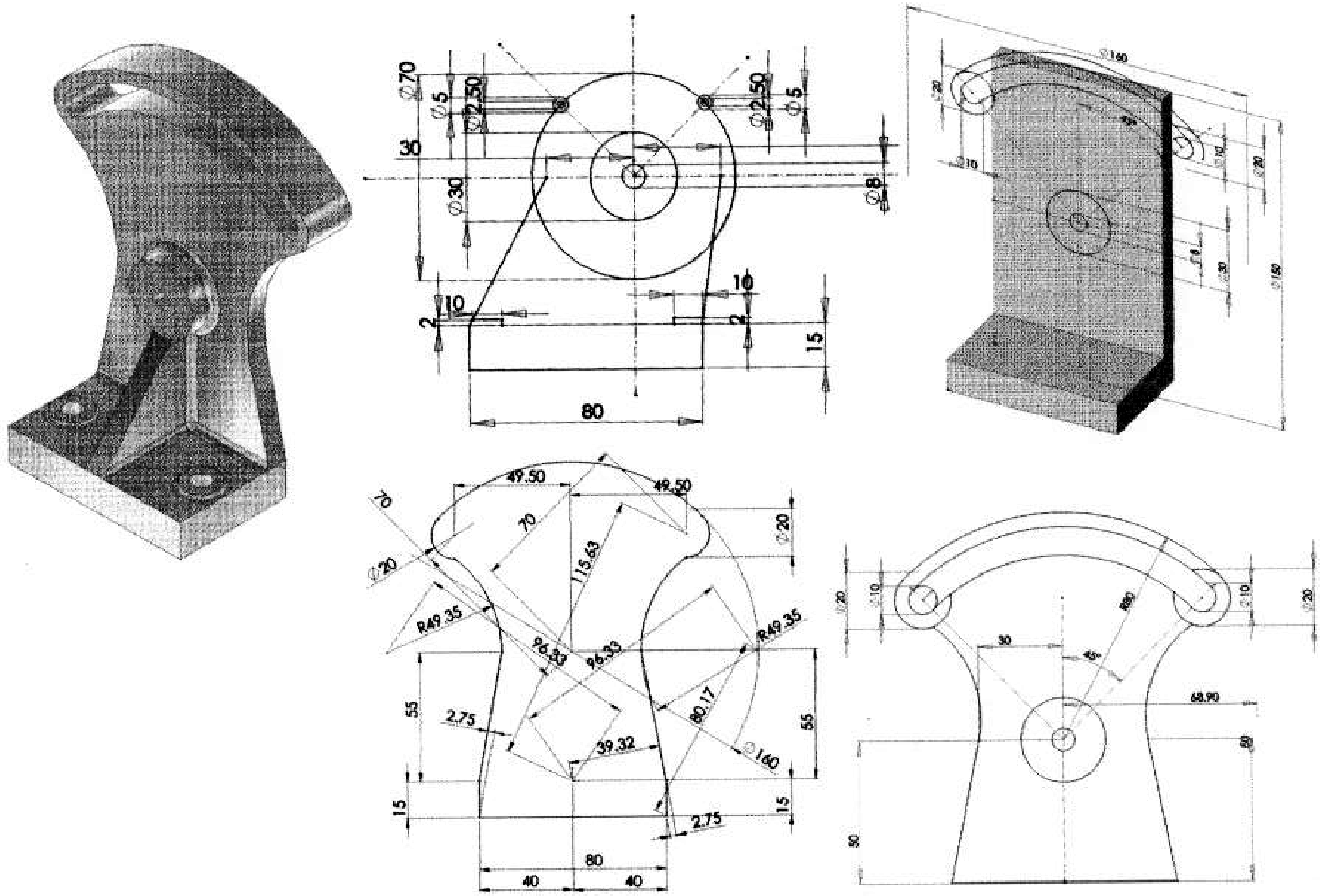

Figure 3. Bracket with actual examples of poor sketching practices.

that are likely to be modified in a design table or individually. Parametric models capture relationships between part features and the size of the features. When a part changes, any related parts then update automatically. Sketches are made up of three parts: sketch entities, geometric relationships, and sketch dimensions. These components are combined to define a sketch and the key is to put them together in sequence so they define the design's intent. The sketching problems encountered by inexperienced PM users are encapsulated in their sketching efforts for the bracket shown in Figure 3 and demonstrate the need for an integrated strategic cognitive modeling approach. Only nine students (13%) out of a cohort of 69 second year technology students obtained more than 75% for modeling this bracket as part of an examination.

The sketch profile on the bottom left is an extreme example of where the user did not add the proper constraints to the geometry prior to dimensioning. Instead the user adds meaningless dimensions until the geometry becomes fully defined. In view of these types of typical sketching and modeling errors it was decided to carry out an exploratory study of four postgraduate students doing a parametric modeling module using SolidWorks.

Exploratory Part Modeling Study

It was decided to observe and analyse how four novice users built the part model shown in Figure 4 to inform the process of developing a coherent cognitive framework for PM part modeling.

Participants

The participants were four post-graduate male students enrolled for a PM module in a taught masters degree course in computer integrated manufacturing at the University of Limerick. Two of the participants were 23 years of age, one was 28 and the fourth was 30 years old, while three of the students had previously used AutoCAD. Each student had studied a different undergraduate degree program and completed a questionnaire on their educational history and views on PM.

Method

The students were given the task of modeling the base for a belt drive-tightening device from the orthographic drawing shown in Figure 4. Students were not given the pictorial view. The PM software used was SolidWorks 2006 and students had received 35 hours of tuition from a department colleague over a 10-week period prior to the test. There was no time limit for the task but students were told to model it as quickly and efficiently as possible. While the software design tree captures the final model feature history, it does not show any deleted incorrect features or sketches so students were closely observed carrying out the task to establish the modeling strategies used.

Findings

The total number of features in the model including required sketch geometry varies slightly depending on the modeling approach used but is about 22 or 24 features if modeled efficiently. Overall this difference is not important but derives from decisions such as whether to use sketch or applied fillet or the hole wizard when modeling. An expert user modeled the bracket in 20 minutes. The design tree for the base bracket show that it was modeled with 10-sketched features and four applied features giving a total of 24 features, when the ten sketches for the sketched features are included. Therefore for the purposes of quantifying the total number of model features, the term features is taken to include sketch geometry, additional planes and axes as counted by the software.

Notwithstanding the small sample the results shown in Table 1 reveal some interesting findings in relation to participant cognitive modeling and modeling strategies. Three of the participants demonstrated awareness of using symmetry appropriately in sketch geometry. Only participant one managed to complete the model. This he achieved in a time of 64 minutes but with three feature errors, two of which were feature dimensional inaccuracies and the other which was related to incorrect model geometry. His model also omitted some cosmetic fillets. Overall however the part was modeled efficiently with the model origin correctly coinciding with the axis of the boss. It was decided to terminate the test after 89 minutes for the other three participants, as they appeared to have done as much as they were going to get done, in what was a generous time allocation.

The second participant who performed very poorly in the test spent a considerable amount of time defining a sketch on the front plane based on the outline of the elevation of the bracket After extruding this sketch he realized that this base feature was incorrect and started again. After eventually modeling the base feature on the top plane but without defining the sketch relative to the origin, he again drew a profile sketch on the front face of the model based on the drawing elevation and proceeded to create the left holes on the sloped surface. Overall his model had 12 features but many of these were incorrectly defined.

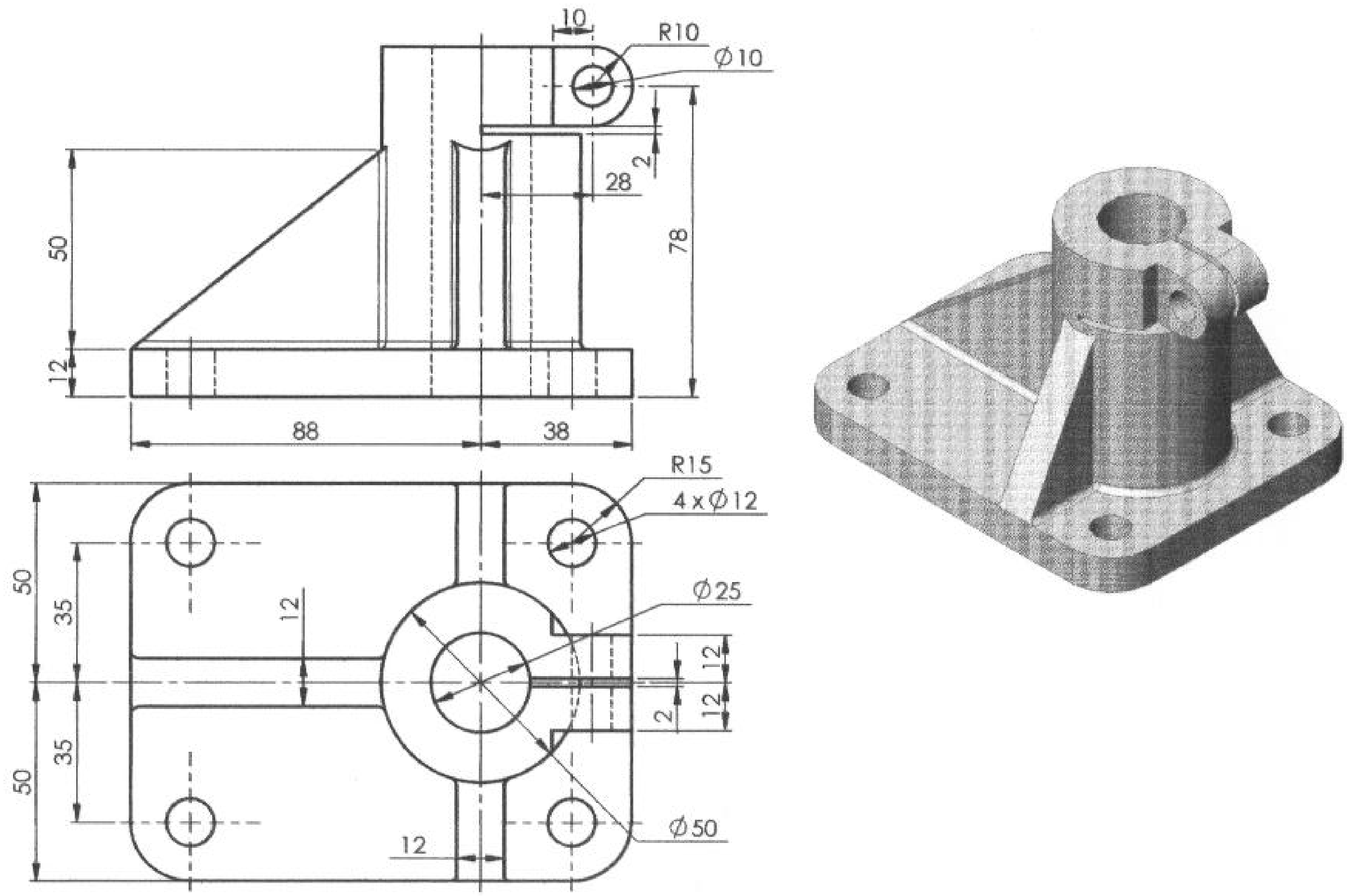

Figure 4. Orthographic drawing of base bracket.

Participant three correctly started on the top plane but without properly defining the sketch relative to the origin for the base feature. Creating the ribs and cut features prove problematic for this student. Amazingly, despite missing many of the required part feature this student's model had 28 features. This was due to the fact that he created, extra sketches not used for features, two planes that were not required, and had to recreate a cut feature because poor modeling procedure resulted in the original cut feature being violated.

Participant four created only 6 features in total, yet scored almost as well as participant three who created 28 features, and over twice as well as participant two who had 12 features in his model. His base feature sketch incorporated the four base holes and the model origin was at the front right corner. The modeling score reflects the capturing of correct design intent if dimensions were modified as well as geometry accuracy. All of these students were familiar with all the software tools required to model the part and had been shown the correct part modeling techniques and procedures to use in SolidWorks by an experienced teacher. Nevertheless three of them performed unacceptably poorly in this test and the reasons for this will now be explored.

Table 1. Participant demographics and Modeling results.

Participant 1	Age	Technical Drawing	Undergraduate degree	Prior CAD Experience	CAD Competence rating (5 point scale: 1=poor, 5 = excellent)	Visualisation rating (5 point scale: 1=poor, 5 = excellent)	Important skills for PM	Modelling Time (Minutes)	No. of Features	Modelling Score
1	30	Y	Electronic Systems	2D /3D AutoCAD	3	3	Ability to interpret drawings	64	22	86%
2	23	N	Applied Physics	None	2	2	Visualisation, interpreting drawings	89	12	16%
3	23	Y	Engineering Teaching	2D /3D AutoCAD	3	3.5	Visualisation ability, interpreting drawings	89	28	37%
4	28	N	Production Management	2D AutoCAD	3	4	Practice time; observing other people modelling	89	6	33%

Students have much greater difficulty in visualizing a 3D object from its orthographic views than they have in visualizing and extracting the orthographic views from a 3D representation and this proved to be the case here. The participant with the weakest spatial visualization did poorest in the test. In general the performance of the four participants is directly related to their ability to create a proper mental or cognitive model for the part prior to commencing modeling. Although limitations in working memory represent a major bottleneck in the operation of many systems, equally important sources of potential failures are the actions people take incorrectly or fail to take because they have forgotten to do them or have forgotten how to do them. This was also the case here, as basic concentric and symmetry relationships, which can be picked up automatically while sketching, were not used. Three of the participants appeared to spend considerable time staring at the screen unsure of how to proceed. The conventions and principles of graphic communication through drawing projection systems readily transfer to the PM environment. Knowledge of the standard planes of reference and reading orthographic drawings is a necessary prerequisite for using PM systems effectively but participants two and four had not studied engineering drawing.

Overall Discussion and Conclusion

Knowing a discipline well does not mean that one has an appreciation of what it takes a learner to assimilate and comprehend it. Pedagogical content knowledge relates to an awareness of the ways in which material can be presented that takes into account what you want students to learn, and the course of learning that is optimal for them. An understanding of the fundamental concepts and best practices of parametric modeling is vital for productive use of these systems. An inexperienced user of PM systems cannot be turned into an expert user by simply telling them what the expert knows. Today's engineers, technologists and product designers must be fluent in PM practices and skills.

Parametric modeling systems record the final sequence of features used to create a model. While users can reorder features in the design tree consistent with parent-child relations during part modeling, the finished model records the users considered best approach to a modeling task. An analysis of many user models has been undertaken to ascertain the cognitive strategies employed and to identify the problems encountered. Analysing student modeling approaches is instructive as to the thought processes undertaken by the user and can form a sound basis on which to develop tutorial interventions to enhance the thinking, visualization, and overall cognitive approach used by 3D CAD users.

Self-paced multimedia instructional training video files that capture and exemplify correct design intent practices have been developed for users of the SolidWorks PM system. Overall the multimedia training videos represent a teaching enhancement and development strategy for PM that have a demonstrable effect on the improvement of teaching in this area and will be discussed in a separate paper. Parametric modeling skills are best developed using a blended approach with multimedia videos integrated with conventional teaching methods. The following attributes combine to give an efficient robust part model with the proper design intent. Learners must be explicitly shown how to incorporate this parametric procedural knowledge into their models as it represents the difference between novice and expert users. These attributes are:

- Correct sketch plane selection for base feature sketch
- Optimum model origin
- Correct base feature
- Correct part orientation
- Appropriate use of symmetry planes
- Simple sketch geometry
- Correct sketch relations
- Fully defined sketch geometry
- Correct feature sequence
- Parent-child feature relations
- Correct feature terminations
- Correct feature duplication
- Correct part design intent
- Part accommodates planned and unforeseen design modification without feature failure.

Improving individual user productivity in using PM systems depends on developing their capability to create a cognitive visual model of parts to be modified. The transition from design ideas and interpreting working drawings to creating intelligent virtual models in a PM system is dependent on the user's ability to create appropriate cognitive visual models of the object. By observing how 3D CAD users approach modeling tasks we get a sense of what they are thinking about the tasks by the modeling strategies used to create them. Moreover by analysing the results of their modeling efforts we can see from the modeling approaches and sequence employed how they went about the task. Users must understand the fundamental generic modeling principles and concepts of PM as this will facilitate knowledge transfer between different parametric modeling systems and lead to more productive use.

Irrespective of the PM system used there are inherently sound and generic modeling strategies and practices that should be used by all users. Technology breakthrough products require user creativity and innovation. Being able to properly use PM systems to explore what-if scenarios not only in the area of product styling but also in product functionality can facilitate user creativity in bringing innovative products to the marketplace. The extent to which PM systems can intelligently capture design intent is directly related to how a user plans and builds the product model. In the design world 3D CAD is a revolutionary tool that reduces development time, improves the way products are conceptualized, and allows designers to focus on being creative. However while PM systems are an invaluable tool for the creative designer they cannot come up with the initial ideas. In this respect manual sketching is important for developing ideas.

Training normally has a narrow focus that is typically concerned with the acquisition of specific skills to perform an explicit task whereas education is viewed as being concerned with learning general principles and concepts and transferable skills. Nevertheless within the CAD domain a blurring of the distinction between teaching and training is desirable and is something that would lead to the mutual enhancement of both. For instance effective CAD training should provide for transferable skills and learning of concepts and principles.

There appears to be a gap in the cognitive modeling ability of users with weak visualization ability. Violating rules of good modeling practice leads to modeling errors and poor model quality. These problems can be difficult to track and fix and will cause problems for downstream applications. With consumers continually demanding higher quality customized products, the integration of cognitive modeling strategies into PM pedagogy is essential for efficient parametric modeling.

The research will be of benefit to teachers and students of technology-based subjects, CAD trainers and educators, education decision-makers and examiners and is also directly applicable to real world 3D CAD training practices. Within second level (high school) education, assessment plays a central role in shaping educational practice, so it is essential that assessment methods in parametric modeling examine how well students have captured design intent. In addition engineering educators must imbue students with the required knowledge and understanding to use PM systems effectively and productively.

In Ireland the Department of Education and Science has decided to incorporate 3D parametric CAD software into the curricula of the four technological subjects in the second level schools education system. This will mean that initially students of the technologies ranging in age from 15 to 18 years will be using a PM system with the likelihood that this will be extended to junior cycle students in the future. Junior Cycle students typically range in age from 12 to 15 years. The senior cycle program is of two years duration while the junior cycle program is normally over a three-year period. It is envisaged that this research will facilitate the integration of 3D parametric CAD software into the school curriculum. Overall the work adds to knowledge of how best to train and teach PM, informs the debate on the best pedagogical approaches, identifies modeling issues about how and where to start on the modeling journey, about how best to develop 3D modeling capabilities in users.

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Biographical Information

Anthony Rynne is a Lecturer in design graphics and communication and in parametric modeling systems at the University of Limerick. He is a consultant to industry and education in PM strategies. He is currently undertaking PhD research in CAD pedagogics with particular reference to parametric modeling.

Bill Gaughran is a Senior Lecturer in the Department of Manufacturing and Operations Engineering at the University of Limerick (UL). He leads a number of research groups, including design strategies, graphics and CAD pedagogy, sustainable design and engineering, which include environmental sustainability in schools and colleges. He is a research partner with the EU INTERREG IIIC/DQE project (Towards a Sustainable Region), and contributes to developing strategies, which inform environmental sustainability policy in EU states. He has undertaken substantial research projects in technologies education, including engineering design graphics, for the Irish National Department of Education and Science. He lectures in design for sustainability, and design and communication graphics across a number of courses in UL, and endeavours to link academic research with industry, through seminars and onsite coaching. He serves on a number of national curriculum course committees and has been instrumental in launching a several technology education high school programs. He holds a PhD in Design and Ergonomics from Brunel University and has a Masters by research in spatial visualization development strategies.