Strategic knowledge-based approach for CAD modelling learning

Abstract

Strategic knowledge is a differentiating factor for conveying the design intent when modelling parts in parametric feature-based CAD systems. Nevertheless, it is rarely considered in training or, when it is tackled, it takes a traditional pedagogical approach that is far from ideal for acquiring knowledge with highly cognitive requirements. This paper demonstrates a contextualised instructional approach that is developed in activities following active learning principles. These activities are structured on a modelling procedure that provides trainees with guidelines to think about the modelling rationale and consider alternative strategies. The paper describes one activity in detail, as an example, so that our proposal can be replicated and adapted to other scenarios. Finally, experimental research has been carried out that validates the proposal as opposed to the traditional teaching focus. Its results support the idea that it can have a favourable impact on developing strategic knowledge for CAD modelling.

Keywords: CAD modelling, strategic knowledge, training

1. Introduction

A familiar scenario in teaching the use of CAD systems involves students having to modify the model they have created and subsequently the model is not capable of withstanding these changes. This is not particular to the teaching environment as the professional world is also plagued with setbacks at different levels (economic and time-related). The key aspect of resolving this problem issue in CAD modelling seems to involve correctly transmitting the design intent for the part to be created on to the model. However, this is not an easy solution when a user's CAD experience is no guarantee that the transmission of the design intent will be appropriate (Bhavnani 2000). Furthermore, it is easy to see that two designers modelling the same part will follow a different process and respond to the requested changes differently (Bodein et al. 2014).

Different authors point to the importance of focussing learning on strategic knowledge right from its initial stages (Chester 2007; Menary et al. 2011; Otey et al. 2014; Rynne et al. 2010). As opposed to specific declarative and procedural knowledge, this knowledge can be transferred between the different CAD systems (Lang et al. 1991) and it is defined as the best way of organising problem-solving in a specific domain (Bhavnani and John 1996) or knowledge of alternative methods and how to choose between them (Bhavnani et al. 1999). Consequently, training cannot stick to merely instrumental use of the tool and it has to consider CAD systems as "knowledge-intensive design and communication tools to properly develop and convey design intent" (Mandorli and Otto 2013), understanding design intent as "the intelligence built into the solid model to control the behaviour of the part when subjected to changes or alteration" (Barnes et al. 2011). This focus requires trainees to develop higher-level cognitive processes.

In this respect, CAD training assiduously follows a traditional teaching structure where the teacher demonstrates how to solve a problem and the student tries to replicate the solution in this or a similar context. However, faced with the highly cognitive learning requirement, the question arises of whether traditional teaching is the most appropriate.

Backed by contributions from different authors on this matter, we believe that it is necessary to propose learning focussed on strategic knowledge and explore instructional suitable strategies for it that consider its context. This paper starts with a review of the relevant literature on training that considers strategic knowledge. In section 3, we develop a learning approach for feature-based CAD modelling with active learning strategies, within the context of developing a design project. Section 4 shows the experimental design to validate the proposal. Section 5 presents and discusses the results obtained from the research. Section 6 outlines the conclusions and the limitations of the proposal.

2. Related work on strategic knowledge

Since the early days of CAD systems, training-teaching on these systems has been considered an important aspect at university and in companies (Piegl 2005; Rossignac 2004; Sapidis and Kim 2004). However, although engineering schools have assimilated CAD teaching into their curriculum, changes that CAD systems caused in professional practice are not reflected in changes made to the curriculum (David et al. 2006). Defining the skills and knowledge that students should acquire for CAD calls for an understanding of what their professional future will require (Dankwort et al. 2004; Ye et al. 2004). In the same way, learning needs differ according to the CAD user level (Lang et al. 1991). For example, Field (2004) identifies and determines the training required for three groups of CAD users in the auto industry environment: majority (including novices), expert and super users. The proposal in this paper is focussed on training, working from the needs of novice users.

Novice users are inclined to focus their attention on learning the commands (declarative knowledge) and ignore other types of information (Lang et al. 1991) such as strategic knowledge. In turn, although strategic knowledge has been identified as key for handling CAD efficiently, its importance is frequently not emphasised during training (Peng et al. 2012). This knowledge is usually not compiled in the documentation associated with the CAD tool (Rynne and Gaughran 2007) and encompasses transmission of the design intent (Ault and Fraser 2013). In the bibliographical review that we performed on CAD learning, we can highlight the following contributions related to training on strategic knowledge:

Lang et al. (1991) mention, for example, that the aim of the training programme is to limit variability in the tasks carried out by the students using CAD systems and, among other contributions, they propose group discussion as useful concerning strategies that target more efficient modelling procedures. These authors highlight the need to assess cognitive strategies that guide modelling. In the same respect, one interpretation of the experimental data obtained by Ault (2011) suggests that discussion on modelling concepts supports development of CAD and design skills, as well as understanding CAD systems. It argues that discussion among students on modelling concepts improves students' understanding and creates a basis to develop better modelling skills.

Chester (2007) approaches CAD training from a cognitive psychology perspective and points out that developing instructional strategies to improve strategic CAD knowledge leads to developing metacognitive processes. He proposes 4 strategies: (1) expert teacher modelling, where the complex cognitive processes are explicitly described so that students can understand them, (2) scaffolding, (3) cooperative learning and (4) self-explanation. He backs techniques that make the modelling process public and that students can observe.

Rynne and Gaughran (2007) consider that successful modelling is derived from appropriate use of mental models and mentions the importance of efficiency in cognitive processes that guide the model creation action in a CAD system. He proposes a pedagogic framework that the training should consider to be effective (Rynne et al. 2010).

Other authors analyse the modelling process from observing how experts act in the matter (Bhavnani 1993; Hartman 2004, 2005). In addition to observation and interviews, they use the think-aloud protocol to analyse the problem-solving process used when creating parts. Leith (2013) applies the think-aloud protocol to assess modelling of the students' parts. Just as Chester (2007) proposes that the modelling process is open, it helps for the observer or apprentice to have some knowledge of the rationale guiding the choice of modelling alternatives.

Bhavnani (1999), proposes basing the teaching on two approaches to strategic use of CAD: *Learning to See* (recognising the opportunities to apply efficient strategies) and *Learning to Do* (implementing these strategies to perform the task) and completes it with action sequences that describe the modelling by the student. The action sequences stimulate student thinking on the modelling process and on the result and as they explain it, feedback is encouraged over time.

Feedback is essential to correct any remaining poor practice in good time. Many authors highlight the importance of immediate and contextualised feedback (Ault and Fraser 2013; Chester 2007; Kirstukas 2016; Wiebe et al. 2003) that helps review the modelling process critically and stimulates improvements. In large teaching groups, feedback and assessment have been studied with a view to automating them (Ault and Fraser 2013; Guerci and Baxter 2003) because individually they are laborious tasks. In this aspect, it would be possible to explore dynamics such as peer interaction or small group discussion (Bhavnani and John 1996) as a means of giving feedback.

Feedback should not only consider the modelling result (geometry accuracy), but also the modelling process and the model's attributes, questioning the cognitive processes that guide them. To perform feedback or a training assessment on the models, rubrics can be used (Branoff 2004; Company et al. 2015), plus tutorial questions devised to supervise the modelling process.

Company suggests a set of modelling best practices from which to define quality dimensions for the CAD models and include them in rubrics to express expectations to the trainees concerning the models right from the start of their instruction. This practice would be related to the style guides mentioned by Aleixos (2004) and the best modelling practices in companies. Other authors (Diwakaran and Johnson 2012; Johnson and Diwakaran 2010; Peng et al. 2012; Rynne et al. 2010) have also defined the attributes for models to match the design intent and that are used to define the preferred modelling procedures to best convey design intent in cross-platform CAD systems.

These model attributes should be met and maintained when creating or redefining the model, or when altering it. Wiebe (2003) proposes dynamic modelling or flexing modelling (Ault and Fraser 2013) as a practice that considers them. Consequently, the problems that are set in training, for which the models are created, would have to be ill-defined for the students to take into account the design considerations and develop modelling strategies based on the situational design intent. These problems promote the students' abilities to question strategic modelling decisions and weigh up alternative methods.

However, these contributions raise the question of whether traditional teaching is sufficiently effective to consider and encourage situations that promote strategic knowledge. This explains why we have developed a contextualised approach based on active learning, focussed on strategic knowledge.

3. Proposal

Context

We have selected Project-based learning as a pedagogic approach to develop CAD modelling learning. Working from a situated problem (real-life ill-structured situation), the students, working in small groups, acquire the knowledge and skills they need to develop a design project that solves a problem or challenge. The design project is the instructional framework and this approach has been selected because it engages experiential learning and promotes thinking about what is being experimented on. In addition, project-based learning stimulates long-term retention of knowledge and skills acquired during the learning experience or training session (Strobel and van Barneveld 2009). In short, it boosts solving higher order cognitive problems which is the focus we are striving for when training on strategic knowledge.

One of the learning outcomes that the students identify in the project is the need to learn about a CAD tool, among other functions, for modelling parts. However, to ensure effective autonomous learning on the use of CAD, we see that it is necessary to design a programme of activities that can be used as scaffolding and lighten the student's cognitive load.These activities emphasize the importance of strategic knowledge as students acquire procedural knowledge and declarative knowledge about the specific software they use.

Modelling procedure

Based on the contributions mentioned in the bibliographic review, these activities are structured so that it is easy to identify guidelines in the modelling procedure. This modelling procedure is a simplified approximation of the complex cognitive processes that an expert tackles when modelling a part. The steps that are marked out are as follows:

1. Geometric interpretation and inference of the design intent: The first step is to create a *cognitive visual model*, as (Rynne and Gaughran 2007) mentions, to interpret the part geometrically and visualise it in 3D. This requires the student to have prior visualization ability. Knowledge of useful techniques such as sketching and understanding fundamental graphic principles (such as prior ability to read engineering drawings) is essential to create this mental model (Bertoline and Wiebe 2007).

   This first step compiles the explicit information, such as annotations, that can help to infer the design intent. In the same way, the assembly drawing is analysed, if it is available, and possible functional requirements for the part are considered. The type of dimensioning used in drawing the part relates functional requirements within product development processes to geometrical specification (Otto and Mandorli 2015). In the same way, dimensioning a part is conditioned by the design intent (Ault et al. 2014; Kirstukas 2013).

2. Deconstruction in physical (geometric) constituent elements of the part. One identification criterion for the geometric features is to relate them to the functional requirements that they satisfy. In turn, dependency relationships are considered between these geometric elements and their possible behaviour when modified. Although it is complicated to anticipate any possible changes to a part, dimensioning should consider the important functional requirements for a part (Ault et al. 2014) and it might help to identify possible alterations.

3. Planning. This step synthesises the geometric features in modelling operations. Relationships are included between geometric features identified in the previous step. Alternatives are weighed up between the modelling strategies taking into account the design intent and establishing the sequence of operations to carry it out.

4. Modelling. The planned sequence of operations is carried out, according to the options offered by the specific software being used. Each operation is listed in detail and the necessary references, sketches, parameters and constraints to create the features are determined. The model recipient perspective is introduced so that the model fulfills the function of putting across the design intent and it is less laborious to make the required modifications. Renaming the operations, inclusion of explicit annotations and ordering the operations are considered as ways of facilitating this communication.

5. Checking: This step has been highlighted due to its importance in how the model responds to any future changes, although checking should be included within the modelling to anticipate possible errors and resolve them before finishing the modelling. Lack of time can lead to omitting these types of checks on the modelling and so the solution to problems generated by modifying dimensions will require a relatively long

time to resolve compared to the modelling time. The rubrics are useful in this task to ensure the quality of the models, as mentioned by Company (2015).

Many authors mention that assessment of parametric solid models should include model modification (Ault and Fraser 2013; Branoff 2004; Guerci and Baxter 2003; Kirstukas 2013) so that it can be seen that appropriate methods have been used. As far as possible, this would attempt to predict any possible alterations to the model according to its functional requirements (Barbero et al. 2016), although they are difficult to predict in the product development process.

Developing activities

Carrying out a design project implies that the students need to learn how to use a piece of software to model CAD parts. For this learning to be effective and be used as a basis to tackle modelling from a modelling rationale perspective, a series of activities have been structured that focus on didactic strategies promoting strategic knowledge. These activities follow the steps of the modelling procedure explained in the previous point and are based on active learning principles.

As an example of the programme of activities, an activity is described below that adapts the cooperative learning technique known as jigsaw (Aronson 1997). This activity promotes discussion and evaluation of modelling procedure alternatives and helps deal with modelling from different perspectives. The activity is developed as follows:

The dynamics of the activity are explained to the class. The trainees form groups of three, each assigned a different problem, in this case, modelling a different part. Individually, they start the first step of the procedure, meaning interpretation to obtain the cognitive model and the inference of the design intent. In order to clarify any possible queries, time is given to open questions or consultation among peers working on the same part.

Individually, they break down the cognitive model into geometric elements and, on paper, plan the sequence of operations to perform in the modelling. Once the first three steps of the modelling have been completed, as described in the previous section, the meeting of experts is held. This meeting consists of discussing alternatives and the rationale when identifying geometric elements and their definition in the sequence of operations. The number of persons in the meeting group will determine whether it is necessary to divide it into smaller groups so that all members can participate.

The teacher supervises to make sure that discussion in these groups leads to a consensual and effective solution. The teacher can help by explaining unknown operations that improve the solution or questions that revive the debate from another point of view.

Once the meeting of experts has finished, each student returns to their original group. The following group dynamic ensures that each student experiences three different roles related to the modelling:

- One student explains the planning for the modelling to the other two members of the group (designer role).
- This student is then told about the other two parts planned by his/her classmates. Later, the student will have to model one of these parts (shaper role) and will have to review the part modelled by another classmate (inspector-evaluator role). This means that each

student takes part in planning one of the parts, modelling a different part and review of a third.

Once a part has been assigned to each group member for modelling, the students will model them individually outside the classroom, bearing mind that another group member will have to make the modifications on it. Once modelling is complete, in the following class session, they will have to check the behaviour of the model that they neither planned nor modelled and observe its behaviour in the light of the requested changes, using a rubric.

The planned, modelled and reviewed models are handed in after approval from the whole group, indicating who participated in each stage of the modelling. The activity will finish with feedback from the teacher in the following session.

In this activity, it can be seen that class time is used for actions targeting higher order cognitive learning results according to the taxonomy by Bloom that requires analysis, assessment and creation (Anderson et al. 2001). Individually, the students work on metacognitive processes such as planning, review and predicting the behaviour of the part when possible modifications are made (Chester 2007). At a group level, the peer discussion, open questions, discussion and consensus in small groups make the modelling process public and mean it is continually reviewed, optimising the solution in an iterative process. In addition, the teacher plays a facilitating role, supervising and providing guidance to help optimise the modelling process.

The students are aware that the learning goal is the effective and efficient use of the CAD tool to obtain good quality models that convey the design intent. They know that the assessment is not limited to the model's geometric correction and that it will undergo changes just like a product development process. Assigning roles in this activity encourages inclusion of different perspectives in the modelling, and consequently, an increase in constructive feedback.

In turn, an activity such as described here is designed by taking into account the positive interdependence between the students and individual accountability in an attempt to encourage cooperation among group members.

The rest of the activity programme supporting the project uses different instruction strategies such as tutorials, expert teacher modelling, peer review, think-aloud procedure, cooperative techniques,… but they consider all the steps in the modelling procedure equally in their development. Repeatedly exposing students to the modelling procedure helps them internalise the procedure. On the whole, the design for these activities is based on active learning principles. Likewise, assigning roles as an instructional technique to encourage students to think about the modelling process from other perspectives is repeated in other activities in the same way as it is used to develop the project.

4. Study

Research context

The study is conformed by a cohort of 176 engineering students from the University of the Basque Country (EHU-UPV, Spain). The study has been carried out in the Computer-Aided Design optional course, involving third and fourth-year students. The students are divided into various groups according to enrolment and instruction language which may vary between Spanish or Basque. The assignment of both the control and experimental group were done randomly. Due to the fact that the students take the subject in different groups, class schedule, classrooms and languages, we estimate that the contamination factors have a minimum incidence. Sampling has been carried out in 3 consecutive years and the software used has been Solid Edge (Siemens).

The students receive 45 hours of training on CAD tools (3 hours a week) following different pedagogic approaches. The intervention group experiments the proposal previously described based on active learning methodologies and contextualized in the development of a design project (as mentioned in the context section of 3. Proposal). The control group continues with a more traditional approach where the figure of the expert-teacher promotes learning. Generally, the teacher presents a problem and the way to solve it, so that later the students replicate the process in a similar context. Active learning techniques are not implemented, so the interaction among students is lower and the teacher is the main source of feedback. The control group also carries out a project during the last weeks of the course, while in the case of the experimental group, the project promotes the learnings of the students from the first week.

Investigation hypothesis and procedure

The aim of this research paper is to find out if there is a difference in the quality of CAD models designed among the students whose learning is based on the new instructional method (experimental group) or the students who receive traditional teaching (control group). The quasi-experimental design of the proposed research is based on a pre-post-test, where the pre-test is carried out due to the fact that random assignation of the students is not possible and the post-test indicates whether there are significant differences between the variables to be measured after applying the treatment to a group.

Research instrument and variables

Two modelling problems are selected for the pre and post-test of two different parts to avoid the "testing effect" with a similar level of difficulty. The post-test part (Fig. 1) is a part that has been validated in previous research papers (Wiebe 1999, 2003).

The research variables are the attributes that define the quality level of a part. The list of variables works from the attributes proposed by Rynne and Gaughran (2007) and it is completed with others from subsequent research (Company et al. 2014; Diwakaran and Johnson 2012; Johnson and Diwakaran 2010; Peng et al. 2012). To clarify the list of attributes, they are grouped together in the quality dimensions suggested by Company et al. (2014). The scale we chose is mainly dichotomous as, despite being more restrictive, it leaves less room for subjective assessments:

D1. Model is complete (dichotomous): the geometric correction is measured when reproducing the shape and original size.

D1a. Failures (whole number): number of failures obtained after contrast with a reference model.

D2. Model is valid (dichotomous): the model does not present the errors indicated by the programme.

D3. Model is consistent (dichotomous): it is completed with the following variables:

D3a. Fully defined sketch geometry (dichotomous)

D3b. Supports dimensional changes (dichotomous) that do not imply geometric errors

D4. Model is concise (dichotomous): implies that it meets the D4a and D4b variables:

D4a. Duplicated or redundant sketch elements (dichotomous)

D4b. Redundant operations (dichotomous)

D4c. Modelling feature number (whole number)

D5. Model conveys design intent (dichotomous): it is defined using the variables

D5a. Base feature positioning (dichotomous)

D5b. Operations not related to convey functionality of parts (dichotomous)

D5c. Modelling sequence conveys design intent (dichotomous)

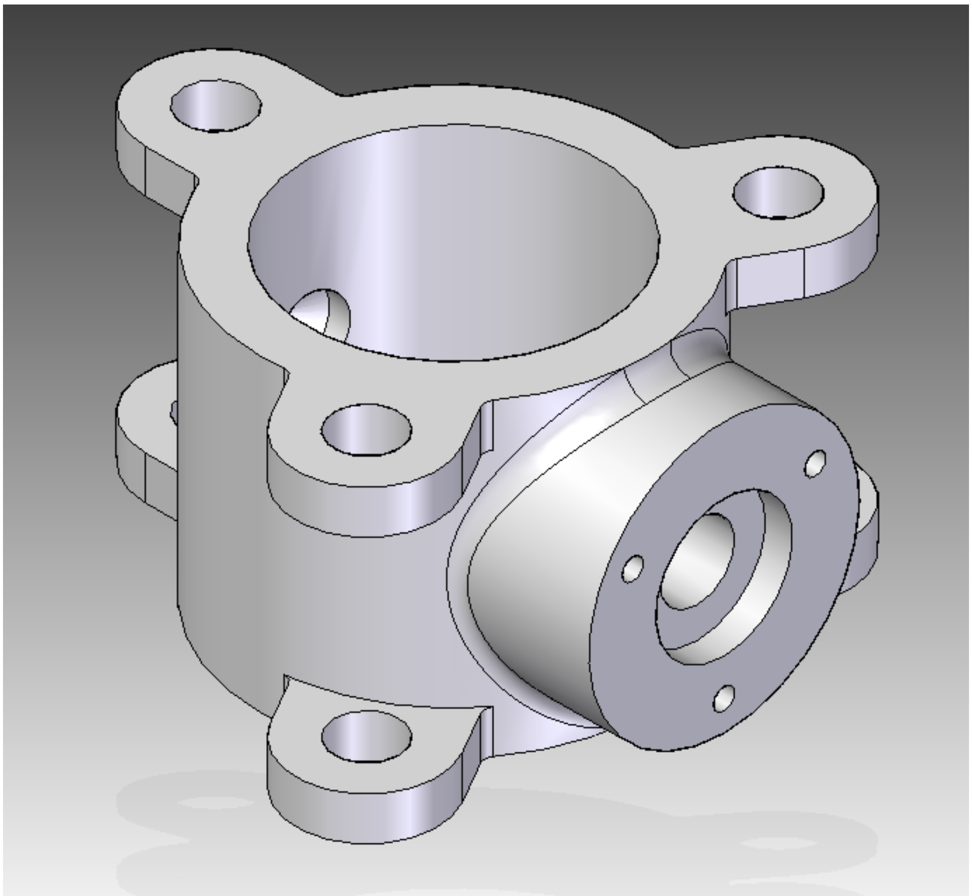

Fig 1. Post-test part

5. Results and discussion

Statistically significant differences for the quantitative variables were identified using non-parametric tests as they do not fit normal distribution. The Mann-Whitnney W test was used to estimate the p-value. In the case of dichotomous variables, the Chi squared test was chosen to calculate the p-value. The effect size was calculated with Cohen's d for quantitative variables and Cramer's V for dichotomous variables.

The pre-treatment test is used to measure differences in initial knowledge among the subjects in the research groups in the empirical research where random assignment is not feasible, and it increases the validity of the research (Slavin 2007). The results from the data obtained reflect similarity in the dimensions and indicators from both groups (E: Experimental; C: Control), except for the indicator that measures the existence of excess elements in the sketches (greater in the experimental group).

The results obtained after treatment can be seen in table 1. The *model completeness* variable is corrected by means of a contrast with a reference model and it has to match perfectly. The results show a greater percentage of occurrences in the experimental group (32.6% compared to 8.6% from the control group). The Chi-squared test shows a statistically significant difference with a $p<0.0001$ and a moderate effect size (Cramer V =0.297). Within this dimension, the *failures* variable stands out with a high effect size (Cohen's d=0.804) for the treatment.

Table 1. Post-treatment table of results

	E (%)	C (%)	p-value	Cramer's V
D1. Model is complete	32.6	8.6	0.0001	0.297
D1a. Failures	1.0 (0-2)*	2.0 (1-3)*	0.0001	0.804**
D2. Model is valid	90.2	75.3	0.0088	0.2711
D3. Model is consistent	17.4	3.7	0.0410	0.2184
D3a. Fully defined sketch geometry	19.6	9.9	0.0752	-
D3b. Supports dimensional changes	66.3	32.1	0.0001	0.3414
D4. Model is concise	68.5	23.5	0.0001	0.4499
D4a. Duplicated or redundant sketch elements	7.6	33.3	0.0001	0.323
D4b. Redundant operations	26.1	66.7	0.0001	0.4069
D4c. Modelling feature number	10.0 (9-10)*	10.0 (9-12)*	0.4426	-
D5. Model conveys design intent	64.1	9.9	0.0001	0.5557
D5a. Base feature positioning	79.3	42.0	0.0001	0.3839
D5b. Operations not related to convey functionality of parts	14.1	50.6	0.0001	0.4069
D5c. Modelling sequence conveys design intent	72.8	21.0	0.0001	0.5176

E: experimental
C: control
*Median and interquartile range
** Cohen´s d effect size
Cramer V: interpretation (0.1 low , 0.3 moderate, 0.5 high)
Cohen d: interpretation (0.2 low , 0.5 moderate, 0.8 high)

As mentioned in the model test correction criteria, a dichotomous scale was chosen as this scale is considered to be more objective for model classification, despite the fact that it might be seen as excessively restrictive. One consequence of using this scale can be seen in the consistency of the models (D3): one of the conditions to consider that a model is consistent is that its sketches are completely defined (D3a), in other words, a missing dimension would eliminate it from this classification. This restriction might explain the low percentages in this dimension. On the other hand, in the activities that we are developing, more probable changes are foreseen, taking into account the design intent and it is checked that these changes do not cause geometric errors on the model. This might mean that the Model withstands changes (D3b) indicator has a higher percentage than the indicator for the Completely defined sketch (D3a). This leads us to consider the equilibrium between robustness and flexibility in the sketches, in other words, should the sketch be completely defined (Diwakaran and Johnson 2012; Johnson and Diwakaran 2010; Rynne and Gaughran 2007) or only as much as necessary (Company et al. 2014)?

Out of the 5 dimensions, the *Concise model* (D4) and *transmits the design intent* (D5) dimensions show a greater percentage difference in favour of the experimental group. They present a high effect size (Cramer's V 0.4499 and 0.5557 respectively), and the completion percentages in the experimental group exceed 64% of the models designed in the test. Within the dimensions, the attribute that presents the greatest effect size is *Modelling sequence conveys design intent* (0.5176).

In addition, within the dimension that the *Model is concise* (D4), the *redundant operations* (D4b) attribute presents the greatest effect size (0.4069). Some authors back the reduction of the number of operations as a distinctive characteristic of experience and skill in handling CAD (Diwakaran and Johnson 2012; Hamade et al. 2007; Johnson and Diwakaran 2010; Peng et al. 2012). In turn, the experimental group models present less dispersion in the modelling feature number (interquartile range 9-10) than the control group (9-12). It could be thought that the treatment has a part to play in reducing erratic modelling sequences (Branoff and Dobelis 2014).

In the light of the results, it can be deduced that the treatment is effective for students to consider that prior thought and planning are aspects that will influence model quality. It could be said that the experimental proposal is useful for CAD modelling training from a perspective that contemplates strategic knowledge from the start of training.

6. Conclusions

This paper shows some insights from an instructional approach based on active learning for training on CAD modelling. The proposal is developed by carrying out selected activities within a context of developing a design project where the student is the centre of the learning. The focus was to encourage acquisition of strategic knowledge so we shift the workload to the previous modelling stages, even before using the computer, where strategic knowledge is most relevant.

The activities were designed to develop metacognitive training. Pedagogic strategies that promote metacognitive processes have been used, helping students become aware of how their learning is progressing and regulate it. These activities follow a procedure that we have defined in an attempt to encourage students to take in certain cognitive processes that an expert carries out when facing CAD modelling.

Among the contexts for CAD learning, mentioned by Yue (1999), development of a specific project was selected. A design project is used so that students have contextualised experiential learning, they experience the iterative nature of the design and see that these interactions directly influence their sets and models being designed. This purposive context stimulates student learning and it is demonstrated to be effective in developing skills and long-term learning. In addition, it is used to include roles that students might take on in the workplace.

From the teacher's perspective, it is not usually easy to apply active learning methodologies such as this the first time around. Our proposal, based on a project-based engineering course, lays the foundations for developing activities in a modelling procedure that encourage acquisition of strategic knowledge and it provides details of running an activity that focuses on active methodologies. The proposal presented in the paper was validated experimentally.

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