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Training Engineers in the Use of Constraints to Create Quality 2D Profiles for 3D Models

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Abstract. Historically, different strategies utilized in engineering and technical graphics reflect growing concern about improvement in CAD instruction and the introduction of product quality data in curricular activities. Our vision was that early introduction of quality criteria through "good practices" is feasible and increases the quality, robustness, and reliability of CAD models. This paper describes a strategy applied to improve the knowledge of novice CAD users on the use of geometric constraints in 2D parametric profiles. This approach consists of supplementing student training with activities in order to provide rapid and effective feedback. A Chi-Squared Test was performed to assess the effectiveness of this strategy, indicating that trainees need continuous and additional autonomous learning to create quality 2D parametric profiles. Future work will include developments to promote student awareness of the need for quality in 3D models using an online checker that acts as a filter of semantic quality errors while providing feedback.

Keywords: CAD model quality, Sketching, Constraints
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1 INTRODUCTION

The development of computer-aided three-dimensional design applications (CAD 3D) has transformed the product development process and has introduced a new paradigm of Model-Based Enterprise (MBE). This principle draws on the use of annotated CAD models as primary elements to support the design, analysis, and manufacture of industrial products. These annotated CAD models contain data and additional information necessary for production and support. For this reason, CAD model quality is essential, since the quality of manufactured products depends on the quality of their data [22]. Consequently, poor data quality compromises CAD model reuse, which is a primary benefit of history-based parametric modeling software.

Three "quality levels" were identified [13] to classify CAD models: morphological, syntactic, and semantic/pragmatic. The morphological level is related to the geometric and topological correction of the CAD model. The syntactic level measures the proper use of modeling conventions. The semantic/pragmatic level is associated with quality that accounts for the capacity of the CAD model for subsequent modifications and reuse. A model is reusable if it allows modifications in other situations while maintaining its design intent [16]. Therefore, this study considers as a good model the one that is reusable and is at the same time robust and flexible [6], [7]. Reusability and the interoperability of a model are the most common functions in MBE. Previous studies revealed that nearly 50% of CAD models fail after making alterations [20].

In our current work, we focus on feature and history-based variational parametric CAD modeling. These CAD applications enhance the creativity of designers, since they allow exploring various alternatives and solutions during the design process of a product. In addition, this modeling strategy is commonly used to create annotated models in the MBE paradigm, shortening design time and increasing business productivity since the reuse is its primary benefit. Specifically, we are interested in analyzing models created using SolidWorks®since this application is used to introduce students of graphic engineering courses to constructive geometry.

At present, commercial tools exist for "Model Quality Testing" (MQT) or "Quality Testers" to detect and correct failures. However, a recent study reports that these tools are limited to analyzing the most elementary aspects of CAD model geometry [15], while quality aspects at the semantic/pragmatic level appear to be absent (ex. the use of fix constraints), which compromises model reusability [17]. In this study, González-Lluch et al. [15] analyzed the capability of the SolidWorks Design Checker®(Model Quality Testing embedded in SolidWorks®) showing that high semantic level quality criteria are not considered during the process and that the checker does not provide much more help and feedback to users of what they receive while modeling.

Constraints are commonly used to acquire robust and flexible profiles that allow for redesign while prevent undesirable geometric changes. Robust profiles must be completely or fully constrained [9]. Profile flexibility does not depend on the quantity of constraints, but on their semantic level. The proper selection and introduction of geometric constraints in 2D profiles determines their applicability for reuse.

Various authors have proposed different classifications constraints [24], [1], [11]. We classify constraints as:

- Dimensional. These constraints define the size and dimensions of the profile.
- Geometric. These constraints define the geometric relationships between the elements of the profile.
- Position and orientation. These constraints relate the profile to the coordinate system.

We strongly believe that over-constrained profiles with redundant relationships are more difficult to edit than those that avoid redundancies. Many experienced CAD instructors have observed that engineers often use redundant relations when creating 2D profiles and that this practice prevents the creation of reusable CAD models. Our goal is to train novice CAD users to create quality parametric 2D profiles based on robust and flexible 3D models for future reuse. When incompatible constraints are introduced during the creation of 2D profiles, the user is alerted by the system. In a previous step, the authors compared the behavior of some representative commercial 3D CAD systems including SolidWorks®when incompatible constraints were added to a profile. In all cases, the systems showed a warning and/or stopped execution until the user changed the strategy. However, the behavior is not homogeneous regarding the detection of redundant constraints. In this case, some applications (such as SolidWorks®) do not issue any warning to the user.

In the literature, a previous work [18] conducted an experiment examining if engineers were able to: (1) identify fully-constrained profiles and (2) detect the types of constraints that were used. Results indicated that more than half of trainees failed to identify which profiles were properly constrained and they also could not identify the type of constraints used in a given example. We concluded that improvements were necessary in training engineers in these skills. A survey of past efforts to improve training of novice CAD users reveals that the following strategies have been successfully implemented:

- Development of rubrics for assessment of CAD models [9], [2], [12], [8].
- Creation of activities to increase student awareness of the methodological aspect of CAD model construction [5], [4], [14], [23].
- Use of automated electronic tools to homogenize and improve CAD grading [21], [3], [25], [19].
- Prompt feedback used to improve modeling strategies [21].

With this approach and from our teaching experience, we firmly believe that users must be trained from the outset to create 3D models considering the quality aspects, in order to design effective and reusable models. A suitable model must incorporate reusability, robustness and flexibility capabilities. This paper is one of the first steps in this direction.

In this paper, we present a strategy to reinforce student training through simple exercises paired with quick and effective feedback. Currently, students enrolled in graphic engineering courses at the Jaume I University, are trained with SolidWorks®through a student license which remains active for an entire year. SolidWorks®is a CAD program widely used by companies, has an intuitive interface which makes it easy to use for beginners and experienced users, and the educational version provides resources for teaching mechanical CAD, design validation and data management. This approach facilitates student performance in identifying and avoiding redundant 2D constraints when drawing 2D profiles. The following section describes the technique that is applied to reinforce this training. Then, this methodology is experimentally evaluated, comparing the results obtained from students who followed the reinforcement activity against a control group comprised of those who did not. Finally, conclusions are drawn from this experiment and plans for future work are elucidated.

2 METHODOLOGY

In a previous study by González-Lluch and Plumed [18], a pilot experiment was performed with students enrolled in a "Graphics Engineering" course (third sequential course in an undergraduate Mechanical Engineering curriculum). The results indicated that novice CAD users failed to identify constraints in sample CAD files even when the examples were at low levels of difficulty. Students were trained to create robust and flexible 2D profiles following the first chapter of an instructor-authored text [10]. This book is aimed for basic 3D CAD courses in Mechanical Engineering and Industrial Design and Product Development degrees grades and in the first chapter, three-dimensional geometric modeling and parametric design of profiles are covered. Moreover, they also received instruction on constraints in additional theoretical and practical-based classes (using SolidWorks®).

In a continuation of this research focus, a new strategy has been introduced to students in a subject entitled, "Computer-aided Design II," which is the third sequential course in an undergraduate Industrial Design and Product Development Engineering curriculum. This subject, along with the previous one, use the same text [10] and both groups of students have similar backgrounds in technical drawing.

The didactic proposal in the subject structures the teaching-learning process into two training activities: lectures and practical teaching (lab sessions). During the theoretical classes, students are introduced to geometrical and dimensional constraints. A common method to identify the quality of 2D profiles is to quantify their degrees of freedom. Each geometrical element is defined by fixing a certain amount of degrees of freedom (DOF). Simultaneously, each constraint restricts a certain number of degrees of freedom (valency). To obtain a robust and quality 2D profile, it must be completely constrained. In other words, the total number of DOF of the profile must be equal to the total valence of all its constraints. Rules to efficiently restrict the profiles are provided to the students: the first step should be restricting the shape and size of the profile (prior to the position) until a rigid figure is reached. This step helps to avoid extrinsic restrictions that relate elements of the figure with external datums in order to make the profile more flexible in terms of location and movement.

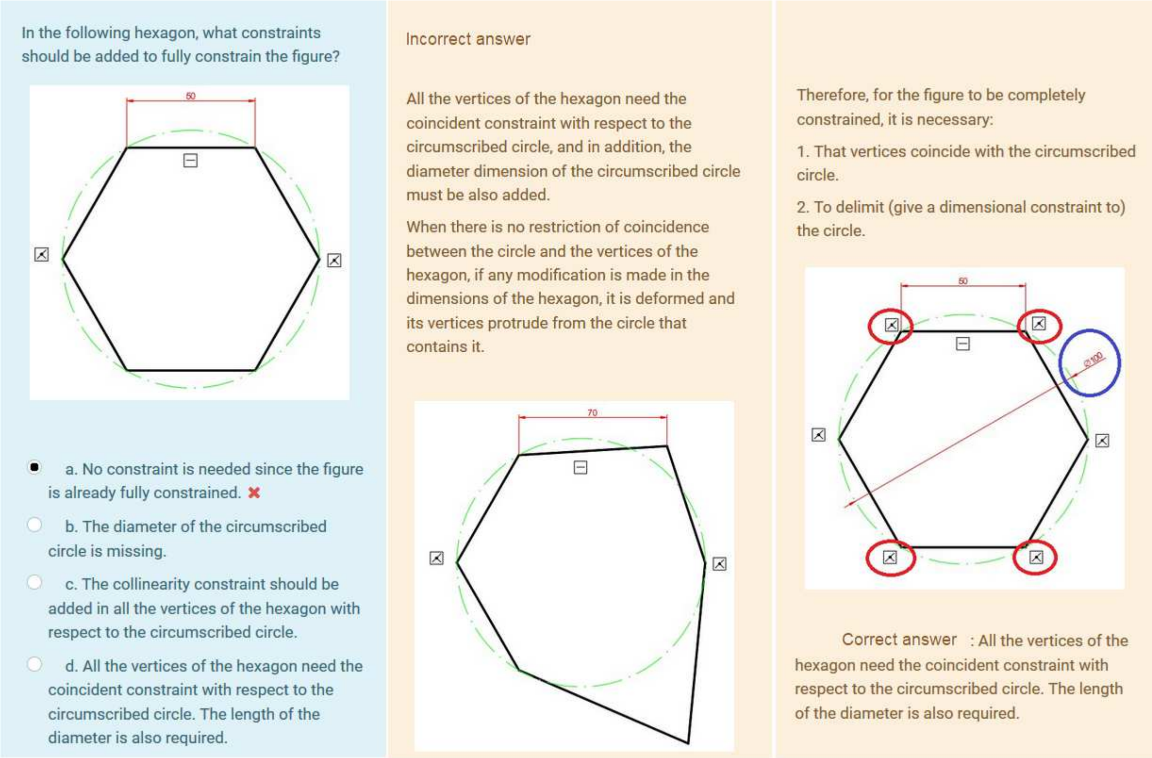
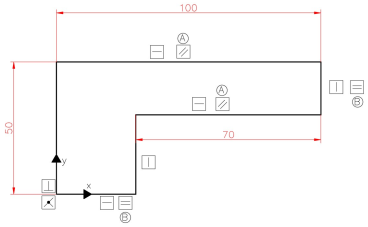
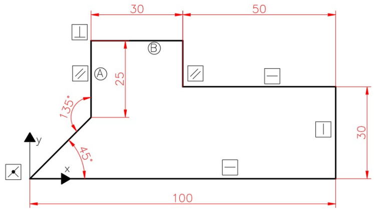
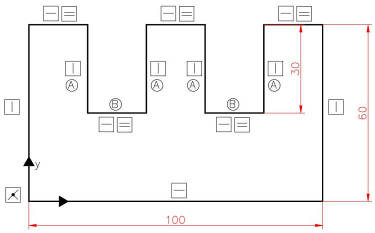


Figure 1: Example of a question with incorrect answer and the feedback obtained

In practical classes, during the creation of 2D profiles in SolidWorks®, students apply the theoretical training while a profile is created. The system provides feedback about this process that has been previously explained by the teachers. In the first eighteen exercises, students create different 2D profiles and during the process, students can check their profile [10]. If the profile is under-constrained, a minus sign (-) precedes the profile name (tree model). Additionally, the configurations' menu allows the user to configure the program to assist in detecting fully constrained sketches by line color. On the other hand, the system warns of incompatible constraints which are included in the name of the profile, but the system does not provide warnings about redundant constraints.

A supplemental activity was designed to improve novice skills with respect to understanding 2D constraints and consists of an eight-question survey, with corresponding figures. The online questionnaire was delivered through a virtual classroom environment as an optional assignment. Each isolated question is displayed full screen, to capture a student's full attention, in multiple-choice format. Questions were delivered in random order. If a student supplies an incorrect answer, the questionnaire provides comments with explanations of the correct answer, as shown in Figure 1. The online platform collects a register of student responses. Student were unable to alter their answers once they were submitted and there was no time limit to respond. Table 1 shows the survey questions and the bolded correct answers. Forty responses were collected from the virtual classroom. Frequency of student answers is also included in the right column (Freq).

	Questions	Figures	Answers	Freq.
1	Is the following sketch completely constrained?		a. True	20%
			b. False	**80%**
2	Select the response that explains your answer to the previous question		**a. The sketch is over-constrained; the parallelism constraints (A) are redundant since both Edges A are horizontal**	**20%**
			b. The sketch is under-constrained	30%
			c. The sketch is completely constrained	37.5%
			d. DK/NA	12.5%
3	How will Edges A and B of the following sketch behave when the angle of 45° is altered to 60°?		a. Edge A will remain vertical and Edge B will remain horizontal	10%
			b. The sketch is fully constrained, so no changes are permitted	25%
			c. Edges A and B will maintain the constraint of perpendicularity	**65%**
			d. Edge B will remain horizontal and Edge A will change	—
4	What constraints should be applied so that all edges A have the same dimension (height) when the 30 mm dimension is modified to 20 mm?		a. An equal length constraint should be applied to all Edges A	60%
			b. Collinearity constraints should be applied to Edges B	—
			c. Both answers a) and b) are correct	**40%**
			d. Each edge should be individually constrained	—

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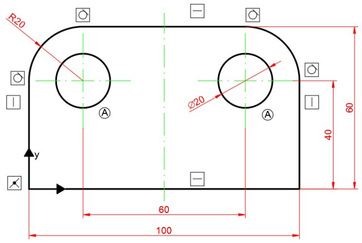
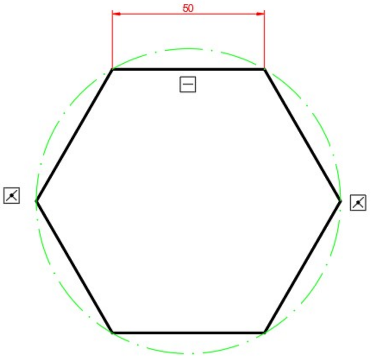
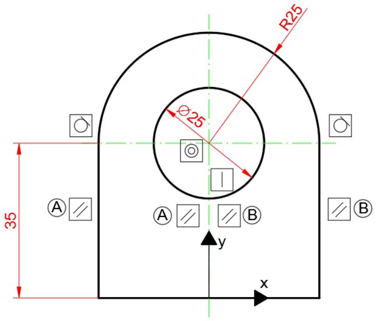
	Questions	Figures	Answers	Freq.
5	What constraint should be applied between Circumferences A so that when the Ø20 dimension is modified, the two circumferences have the same diameter (equal dimension)?		**a. The equal constraint should be applied to both circles**	**85%**
			b. The Ø20 circle should have a concentricity constraint	5%
			c. Equal and horizontal constraints should be applied	10%
			d. Each circumference should be individually constrained	—
6	In the following hexagon, what constraints should be added to fully constrain the figure?		a. No constraints are needed since the sketch is already fully constrained	15%
			b. The collinearity constraint should be added to all vertices of the hexagon with respect to the circumscribed circle	2.5%
			c. The diameter of the circumscribed circle is missing	15%
			d. All vertices of the hexagon need the coincidence constraint with respect to the circumscribed circle. The Ødimension is also required	**67.5%**
7	What will happen if R25 is modified to R30?		a. The height of 35 mm will increase, but the sketch will not deform	—
			b. The values of the outer arc and the circle of Ø25 will increase, but the sketch will not deform	5%
			c. The sketch will be deformed because there are missing constraints	2.5%
			d. The sketch will maintain its shape, the dimension of Ø25 will remain unchanged, and the width of the figure will increase	**92.5%**

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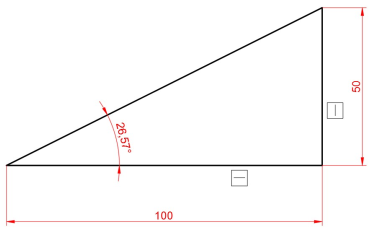
Questions	Figures	Answers	Freq.
8 How would the following sketch be defined in Solidworks?		a. Fully constrained	15%
		b. Under-constrained	55%
		c. Over-constrained *(the angular constraint is redundant)*	**30%**

Table 1: Summary of the questionnaire and alternate answers. Correct answers are in bold.

In the light of these results, we notice that when determining if a sketch is completely constrained, students appear to focus only on dimensional constraints, while completely overlooking geometric constraints. For this reason, questions about defining a profile as fully, under, or over-constrained have low ratios of student success. Nevertheless, students understand the function of geometric constraints (i.e. how the constraints influence the profile's shape when any dimensional constraint is modified). In order to gain more insight about student impressions of the activity, the questionnaire also queried their opinions of the effectiveness of these exercises (Table 2). The most frequent answers are bolded.

	Questions	Answers	
9	Has this questionnaire aided you in an increased understanding of how to use constraints in sketches to build 3D models?	**YES**	**92.50%**
		NO	7.5%
10	Have you used or been made aware of any new geometric constraints?	YES	30%
		NO	**70%**
11	Has this questionnaire helped you to distinguish between under-constrained, over-constrained, and fully constrained sketches?	**YES**	**77.5%**
		NO	22.5%
12	Do you think it will be useful for sketches you create in the future?	**YES**	**95%**
		NO	5%

Table 2: Student opinion about the effectiveness of the training.

According to the answers obtained, we notice that students showed positive opinions about the utility of the questionnaire to differentiate between fully, under-, and over-constrained sketches. It is also notable that a majority of participants recognized all symbols and geometric constraints used in the questionnaire.

3 METHODOLOGY ASSESSMENT

The effectiveness of the training activity was assessed during the midterm exam. The students were required to solve two questions related to constraints, using the same questions that were proposed by González-Lluch and Plumed [18]. The first question queried students about whether the profile shown in Figure 2a was fully-constrained, over-constrained, or under-constrained. The correct response is that this 2D profile is fully-constrained, and this answer is easily verified when using a 3D CAD application (ex. Solidworks®), as shown in Figure 2b.

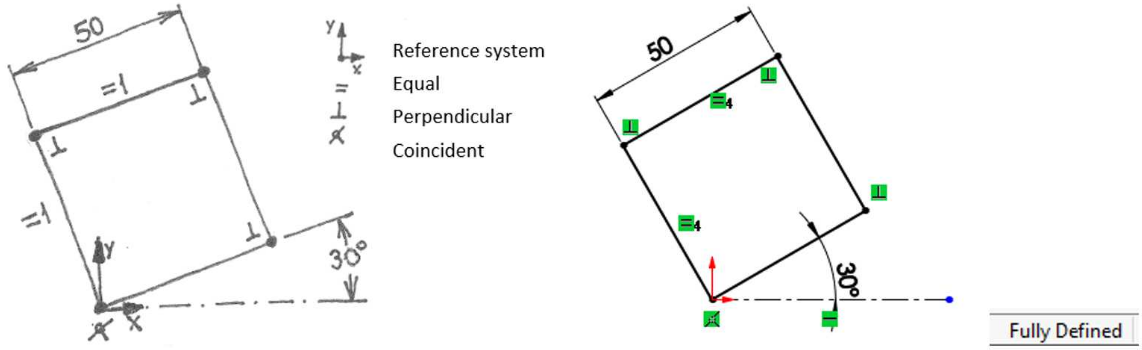


Figure 2: Left: The first question of midterm exam; Right: Verifying the same sketch using Solidworks®

The second question referred to the same sketch used previously. Students were required to identify and locate each type of constraint (listed below):

- Dimensional or geometric (F)
- Position and orientation (P)
- Others (B)

The students also were required to explain their answer. Considering the possibility of multiple correct answers, we consider that the 2D profile includes the following constraints (Figure 3):

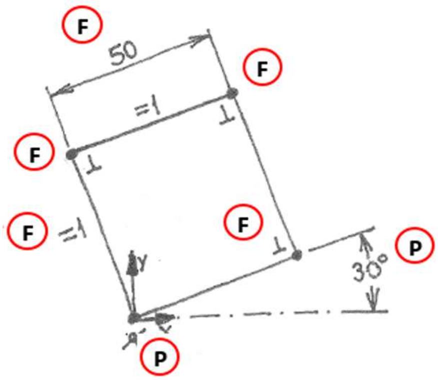


Figure 3: Correct answer for second questions

3.1 Assessment Results

Fifty-eight answers were collected and considered for the study. Forty students followed the reinforcement activity, while eighteen did not. All students answered both questions, and we classified the answers according to whether students completed the training activity. With reference to the first question, Table 3 summarizes

		Training	**No Training**
Fully-Constrained	Total	27	11
	Frequency	*67.5%*	*61.1%*
Under-Constrained	Total	3	2
	Frequency	*7.5%*	*11.1%*
Over-Constrained	Total	10	5
	Frequency	*25%*	*27.8%*

Table 3: Answers for the first question.

the total answers given by the students in each group, along with their corresponding frequencies. The correct response is that the sketch shown in Figure 2a depicts a fully-constrained profile.

Results reveal that more than half of the students correctly answered the first question. In fact, the percentage of correct answers was slightly higher in the trained group (67.5%), than in the group of students that did not perform the reinforcement activity (61.1%). Students who answered incorrectly considered the profile as over-constrained in both groups (trained group, 25%; without training, 27.8%).

To determine whether there is a difference in success rates between groups, answers were grouped into correct (fully-constrained) and incorrect (under- and over-constrained) categories. A contingency table was then constructed in order to compare the rate of correct answers given by each of the two groups. The observed count and expected frequency results for each group are displayed in Table 4.

		Training	**No Training**	**Total**
Correct	Count	27	11	38
	Expected Frequency	*26.2%*	*11.8%*	38
Incorrect	Count	13	7	20
	Expected Frequency	*13.8%*	*6.2%*	20
Total		40	18	58

Table 4: Comparison of the success rates for the first question.

We contrast the null hypothesis (H_0: "There is no difference in the success rate between groups with different training") using a Chi-Square Independence Test. No significant relationship exists between these variables [X^2(1, N=58) = 0.2248, p< .05], thus we can conclude that there are no significant differences in the success rates of the groups. The training reinforcement through the questionnaire has no impact on student ability to recognize fully-constrained profiles.

A similar procedure was performed on the results from the second question (identifying constraint types as either geometric/dimensional, position/orientation, or others). Table 5 summarizes student answers, with incorrect answers categorized and described.

Results reflect that although the percentage of correct answers of the trained group (37.5%) is slightly higher than the No-trained group (33.3%), students generally are deficient in their ability in classifying the types of constraints.

To determine whether there is a difference in success rates between groups for the second question, answers were grouped into correct and incorrect answers. Table 6 shows the observed count and expected frequency results for each group.

		Training	No Training
Correct answer	Total	15	6
	Frequency	*37.5%*	*33.3%*
Ill-defined equality constraints	Total	7	4
	Frequency	*17.5%*	*22.2%*
Ill-defined perpendicular constraint	Total	10	5
	Frequency	*25%*	*27.8%*
Ill-defined angular constraint	Total	10	8
	Frequency	*25%*	*44.4%*
Ill-defined linear dimensional constraint	Total	3	1
	Frequency	*7.5%*	*5.5%*
The origin of the reference system is not fixed	Total	7	4
	Frequency	*17.5%*	*22.2%*

Table 5: Answers for the second question.

		Training	No Training	Total
Correct	Count	15	6	21
	Expected Frequency	*14.5%*	*6.5%*	21
Incorrect	Count	25	12	37
	Expected Frequency	*25.5%*	*11.5%*	37
Total		40	18	58

Table 6: Comparison of the success rates for the first question.

Using a Chi-Square Independence Test, the results reveal that there is no significant difference between the answers [X^2(1, N=58) = .0933, p< .05]. Therefore, reinforcement training does not appear to improve student outcomes in identifying constraint types.

One-time training does not improve student performance in the use of constraints, so we conclude that students need continuous and autonomous learning. As a response, future work on this ambit should include both the creation of exercises necessary to create awareness about the importance of reusability in 3D MCAD models, and the design of an online checker. The latter could provide model quality information to the students and filter errors at the semantic level in 2D parametric profile drawings. Future training should primarily address the construction of 2D parametric profiles without redundant constraints.

4 CONCLUSIONS

Our driving idea is that the effective use of constraints during the creation of 2D profiles to build 3D models improves CAD model quality since constraints help to convey design intent and permit subsequent reusability of 3D CAD models. According to previous studies, many designers, engineers, and students oftentimes apply redundant constraints during the creation of parametric profiles when using 3D MCAD applications.

In this paper, we describe a tentative methodology used to reinforce the training of future engineers and designers through a collection of online exercises with self-correction. The goal is to improve the ability of new users of 3D MCAD applications to create quality parametric profiles, while avoiding the use of redundant constraints. Results reflect that the ratios of correct answers are slightly higher in students who followed the training, but the differences are not statistically significant. The lesson learned from this experiment can be summarized by saying that students seem to forget geometric constraints, considering only dimensional constraints.

We conclude that students need continuous and autonomous learning. Furthermore, results of the questionnaire reflected positive opinions about its utility. The next step in this process consists of building exercises designed to create awareness in trainees about the importance of reusability in 3D MCAD models. As a future development, we suggest another useful strategy, which is to design an online checker which would act as a filter of quality errors at the semantic level in the 2D parametric profile drawing. In this way, students would have the tools necessary to train themselves by performing the exercises and receiving automatic feedback. This strategy is expected to provide two advantages: reducing the teaching workload and developing independent learning capacity in the students.

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