Developing Expertise in 3D Parametric Modelling

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Abstract

Properly used parametric 3D CAD modelling systems can be an indispensable tool for developing problem solving skills, design and reasoning skills, fostering creativity and innovation, promoting engineering and technology generally and even contributing to student retention in education. However a coherent pedagogic approach to integrating training and education in 3D CAD modelling within engineering, technology and design courses at all levels is necessary if the benefits of these systems are to be properly realised. While on the one hand, 3D CAD systems have become easier to learn and use with the development of context sensitive toolbars and shortcut menus that allow the user to focus more on design than on the structure of the CAD system, on the other hand they have become increasingly sophisticated with an ever increasing array of tools for complex modelling and built in extended design capabilities such as intricate surfacing, design analysis and simulation, configuration logic, assembly management and model quality checking. Observation and assessment of 3D CAD SolidWorks learners at the University of Limerick suggests that many otherwise capable students often have difficulty in thinking through efficient modelling sequences even though they know how to use the individual software tools. The absence or lack of strategic CAD knowledge in novice users is explored and a coherent cognitive model for effective parametric part modelling is proposed. In addition it is suggested that the provision of online video tutorials as part of blended learning programmes is the most effective way to build learners strategic CAD knowledge and develop their overall modelling expertise. The modelling approaches of novice users are compared with those of an expert user and the particular impediments to efficient modelling are identified.

Introduction

Within Ireland the shortage of engineers graduating from third level education has been identified as a major concern for the future economic competitiveness of the country in the challenging global economy of the 21st century (National Skills Strategy Research Report, 2007). The future development of the purported smart economy in Ireland is viewed as being contingent on an education system which promotes independent thinking, creativity, innovation and entrepreneurial skills at second and third level. These and other generic and transferable skillsets can be provided through the distinctive learning experiences provided through 3D parametric modelling as part of product design and design-based technological education. The recent Government Innovation Taskforce report (March, 2010) recommended that steps be taken to embed product design teaching and research in Ireland’s engineering schools, and that design education in Ireland should shift to a model where creativity and innovation in product design are encouraged. The report also highlighted the need to substantially raise levels of competence and attainment in maths and sciences such that they feed into Science, Technology, Engineering and Maths (STEM) disciplines at third level. Parametric modelling through SolidWorks is the ideal vehicle to inspire young people to engage in a STEM based education. President Obama recently highlighted the role of STEM education in helping to drive innovation and scientific discovery, and to maintain the nation’s economic competitiveness. (Obama, 2010). SolidWorks have a STEM-based curriculum which provides interactive hands-on projects that make learning fun.

In this context the decision in April 2007 of the Irish Department of Education and Science to purchase 25,000 seats of the SolidWorks 3D CAD software as part of the expansion and updating of the second level (high) school curriculum in four technology subjects marked a welcome and significant paradigm shift in the teaching of design, engineering and technology skills and concepts in Ireland. However, while students of technology will now be exposed to the same design and problem solving tool used by professional designers and engineers, for the investment to ultimately be a driver for future economic success, it is vital that education and training programmes inculcates and promotes best practice modelling strategies required to build robust digital models, and that student achievement in these best practices are evaluated and measured as part of the assessment in these subjects. Parametric modelling provides a distinctive educational experience as an increasingly integral part of the design process in technological education generally and more particularly as part of the subject Design and Communication Graphics in the Irish School System. The recent involvement of many second level Technology students in the Formula Schools model car racing competition is an exciting way to get young people enthused about engineering and technology although oftentimes the modelling techniques employed to achieve the overall shape of the model car body are less than efficient.

The whole 3D CAD modelling domain is in essence a new language for learners. Within second and third level education, students must be shown best practice strategies from the outset so that they will have the necessary skillsets for future complex modelling in industry. In addition the increasing incorporation of 3D CAD modelling into both industry and school and college programmes has resulted in a wide diversity of users with a hugely varying age profile. This research suggests that coherent best practice 3D CAD pedagogy requires users to have training in freehand sketching, visualization and engineering drawing as essential prerequisite skillsets that facilitate the necessary 3D thinking and planning processes required for an overall strategic approach to creating efficient product models. As part of a best practice strategic approach to developing user expertise in 3D CAD modelling, online video tutorials that capture the decision making processes involved in building 3D models and make explicit the strategies required to capture design intent have been developed and tested. The video tutorials are part of a rich multimedia learning experience that takes cognisance of learning theory and the principles of instructional design. The results show that the flexibility of time, place and pace provided through these online video tutorials increases learner modelling competence and provides a means by which best practice 3D CAD strategies can be made accessible to all users.

Cognitive Modelling for 3D Parametric Modelling

While creating a mental model in sentence reasoning depends on working memory, constructing and encoding a cognitive visual model of an object to be modelled will depend on the visualisation skill of the user together with their knowledge of projection systems, their ability to create manual sketches and read drawings, as well as their dimensioning and modelling knowledge. Building on the approach of Lang et al. (1991) for extracting procedural knowledge, and the work of Chester (2006, 2007) on developing CAD expertise, drawing from cognitive psychology as well as considerable pedagogic experience in teaching 3D CAD systems, observing users and assessing their performance, the cognitive process model for developing expertise in parametric part modelling shown in Figure 1 is proposed.

For effective modelling the user should first learn to create a mental or cognitive model of a part prior to commencing building it in a parametric modelling system. Incidentally, at the assembly level similar principles apply especially for complex assemblies.

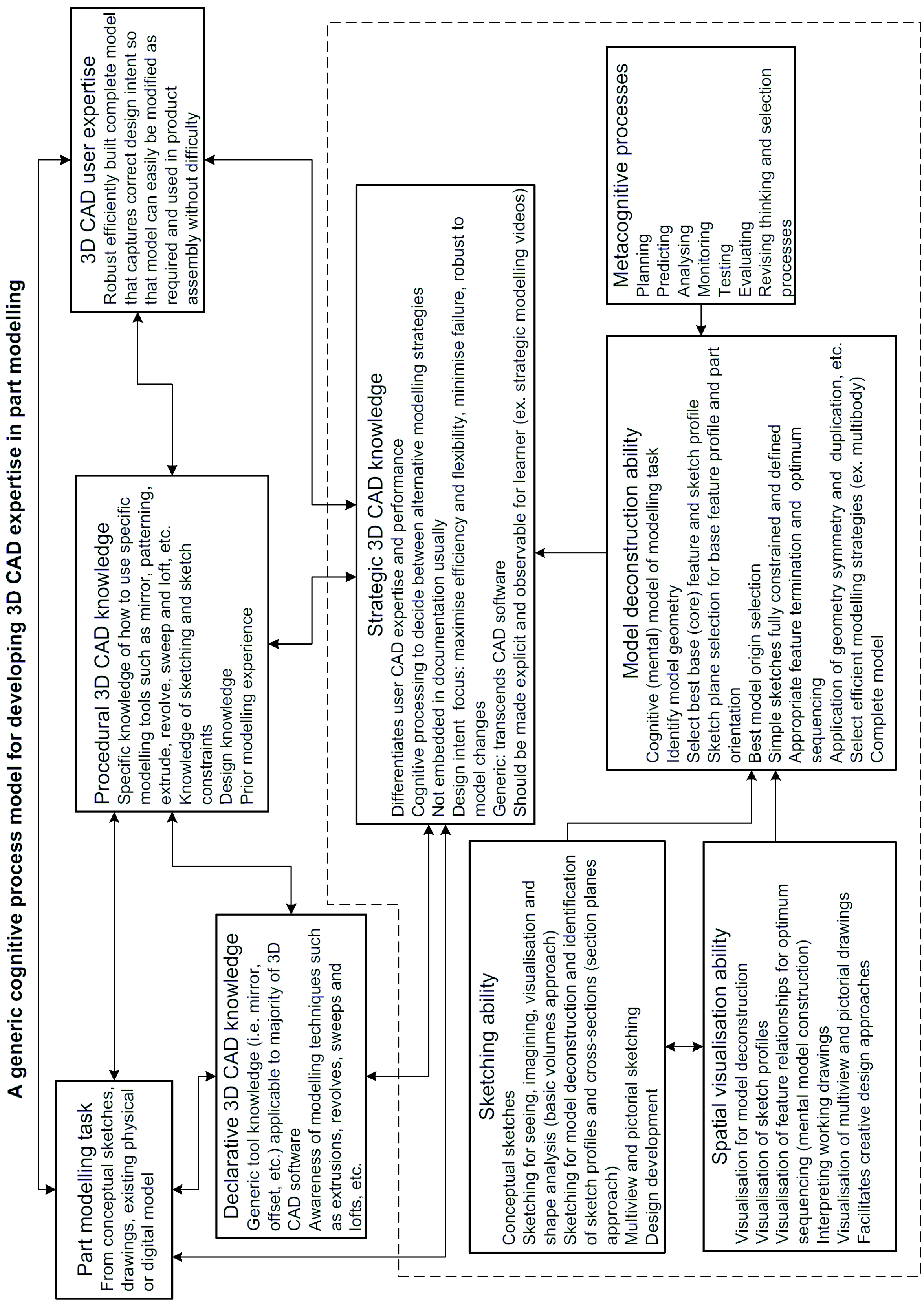

Figure 1 Cognitive model structure for developing expertise in 3D CAD part modelling

However, the type of CAD knowledge and instruction provided in manuals and textbooks invariably include only details of specific commands but not higher-level strategic knowledge. However it is strategic 3D CAD knowledge that differentiates the expert from the novice user.

The 3D cognitive CAD model suggests that declarative and strategic knowledge, sketching and visualisation aptitudes, metacognition and model deconstruction all contribute to a greater or lesser extent to developing the users strategic 3D CAD knowledge. Metacognition has been defined as knowledge or awareness of cognitive processes and the ability to use self-regulatory mechanisms to control these processes (Eggen and Kauchak, 1997). It is vital to teach learners best practice modelling strategies and how to decide between them when modelling and to build on knowledge of core concepts from traditional engineering graphics courses. 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). While the proposed cognitive model for 3D CAD modelling is generic the focus of this research is on using SolidWorks.

In a study that looked at the modelling practices of five experienced practicing designers, Hartman (2005) used knowledge mapping and think aloud modelling to examine the modelling strategies used. Think aloud modelling is an instructional component of cognitive apprenticeship (Duncan, 1996) which is a pedagogic strategy in which instructors model the strategies and activities necessary to solve problems while providing scaffolding to support learners. The method mirrors that used by experts and apprentices for hundreds of years. Think aloud modelling reveals the most complete description of the cognitive activities and strategies used by an instructor in completing a task.

Practice and prior experience with a solid modeller can speed up the modelling process but it will invariably be inefficient unless a sound cognitive model of the part to be modelled is first developed in the user's intellect that will then subsequently direct the procedural task knowledge. The goal state of the developed part cognitive model is a robust efficient model that meets the required design intent 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 and other downstream applications, relationship between features, dimensions, and the use of equations. The adoption of a strategic approach is even more critical for models with complex curved and inclined surfaces. When building components with curved surfaces or particularly with complex organic geometry, the user must be able to dissect the model into its key profiles and then build the model using splines and surfaces before converting the model to a solid.

Just as cognitive scientists have developed a grammar of vision, a set of rules that direct our perception of line, colour, form, depth, and motion so too there is a need to develop a coherent grammar of design intent for parametric modelling. 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 mind-set to actively and intelligently deconstruct and reconstruct part and assembly models. Irrespective of whether the modelling start point is the interpretation of engineering drawings, reverse engineering a part or working from conceptual sketches, the process of building a 3D model is one of actively constructing what the user sees using appropriate 3D CAD modelling strategies.

Efficient design modelling is contingent on capturing the correct design intent of the component from the outset through to the completed model. The same applies at the assembly level where a combination of bottom-up and top-down assembly modelling strategies should be appropriately applied. For instance if modelling a mechanism, assembly layout sketches can be used to create a functional mechanism layout where the position, size and shape of the parts can all be driven from a single sketch. Comparatively little effort is required to build a mental image of a part from its 3D model as compared to that required to create a mental picture of the same part from its 2D drawings. However given that the starting point for a model is oftentimes a legacy 2D drawing or a manual sketch, users must possess the necessary visualisation and model deconstruction capabilities to build a robust efficient model. At all times model geometry must be viewed as a dynamic rather than a static entity that will probably need to be changed in the future.

Online learning for 3D CAD

The almost incessant demands of today's learners for instant access to online learning resources that can enhance and extend their learning are particularly applicable to the 3D parametric solid modelling domain where learners need to not only understand the modelling process but be able to review and apply it to solve design modelling problems. Students are increasingly comfortable with logging on to websites and navigating around them to find information. The videos integrate pedagogy and technology in capturing and making design modelling strategies explicit and readily accessible to learners.

Research on the design of e-learning courses (Clark and Mayer, 2003) with a focus on building user knowledge and skills advocates the following six principles for e-learning design:

- The multimedia principle: use words and graphics rather than words alone.
- The contiguity principle: place corresponding words and graphics near each other.
- The modality principle: present words as audio narration rather than onscreen text.
- The redundancy principle: presenting words in both text and audio narration can hurt learning.
- The coherence principle: adding interesting material can hurt learning.
- The personalisation principle: use conversational (informal) style.

They further suggest that e-learning should promote psychological engagement between the learner and the lesson content in ways that help learners to select important information, integrate this into existing knowledge and be able to retrieve new knowledge and skills from memory when working on problems. Based on empirical evidence (Clark and Mayer, 2003) also recommend four guidelines for effective practice in e-learning:

- Interactions should mirror the thinking processes and environment of the job.
- Better learning results from more practice questions interspersed throughout the lesson.
- Practice questions should be formatted to be consistent with the six media elements principles identified by Clark and Mayer (2003).
- Learners should be trained to provide their own questions when they are studying from receptive (expository) materials.

Research (Ericsson, 1990) suggests that skill development and expertise are strongly related to the time and efficiency of deliberate practice. In other words the more a person practices the better they will become irrespective of initial talent and ability. In the absence of practice the performance of more talented individuals will lose their edge relative to less talented individuals who continue a regimen of deliberate practice. Studies provide strong evidence of the relationship between sustained practice and high levels of proficient performance.

Sweller and his colleagues distinguish between the intrinsic load of instructional materials that result from the inherent complexity of the content itself and the extraneous load imposed by the instructional design (Sweller, 1999; Sweller, Van Merrienboer, and Paas, 1998). Using worked examples especially with novice learners reduces the extraneous load, thereby freeing working memory to allocate resources to the learning process.

The use of practice exercises (practice principle) and examples (worked examples principle, encoding specificity principle) are two common but powerful elements of effective training to maximise learning efficiency (Clark and Mayer, 2003). Different research studies that compared the test performance of students who learned from animation and narration versus narration alone, or from text and illustrations versus text alone (Mayer and Gallini, 1990; Mayer and Anderson, 1992) consistently showed that students who received a multimedia lesson performed better in subsequent transfer tests.

Cognitive learning theory on learning transfer and empirical evaluations of thinking skills support an approach that focuses on the process that expert users use when solving real problems. By making the mental processes as well as the solutions to CAD modelling problems explicit, video tutorials provide a unique opportunity to help novice and experienced learners to solve problems. In essence videos provide expert problem solving thoughts and actions applied to real world CAD modelling problems.

According to Mayer (1998) success in problem-solving relies on:

- Cognitive skills: the facts, concepts, and procedures unique to a skill field.
- Metaskills: the ability to plan, monitor and assess actions associated with problem-solving.
- Motivation: an investigation of effort to persist and solve the problem.

Success in problem-solving requires both cognitive and metacognitive skills (Schoenfeld, 1987). In studying the thinking processes of mathematics students Schoenfeld (1987) compared the thinking patterns of novice and expert problem-solvers using a think aloud approach and found novice problem-solvers stuck to one approach, whereas expert problem-solvers moved iteratively among planning, implementing, and evaluating problem-solving actions.

Based on the work of Schoenfeld (1987), Clark and Mayer (2003) suggest two guidelines for building problem-solving processes through e-learning:

- Provide examples of expert problem-solving actions and thinking.
- Promote learner awareness of and reflection on their problem-solving process by making learners document their plans and by showing maps of novice and expert problem-solving paths.

Having invested in 3D CAD software and hardware is only the beginning and ultimately is of little benefit unless teachers and students are able to use it productively. With proper training all users can be inspired to not only utilise 3D CAD to design effectively but to also have the opportunity for the distinctive learning experience this tool can provide. While one is not suggesting that 3D CAD is a panacea for solving every problem, properly used it is an invaluable tool for creativity, innovation and problem solving through the design process as part of technological education.

Discussion

The provision of online video tutorials as a means of accelerating and stimulating learning is applicable to many disciplines that require skill and competency development. Other cited reasons for adopting online video tutorials include improved student successes in achieving learning outcomes, and increased student retention. Oftentimes experts cannot easily articulate how they perform mental tasks so capturing think aloud modelling strategies and tactics on video is an invaluable learning tool for novice and even experienced 3D CAD users. The developed 3D CAD online SolidWorks video tutorials provide explicit examples of expert user modelling strategies, thoughts and actions while solving a range of meaningful modelling tasks to help novice learners build their own mental models for 3D CAD. The developed online 3D CAD SolidWorks video tutorials intervention embeds and exemplifies such learning theories as cognitive apprenticeship, (Collins, et al., 1987; Duncan, 1996) scaffolding and the zone of proximal development (Vygotsky,1978) think aloud modelling strategies (Duncan, 1996; Hartman, 2005), cognitive load during problem solving (Sweller, 1988; Sweller et al., 1990; Chandler and Sweller, 1996), metacognitive modelling strategies (Eggen and Kauchak, 1997).

Any meaningful assessment of a digital product model must involve the interrogation of the model sketching strategies and feature definition and creation strategies, as well as the relationship between components in the product assembly. Based on research and observational studies (Jankowski, 2002; Rynne, 2008; Lombard, 2009) the following checklist represents the basis of an effective workflow for efficient robust parametric solid modelling of non-complex parts in SolidWorks and other modellers:

- Correct sketch plane selection for base feature sketch
- Optimum model origin for base feature sketch
- Right base feature
- Correct part orientation
- Appropriate use of symmetry planes
- Simple sketch geometry
- Automatic and manual sketch relations
- Fully defined sketch geometry with dimensioning
- Intelligent sketch relationships for design intent
- Correct feature sequence
- Parent-child feature relations
- Intelligent feature terminations
- Efficient feature duplication
- Appropriate overall part design intent such that part accommodates planned and unforeseen design modification without feature errors.

Results

A selection of inefficient and poor modelling strategies from industry and third level students are shown in Figures 2, 3 and 4 in the Appendix of this paper. Among research participants at the University of Limerick, the preferred SolidWorks video duration was 6-10 minutes (N=74, 37.4 per cent) followed by a video length of 11-15 minutes (N=56, 28.3 per cent).

In relation to the usefulness of the video tutorials for learning to use SolidWorks effectively, 54 (27.7 per cent) of the 195 participants who used them thought they were excellent, 91 (46.7 per cent) considered they were very good and 42 (21.5 per cent) believed they were good.

However participants were not as positive in relation to the inclusion of explanatory and background PowerPoint slides at the start of the SolidWorks video tutorials, with 68 students (34.9 per cent) being neutral on their value, while 15 (7.7 per cent) did not think that including the slides helped them understand the content.

Conclusion

The use of strategic online video tutorials that exemplify best practice design intent strategies for part and assembly modelling can greatly enhance the user's learning experience and their overall comprehension of parametric modelling concepts. The use of such video tutorials is relevant to both novice learners and experienced users and is universally applicable to both education and industrial learners. The effective use of SolidWorks is contingent on best practices being taught from the outset which requires teachers to be properly trained in how to strategically teach these strategies. While SolidWorks provides visual and other clues to denote errors within sketches, features and assemblies, novice users find some of the terminology used in error dialog boxes to be confusing, and often encounter great difficulty in fixing errors even when the system flags the location of the problem.

The proposed cognitive 3D CAD model implies that knowing and understanding correct part modelling procedure and having the relevant knowledge of the software tools is not sufficient for efficient part modelling. Users 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 complex 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. In essence strategic 3D CAD knowledge should become an integral part of how parametric modelling is taught in schools and colleges.

References

Chester, I. (2006). Delineating and Developing Expertise in Three-Dimensional Computer Aided Design, unpublished thesis (PhD), Griffith University.

Chester, I. (2007). "3D-CAD: Modern Technology-Outdated pedagogy?" *Design and Technology Education: An international Journal*, 12 (1), 7-9.

Chester, I. (2007). "Teaching for CAD Expertise." *International Journal of Technology and Design Education*, 17 (1), 23-35.

Clark, R. C. and R. E. Mayer (2003). *E-learning and the Science of Instruction: Proven Guidelines for Consumers and Designers of Multimedia Learning*. Pfeiffer, San Francisco, CA.

Collins, A., Brown, J. S., & Newman, S. E. (1987). Cognitive apprenticeship: Teaching the craft of reading, writing and mathematics. (Technical Report No. 403). BBN Laboratories, Cambridge, MA. Centre for the Study of Reading, University of Illinois. January, 1987.

Duncan, S.L.S., (1996). "Cognitive apprenticeship in classroom instruction: implications for industrial and technical teacher education." *Journal of Industrial Teacher Education*, 33(3), 66-86.

EGFSN Forfás Report, (2008). Future Skills Needs of the Irish Medical Devices Sector: 2007-2013. report of the Expert Group on Future Skills Needs (EGFSN), Forfás, Wilton Place, Dublin 2, Ireland.

Eggen, P and D. Kauchak, (1997). Educational Psychology: Windows on Classrooms, 3rd ed. Merrill, Upper Saddle River, NJ.

Ericsson, K.A. (1990). Theoretical Issues in the Study of Exceptional Performance. In Gilhooly, K.J., M.T.G. Keane, R.H. Logie and G. Erdos, (Eds.) *Lines of Thinking: Reflections on the Psychology of Thought.* John Wiley & Sons., New York.

Hartman, N.W., (2005). "Defining Expertise in the Use of Constraint-based CAD tools by Examining Practicing Professionals." *The Engineering Design Graphics Journal*, 69 (1), 6-15.

Innovation Taskforce Report, (2010). *Innovation Ireland: Report of the Innovation Taskforce*, Government Publications Office, Sun alliance house, Molesworth Street, Dublin 2, Ireland. [online] available: http:// www.innovationtaskforce.ie [accessed 24 November 2010].

Jankowski, G., (2002). "Creating robust parametric sketches." *Cadence magazine*, September 2002.

Lang, G.T., Eberts, R.E., Gabel, M. G. and M.M. Barash, (1991). " Extracting and Using Procedural Knowledge in a CAD Task." IEEE Transactions on Engineering Management, 38, 257-68.

Lombard, M. (2009). *SolidWorks 2009 Bible*, Wiley Publishing, Inc. Indianapolis, Indiana.

Mayer, R.E. (1998). "Cognitive, Metacognitive, and Motivational Aspects of Problem Solving." *Instructional Science*, 26, 49-63.

Mayer, R.E. and J.K. Gallini, (1990). "When is an Illustration Worth Ten Thousand Words?" *Journal of Educational Psychology,* 88, 64-73.

Mayer, R.E. and R.B. Anderson, (1992). "The Instructive Animation: Helping Students Build Connections Between Words and Pictures in Multimedia Learning." *Journal of Educational Psychology*, 84, 444-452.

National Skills Strategy Research Report, (2007). *Tomorrow's Skills: Towards a National Skills Strategy*, 5th report of the Expert Group on Future Skills Needs (EGFSN), Forfás, Wilton Place, Dublin 2, Ireland.

Obama, B. H. (2010) *National STEM Video Game Challenge*, Press Release, New York, NY, September 16, 2010.

Rynne, A. and W.F. Gaughran. (2008). "Cognitive modelling strategies for optimum design intent in Parametric Modelling". *Computers in Education Journal.* XVIII (3) 55-68.

Schoenfeld, A.H. (1987). What's all the fuss about Metacognition? In Schoenfeld, (Ed.) *Cognitive Science and Mathematics Education.* Hillsdale, HJ: Lawrence Erlbaum Associates.

Sweller, J. (1999). *Instructional design in Technical Areas.* Acer Press, Camberwell, Australia.

Sweller, J. and Chandler, P., (1991). "Evidence for cognitive load theory." *Cognition and Instruction.* 8 (4), 351-362.

Sweller, J., (1988). "Cognitive load during problem solving: effects on learning." *Cognitive Science.* 12, 257-285.

Sweller, J., Chandler, P., Tierney P. and Cooper, M., (1990). “Cognitive load as a factor in the structuring of technical material.” *Journal of Experimental Psychology: General*. 119 (2), 176-192.

Sweller, J., J.J.G. Van Merrienboer and F. Paas, (1998). “Cognitive architecture and instructional design.” *Educational Psychology Review*. 10, 251-296.

Vygotsky, L.S. (1978). *Mind and society: The development of higher mental processes*. Cambridge, MA: Harvard University Press.

Appendix

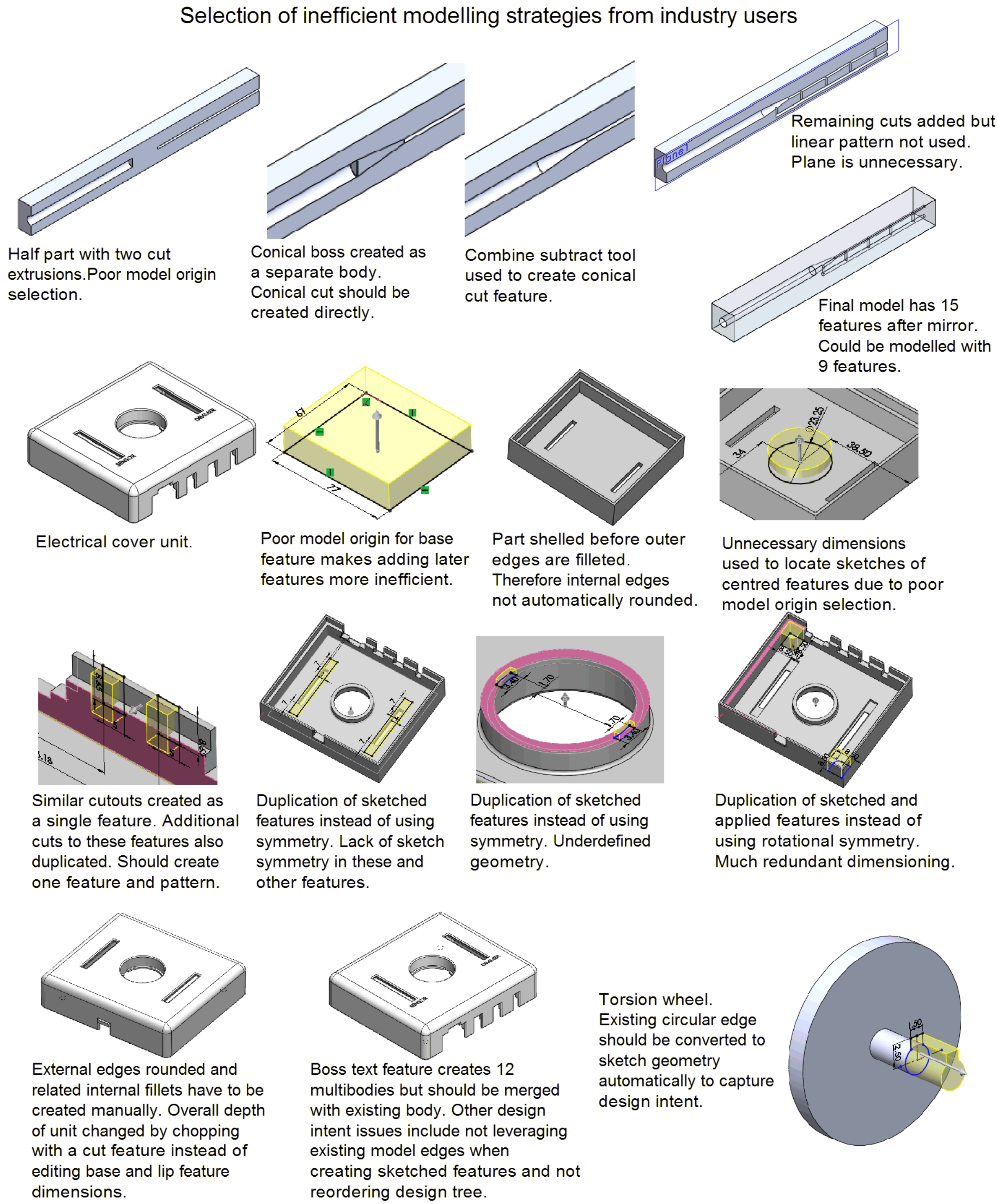

Figure 2 Selection of inefficient modelling strategies from industry users

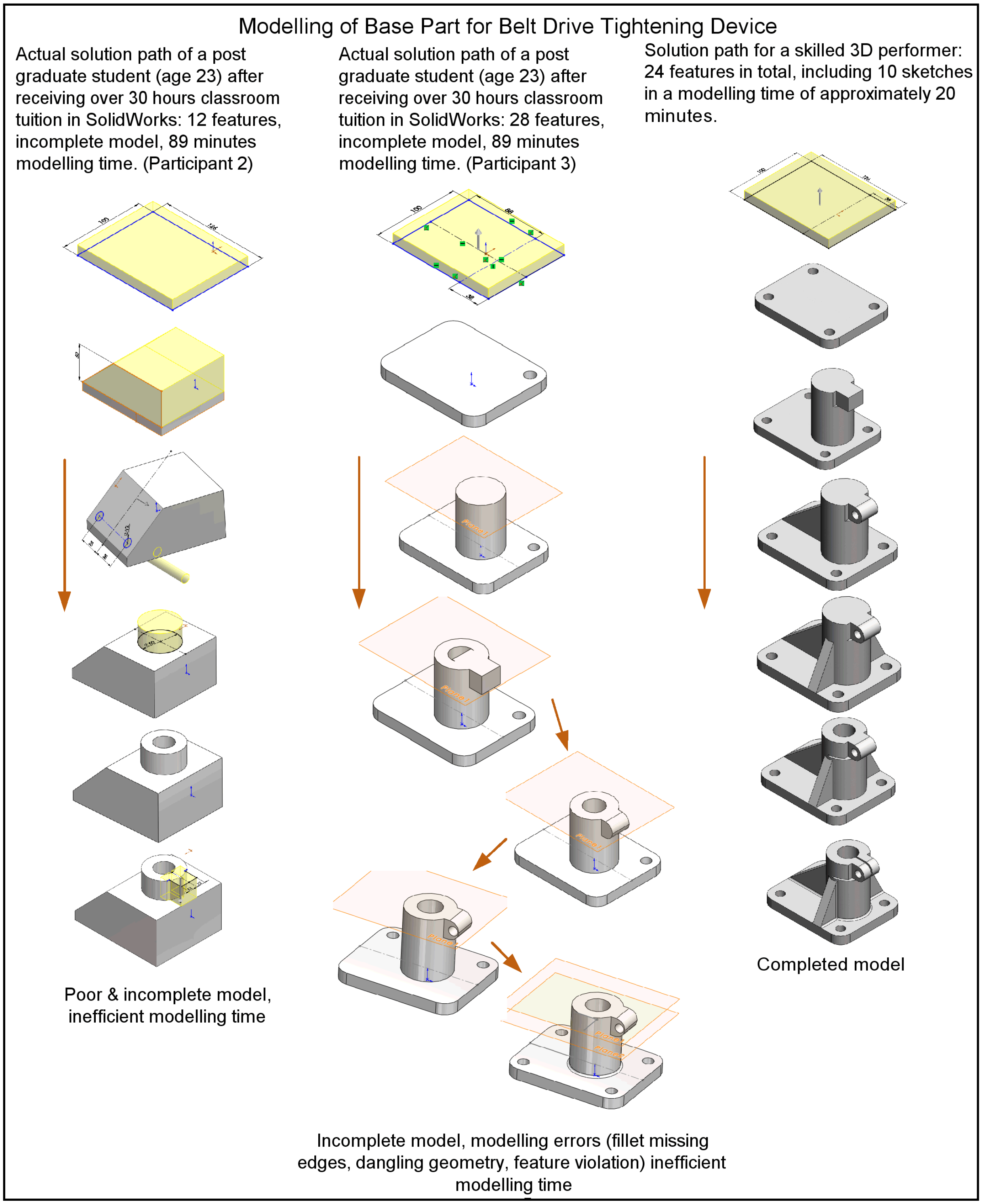

Figure 3 Comparing modelling solution paths for Part model for two novice users and a skilled performer

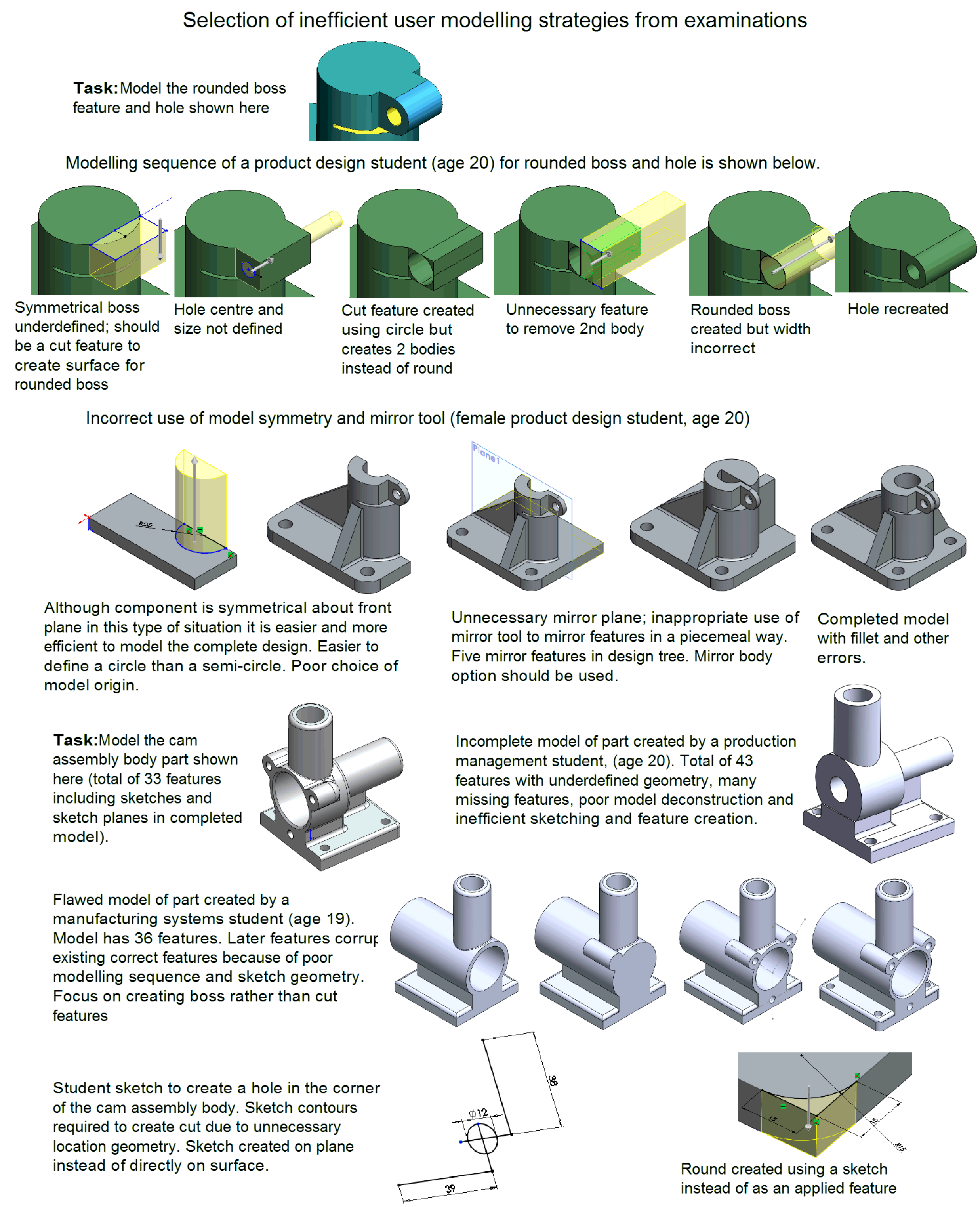

Figure 4 Selection of inefficient modelling strategies from student examinations