CAD Learning in Mechanical Engineering at Universities

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Abstract. In this study, we attempt to compile all the CAD-related concepts, contents and working methods that students of mechanical engineering should learn at universities. To do so, we first study the background to CAD-related methodologies. In second place, we compile the results of surveys administered over the past three years to our students of CAD studying mechanical engineering at our university. In third place, different publications in the literature relating to the need for CAD in industry are studied to understand the sort of CAD training that is needed in industry. In fourth place, an exploratory analysis is performed of the CAD-related contents taught at the 50 universities that top the QS (Quacquarelli Symonds) ranking. In fifth place, a survey of possible CAD-related contents is administered to teachers, instructors, and experts in CAD from those 50 leading universities in the QS ranking. The basic pillars of modeling in 3D are: methodologies of modeling, solid modeling, assemblies, and the design of technical drawings. The use of 3D printers in CAD learning means that thinking, designing, and manufacturing any object is easy at university. Knowledge of top-down/bottom-up/in-context methodologies has to be widened both for industry and for students. Design intent must be introduced in CAD from the very beginning so that all the models are flexible and robust. The students expressed a preference to learn the concepts through a set of good practice exercises and to be evaluated by completing a final course assignment of their choice.

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1 INTRODUCTION

As Sadowski [33] has affirmed, Graphic Engineering has throughout history made use of the tools available to it at any one time, passing from manual drafting techniques to 2D computer-assisted design and, finally, to fully integrated CAD 3D design systems. CAD educators have discussed the need for some tools rather than other ones, centering on industrial needs, but very rarely have they discussed the fundamental concepts that should be included in the different CAD training courses.

Over the past 15 to 20 years, the development of CAD 3D tools has been very rapid and CAD learning skills and capabilities have had to adapt to that pace of change. Each CAD software package has been evolving, through the addition of new modules, new commands, and by enlarging the range of commands. These technical developments are nevertheless converging towards the use of fundamentally similar commands and even, in some cases, the same ones, in the different CAD software packages. An inordinately lengthy study program, unavailable at any university, would be necessary for students to learn CAD sufficiently well for them to be conversant with all of the different CAD modules. Strategic learning should therefore be applied rather than command-based learning [9], by mans of a set of properly selected exercises, where the student learns the fundamental concepts, contents, and methods of CAD. The field of study of CAD is so broad that there is no consensus over the definition of the concepts and contents that should be included in the CAD learning [2][14]. In 2005, Piegl [29] identified "CAD education" as one of the ten challenges of CAD, stating that CAD-based education was lagging behind basic sciences such as mathematics and that there was a need to define study plans for accreditation in this subject matter.

When reviewing and validating the concepts, contents, and fundamental methods of CAD subject matter that should be taught on mechanical engineering courses at universities, it is necessary to do so from different points of view:

- First, by taking into account the CAD training that students are at present taught and the training that they request.
- Second, by taking into account the content of the different courses that are taught at some of the most prestigious universities.
- And, third, by evaluating what CAD contents are adapted to the needs of industry.

Our objective in this article is therefore to identify the CAD-related concepts, contents and methods that the students of mechanical engineering should learn at universities, taking into account the three points of view mentioned above. To do so, students of mechanical engineering at the University of Burgos were administered questionnaires after having completed their CAD course. The course contents taught at the first 50 universities at the top of the QS ranking were determined through their webpages and a survey was administered to CAD teachers, instructors, and experts from those universities.

2 BACKGROUND

Our paper is oriented towards sound knowledge of the contents of CAD courses taught at university, but these can only be separated from CAD methodology with difficulty. Each methodology requires knowledge of certain shared concepts and contents and of other different concepts and contents. Bodein [6] found that there was no single modeling methodology in CAD, for parts with a degree of complexity, after comparing the way in which students and industrial designers modeled various parts. Hartman [16] had by 2009 identified various common steps in the procedure of solid modeling: 1) Identification of the plane of the sketch 2) sketch of the profile; 3) Add constraints/relations; 4) Add dimensions; 5) Apply feature form; 6) Repeat the earlier steps to obtain other features that will either add or remove material from the model. The part will be finished with finishing operations such as rounding, chamfering … Various authors investigated different modeling methodologies in CAD among which we can highlight:

- Modeling methodology of explicit functional references: the part is broken down into its functional components, each component contains certain explicit references that are used in the modeling features, finishing each element by means of Boolean operations. These explicit references permit the design intent to be transmitted. The key to this method lies in determining the functional pieces of the part and in identifying the link between these pieces through explicit references [6].
- Parametric methodology: Bodein [5] included a road map to incorporate the parametric design in the automobile industry, including different aspects of the parametric design, such as: sketch with parametric relations; sequential features with relations to parameters; integration of the know-how by means of parameters/rules /external parameters (such as for example design tables); and fully parameterized assemblies.
- Top-down methodology: based on defining a global skeleton or set of reference data, which is transferred to the skeletons in the sub-assemblies and from those sub-assemblies to the

parts [1]. The transfer of these fundamental data is done by means of planes or other geometric elements in the structure of the tree. The main pieces of advice for this methodology are: to organize the reference data at different levels; to ensure that the structural levels are as independent as possible; to create reference data within each feature; to reference the features to a system of coordinates; to use curves and reference surfaces to create complex forms, so that both pieces are related to each other…

- Resilient Modeling Strategy (RMS) [13] Methodology: this methodology manages the tree structure of the CAD part, so that the CAD models can be edited, obvious and reusable; editable models being understood as models that can be modified. Obvious models are understood to be those models that in no way depend on the intuition of the person wishing to modify them and reusable models are those models in which the geometry that exists in other contexts and applications can be used. The tree structure is organized into six sequential groups of features with a view to minimizing the effort that is required to understand the design intent. These groups are:

  Group 1- Ref. Contains all the necessary elements and reference data (sketches, coordinate systems, reference planes).

  Group 2- Construction. If necessary, it will contain auxiliary constructive features (surfaces and 3D curves).

  Group 3- Core. Contains the principal features of the model that define the form. These are features that add material such as: Extrude, Sweep, Thin Wall, Revolve, Loft, Shell.

  Group 4- Detail. These are features that remove material from the part, such as: holes, slots, and cuts.

  Group 5- Modify. If used, it will contain final features (Draft, Pattern, Mirror, Final Features).

  Group 6- Quarantine. The features in use must not be parent features (Chamfer, Blend, Rond).

  Camba [7] compared the reuse of the models in the RMS methodologies and explicit references, confirming the greater effectiveness of the RMS methodology, in terms of final model quality, alteration time and reutilization.

- Hybrid methodology: increasingly used due to the appearance of CAD modules that incorporate knowledge of different design processes; for example, the design of molds and cavities in plastic injection processes [27]. This modeling obtains solids from surfaces through various commands (thickening surfaces by conversion into a solid, defining a solid from a set of closed surfaces, and dividing a solid by means of a surface). It also permits surfaces to be extracted from a solid and then to be sewn.
- Direct Model Methodology: similar to conventional solid modeling, but with no history trees. The absence of history trees allows the selection of a point, an edge or a face on the CAD models and its easy modification by means of push-pull on these elements. Bodein [6] stated that the use of direct modeling in industry is currently limited to the initial phases of the projects (conceptual phases and initial prototypes) and that the information is then transmitted to CAD packages with history trees and feature methodologies. Direct modeling methodology, despite the advantages of its rapidity, freedom and ease of modification, will neither permit the integration of knowledge, parameterization, nor the definition of entity restrictions, relations and dependencies; in other words, no modifications are permitted that maintain the design intent.
- Context methodology: a combination of the top-down and bottom-up design methodologies. Initially, the general structure of the device is defined with the top-down methodology. Part of this structure is transferred to the first parts, subsequently designing these first parts with bottom-up methodology. Some elements of the first parts come to form part of the general structure of the device and part of these structures are copied in second parts; both methodologies can be successively repeated.

Regardless of the methodologies, present-day CAD is dependent on various vertical applications (software modules integrated in CAD packets related with manufacturing processes, obtaining styled surfaces...) which are known as CAx. Covering the learning of all these vertical applications at university is impossible, but it is possible to introduce some exercises as an example of these vertical applications. Along those lines, Dankwort [11] stated that "Universities have to teach the CAx-basics and design methodology to all students. It is in the responsibilities of the students to enlarge their knowledge in certain areas", and went on to divide the learning of CAx into three levels. The first basic level that includes CAS/CAD/CAM, a second level that includes PDM (Product Data Management), Data Exchange, FEM and others, and a third advanced level that includes PLM (Product Lifecycle Management). In this sense, some authors introduce class A surface modeling tools, beginning with freeform surfaces that are created in the CAS (Computer Aided Styling) model [15].

Neither can the CAD-related contents at university be separated from some concepts that are used in industry, which are: design intent, design flexibility and robustness, design rules, reutilization of design, conceptual design, skeleton, tree structure… Jackson [19] stated that a key concept is "the reuse of design" that can reduce 80% of the design time for a new product, if that product is based on a previous model in which the reutilization of the design has been taken into account in its modeling. The following CAD concepts can be incorporated:

- Through the use of rubrics that value the concepts in the different CAD practices [10][26].
- Through exercises based on good practice which include the key CAD concepts. For example, the inclusion of exercises on design intent that Otey [26] and Barbero [4] proposed.
- Through explicit rules. Otto [27] incorporated a set of rules that have to be taken into account when designing surfaces. For example, those related with the characteristics of patches, curve degrees, number of control points... It also includes defects in the models that must be avoided, for example: self-intersecting patch, peak and bump, degenerated patch, and open boundary. Barbero [4] incorporated a set of rules, that take into account design intent, with demonstrable improvements in the CAD designs of the students to whom those rules were available, especially in the creation of skeletons that included design intent, in the functional division of a part into its pieces, lending attention to the design process and the restrictions of the sketches.
- Through the inclusion of negative knowledge rules. After applying a set of rules in CAD modeling (so-called positive knowledge rules), CAD modeling can on occasions have different weaknesses. Mandorli [22] and Otto [27] proposed the joint application of both positive and negative knowledge to avoid those weaknesses. Negative knowledge consists of identifying the weaknesses of the CAD models, taking into account previous experience, and proposing preventive actions that avoid those weaknesses in the CAD models that are subsequently designed.

3 METHODOLOGY

In 2017, Shan [35] affirmed that reforms to CAD teaching were necessary, in relation to the contents and the methods at a general level and, in particular, at universities, based on the use of short videos, animations, practical demonstrations, and PowerPoint displays containing the key CAD content. Likewise, Webster [37] indicated that there was a need for investigation into the most effective CAD learning methods.

The literature on CAD relating to the use of CAD in industry was studied, in order to gain a full understanding of CAD training needs for industry [6][3].

A survey was prepared between our students, in order to inquire into their opinions and to determine which aspects of the CAD course unit they would maintain and which they would remove. Mandorli and Otto have completed the most recent studies on this question [23][28].

Beginning with the premise that it is difficult to establish comparisons between different course units, national educational systems, countries, cultures, etc. the aim of this study will be to review the existing bibliography on the contents that should be taught on CAD. The universities have been selected according to the QS ranking, in order to understand the CAD-related content that is at present taught at university. The QS ranking has been employed by Novoa [25] in matters other than CAD. This process, as will be mentioned further on, entails both searches through the teaching guidelines of leading universities and through certain articles or news items relating to the content that is taught.

Together with the opinions of the students and the searches through the webpages of the prestigious universities that were selected, a survey was also administered to teachers at those universities (see annex 1), in order to understand the CAD-related content that is taught at their universities.

4 SURVEY ADMINISTERED TO STUDENTS

Initially in the first year, two open questions were set in writing to the 73 students enrolled on the course after completion of the CAD course units at our university: 1) What course content would you maintain? And, 2) What course content would you change on the course unit? And how? The answers were studied and grouped in qualitative terms and a questionnaire was administered to the students, in which they were asked to assess their degree of agreement on a Likert scale with the aspects to maintain on the course and with the proposed changes.

At the end of the course, this questionnaire was completed in the second year by 68 students, representing a response rate of 93%. In the third year, the same questionnaire was answered by 74 of the 89 students enrolled on the course, representing a response rate of 83%.

A hypothesis test was proposed with the t-student test for a sample with a cut-off point of 3, the average value on the five-point Likert scale (values of 1-5). In tables 1 and 2, the values of the average of each response, the standard error of the average and its significance are all shown.

Sample Test	*Second year*		*Third year*	
Aspects to maintain	*Mean (Std. Error Mean)*	*Value=3 Sig.*	*Mean (Std. Error Mean)*	*Value=3 Sig.*
Practical course work	4.34 (0.088)	0.000	4.61 (0.060)	0.000
Learning model	3.62 (0.096)	0.000	4.00 (0.092)	0.000
Continuous evaluation	3.99 (0.119)	0.000	4.35 (0.097)	0.000
Final course assignment	3.85 (0.141)	0.000	4.53 (0.075)	0.000
Handing in practices that are given as home work	4.00 (0.115)	0.000	4.19 (0.103	0.000
Evaluation criteria	3.34 (0.106)	0.002	3.91 (0.114)	0.000

Table 1: Aspects to be maintained.

The proposals to be maintained are listed in table 1. All the items are over 3 in a significant way at a confidence level of 95%, in both years, and the numbers of students that scored the aspects to be maintained with higher and lower scores than 3 are shown in figure 1, removing the students that scored 3.

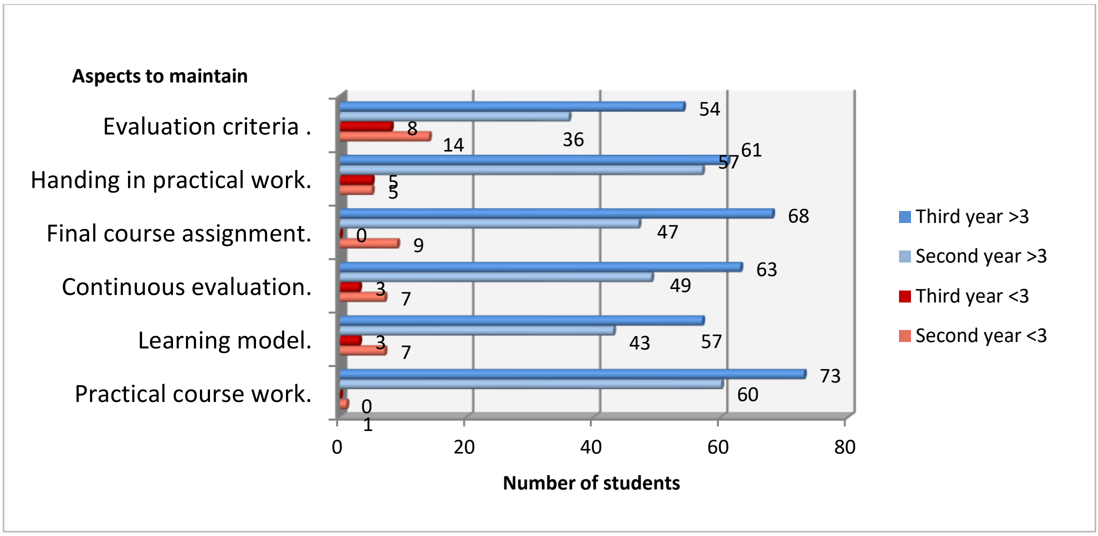

Figure 1: Higher and lower scores than 3 in aspects to be maintained.

Given that these 6 aspects of table 1 are significant and some of them are inter-related, it is worth explaining them, taking into account that two modifications have been introduced with regard to the preceding year: design intent in the 3D models has been introduced from the start of the course, as well as a different final course assignment for each student.

- The learning model is a strategic learning model, following the methodology employed by Chester [9]. Our CAD course contemplates: 3D surface and solid and hybrid modeling, parametric design of parts, assemblies, functional simulation, technical plans, reverse engineering, and vertical CAD applications.

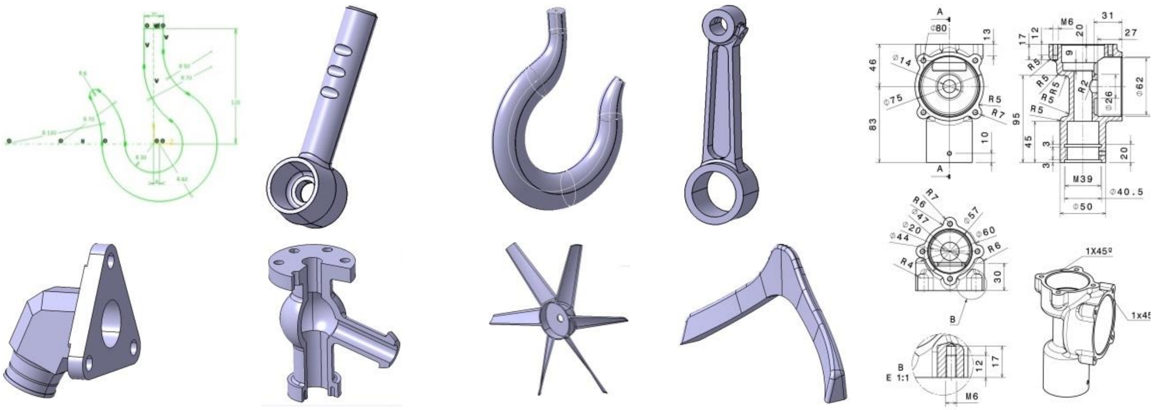

Figure 2: Examples of good CAD practice.

- Practical course work. A set of good practices were selected, as proposed by Company [10] and Otey [26], which included key CAD concepts such as design methodologies and design intent. In figure 2, some examples of good practice are included that are used in theoretical and practical classes.

- Handing in practice exercises that are set as homework. The students preferred practice exercises with more time for their completion than the time available in practical classes, because, in their opinion, if they make a mistake with the method, they can rectify it and they can learn which strategic 3D design paths are the most effective.
- The final course assignment. Some of the projects that our students completed are shown in figure 3. Our proposal is in agreement with the one that Ramani [31], at Purdue University, proposed: to make toys for CAD training. He stated that the best way of learning CAD is by "doing" and by "experimenting". Students therefore prefer a final course assignment rather than the usual exams.

Figure 3: Final course assignments.

- Continuous evaluation and the evaluation criteria are inter-related. In the evaluation criteria that are indicated to the students, we highlight the importance of giving proper names to the different pieces of each part, the use of skeletons, the need to remember that the 3D models will be modified, and that after the modifications they should maintain the design intent. We believe that the introduction of design intent from the start of the course in different practical exercises in the third year, rather than in the second year when it was introduced in the middle of the course, has had some influence on the higher scores given to those two aspects in table 1 and has perhaps influenced some other aspects to be maintained.

The aspects to be changed are listed in Table 2. In the first item, the students preferred the theory classes in a classroom with computers, because by explaining theory through good practice exercises in strategic learning, they could do exercises connected with that practical work, instead of only learning those concepts in a theoretical way. With regard to the second item, the students preferred to spend more time on the most complex parts (the use of skeletons in the parts, surfaces, in-context product design and kinematic) rather than the initial parts where sketch restrictions and solid design of parts are mainly practiced.

Item	*Second year*		*Third year*	
	Mean (Std. Error Mean)	*Test value = 3* *Sig.*	*Mean (Std. Error Mean)*	*Test value = 3* *Sig.*
1 Give the theory in the practical classes to follow the exercises on the computer	4.10 (0.113)	0.000	3.69 (0.126)	0.000
2 Spend less time on the initial part and more time on the more complex parts	4.01 (0.118)	0.000	3.96 (0.118)	0.000
2a In-context product design	4.03 (0.094)	0.000	4.00 (0.088)	0.000
2b Reverse engineering	2.54 (0.130)	0.001	2.58 (0.114)	0.000
2c Kinematic	4.03 (0.127)	0.000	4.38 (0.094)	0.000
2d Surfaces	4.25 (0.106)	0.000	4.07 (0.097)	0.000
2e Technical drawing	3.00 (0.124)	1.000	2.84 (0.109)	0.141
2f Parameterization	3.29 (0.111)	0.010	2.89 (0.101)	0.288
2g Exercises with skeletal structures	3.62 (0.129)	0.000	3.22 (0.111)	0.055
3 Be able to choose the final course assignment instead of all students completing the same one	3.76 (0.177)	0.000	4.45 (0.119)	0.000
4 Propose exercises where dimensions and/or forms are modified in order to maintain the design intent.	3.56 (0.117)	0.000	3.53 (0.100)	0.000
5 Explain the theory by commands and not by strategic learning.	3.25 (0.128)	0.055	3.08 (0.112)	0.471

Table 2: Aspects to change.

Perhaps the most surprising aspect is the little interest that was shown in reverse engineering, the reasons for which we are unable to explain with certainty. It was perhaps due to the intensive commitment of time that is required, or because the majority of students use no reverse engineering to complete the final course assignment, or because they use two CATIA modules instead of a proper reverse engineering software package that has a wider range of tools. With regard to the third item, the students preferred to be able to select the final course assignment, instead of all students completing the same work. It may be highlighted that all the students completed the same assignment in the second year: the office chair in figure 3, beginning with its model given in 3D and in *.stp format. The students clearly stated that this type of work prevented them from developing their creative activity and imagination. In the third year, therefore, each student selected a different assignment that the student had proposed (see examples from figure 3). The improvement in the scores in the third year was notable, passing from a score of 3.76 to 4.45 out of 5. One possible reason for the improvement of this score might be that the students could chose the work themselves and felt greater motivation, causing a change of attitude and an improvement in their learning results [8].

In the fourth item, the students were in agreement with the proposal of exercises where the dimensions and/or forms to maintain the design intent could be modified. The purpose of these modifications was above all to identify which design paths were acceptable and which were not acceptable to maintain the design intent. The students who constructed the 3D model introduced some of the modifications, but others were done by their classmates, thereby checking the way in which other students worked with their strong points and improvements.

After talking with the student representatives from this subject area (student delegates who listen to the doubts, complaints and suggestions from the other students), they informed us that more time must be given to both surface design and in-context design. The teachers of this subject area shared that same feeling, because they could observe the difficulties that students had when beginning the final course assignment. In addition, the results of table 2, for these two aspects, were statistically significant, in the third year. We may say that the majority of students from our university must give more time to the practice of both surface design and in-context design.

5 EXPLORATORY ANALYSIS OF THE CAD CONTENTS AT THE PRESTIGIOUS UNIVERSITIES

An exploration of the course contents was conducted at the 50 leading universities listed in the 2018 QS (Quacquarelli Symonds) [30] Global Ranking of Universities for mechanical engineering, aeronautics, and manufacturing, in order to understand the contents of the CAD course unit. The QS university rankings are considered among the three most influential and closely followed across the world.

Data collection was, fundamentally, done by consulting the teaching guidelines that the universities offer on CAD-3D course units on Mechanical Engineering Degrees or similar. In addition, in some cases, different articles were consulted in relation to the universities themselves. Only one concept was ticked in the table, if it appeared in an explicit and clear way in some of these sources, which in no way really implies that those concepts are not covered, even they may have been ticked off.

In table 3, the first 50 universities of the QS ranking are presented and the different fundamental CAD-related learning concepts are grouped into blocks with color coding. The concepts were chosen on the basis of the teaching experience of the authors, through the survey responses of the students and exploration at some pilot universities. Those concepts were grouped into content blocks:

- In the block on modeling methodologies, 64% of universities expressed in an explicit way that they teach design methodology, in many of them without clearly specifying what type of methodology they used. But where they do indicate the type of methodology, it appears that the most widely used one is the "Top-Down/Bottom-Up/In-context Methodology". The other aspect to highlight in this block is that 7 universities explicitly indicated that they teach design intent.
- Solid modeling block. Given that solids are the final result of 3D modeling, it may be affirmed that all universities teach "Solid modeling", and 92% of them do so explicitly. In this block, the column under the heading "Sketch" has been maintained. We believe that it is an essential aspect of 3D modeling, both for solid and for surface designs. We suppose that this concept is covered in all universities. However, it is not explicitly mentioned in some of the teaching guidelines, but only in 48%. The "Geometric restrictions" are also maintained in the same way as the sketches. Approximately 34% of the universities in the study explicitly mentioned the teaching of geometric restrictions in sketches. "Feature-based modeling", also a basic concept of solid modeling, was mentioned by 46% of universities. The study of 3D curves was only indicated by 18% of universities. Curves in space are useful both for surface modeling and for solid modeling, although to a lesser extent in the latter type of modeling.

Ranking 2018	Design intent	Top-Down/ Bottom-Up	Resilient modeling strategy	Direct model methodology	**Modeling methodologies**	Sketches	Geometric restrictions	Feature-based modeling	3D curves	**Solid modeling**	Part families	Design tables	Parametric assemblies	**Parametric modeling**	Class A surfaces	Free form surface modeling	**Surface modeling**	Geometric restrictions and degrees of freedom	Exploded/assembled	Interferences and collisions	Calculation of trajectories and kinematic analysis	**Assemblies**	Technical drawings	Tolerance dimensioning	3D annotations	Rendering	Simulation	**Technical drawing and product presentation**	Digitization. Reverse Engineering	Rapid prototyping, 3D printing	File management, PML, PDM, Concurrent engineering	Finite element analysis module	Machining modules	Mold modules	Sheet bending and stamping modules
1	x				x	x	x	x		x	x	x		x			x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	
2						x	x	x		x												x							x	x					
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4						x	x	x		x												x								x	x	x	x		
5	x	x			x	x	x	x		x	x	x		x			x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x		x
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22	x	x			x		x	x		x			x	x			x			x	x	x	x	x			x	x		x	x	x			
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	8	7	1	1	32	24	17	23	9	46	9	8	8	16	2	5	18	11	7	9	4	44	37	20	5	15	25	40	10	30	16	22	23	3	4

Table 3: CAD contents in the 50 leading universities.

- Parametric modeling block. 16 universities explicitly mentioned parametric design. In this block the teaching is almost in the same proportion as the part family concepts, design tables and parametric design of assemblies.
- Drawing to a close with the modeling of parts, we included the block on "Surface modeling": 16 universities mentioned that they include surface design. It is used to design parts with more complex surfaces than those done directly by solids. The possibility of hybrid modeling is worth highlighting. The surfaces can be done with basic operations of extrusion, revolution, sweeping, multi-sections, etc., or with advanced operations such as combination, filling, fillet, etc. The concepts of "Class A surfaces" and "Free form surface modeling" are covered by a minority of universities and mainly in master's degree courses.
- In the general block of "Assemblies", as all parts of a mechanism have to be assembled, we suppose that all universities refer to the design of assemblies in their teaching guidelines, although we only noted it in 88% of cases. It includes both the insertion of components and the restrictions rules among them. As in the case of parts, the concept of "Geometric restrictions and degrees of freedom" was maintained, but referring now to relations between two parts, in such a way that if one is modified, the other is also modified (for example, a hole and a bolt). It is a design characteristic that gives the final part flexibility and robustness. This concept was mentioned in 11 universities in an explicit way. The concepts of "Exploded/assembled" (14%) and "Interferences and collisions" (18%) although important for calculation and subsequent analysis of the mechanism are mentioned in a minority of cases. The "Calculation of trajectories and kinematic analysis" is taught in a minority of universities.
- In the last block of CAD-related concepts "Technical drawing and product presentation", 80% of universities stated that they taught those concepts. Given that plans are necessary for the manufacture of the parts, a large majority of universities included the concept of "Technical drawing plans" (74%). Views, orthogonal projections, cross-sections and sections are concepts that we consider inherent to the design of technical drawings. The concept of "Dimensioning with tolerances" was included by 40%. Only 10% of universities included "3D annotations" in an explicit way. With regard to final product presentation, we considered that the concepts of "Rendering" and "Simulation" were in this block of concepts. 30% of the universities in the study used the concept of rendering and 50% taught simulation.
- In the last seven columns, different vertical applications were ticked that are jointly taught with CAD on different course units. We can highlight the relation between CAD and rapid prototyping, as 60% of the universities explicitly stated that they used 3D printers jointly with CAD, in "Finite element analysis modules" (44%), and "Machining modules" (46%). CAD is also taught on various course units jointly with: "Digitization. Reverse engineering", "File management, PLM, PDM and concurrent engineering". However, at very few universities is CAD jointly taught with: "Molding modules", and "Sheet bending and stamping modules".

In the following, we will highlight some particularities found in our search:

At the University of California, Berkeley (UCB), they place special attention on designs that can be manufactured with the desired end-result and functionality, stressing the importance of design intent. They test these achievements through rapid prototyping and, having presented the project in small groups, the parts and the technical drawings are given to another group of students, which should be able to assemble it. In this way, the second group can "correct" it, suggesting improvements in the definition of the technical drawings where they were not sufficiently clear. In addition, the 3D models that they prepare have to be easy to modify, as the group work is open and groups can suggest modifications half-way through the process. By doing so, students are taught to design flexible and robust models open to possible modifications in the design.

At Harvard University [17], they conduct some projects [12] by incentivizing competitiveness among the students, giving them a series of materials, such as gearing, bolts, and wheels, and the students are expected to design all-terrain electric vehicles, complying with strict requirements. After designing them and having printed them in 3D, all the models have to compete in an obstacle course, which stimulates the ingenuity of the students. In addition, the teams that have problems in some of the tests have to redesign the model, at which point the importance of flexibility in the 3D designs is tested.

At Purdue University [24], proper use of parametric design is emphasized, complying with design intent. As with the earlier example, they evaluate the design process of the parts and their implications. Like the majority of universities, importance is given to team work and to clarity in the presentation of results. One of the topics that is taught is the diversity of CAD files and file exchangeability between different software packages.

In summary, the basic pillars for 3D modeling are as follows: Modeling methodologies (64%); Solid modeling (92%); Assemblies (88%); and Technical drawing plans (74%). With regard to the learning of CAD jointly with other applications, "Rapid prototyping. 3D printing" can be highlighted (60%), rather than other more customary applications such as mechanization and finite-element analysis. However, if it is a question of testing the proper functioning of a mechanism and that there are no interferences between parts, the most logical approach would be to make use of software-based simulations, which are covered to a lesser extent (25%) at the universities.

After having studied how CAD is learnt at leading universities, such as the Massachusetts Institute of Technology (MIT), the Universities of Harvard and Stanford, and taking into account the report on the evaluation of CAD in engineering training, 2012, by OCR (Oxford Cambridge and RSA), the authors of this study are of the opinion that learning CAD modeling must be linked to the process of manufacturing and that the appearance of 3D printers at present allows us to think, to design, and to manufacture any device easily at university. Education is done better through creative processes. Students of mechanical engineering learn by doing, experiencing a level of understanding that only occurs when engaged in creativity.

6 SURVEY ADMINISTERED TO TEACHERS

Finally, a survey was administered (see the Appendix) by email to teachers, instructors and experts in CAD at the 50 leading universities in the QS ranking. The general CAD concepts were taken from the previous exploratory analysis, although their number was reduced with a view to shortening the survey. The survey was answered by 35 teachers from 26 different universities. The response rate by university was 52%, with which, although it might appear low, we are satisfied, as a large number of expert teachers of CAD responded.

From the items ticked in question 2 of annex 1, we can say that the following concepts are taught in practically all the universities: Modeling methodologies, Basic solid modeling, Assemblies, Technical drawing and Rapid prototyping, 3D printing (See figure 4), all which coincides with what may be observed in table 3.

Advanced solid modeling (77%), simulation (69%), surface modeling (77%), 3D curves (65%), and parametric modeling (65%) may also be highlighted. Design intent is also found among the contents taught by 58% of universities.

Question 3 was answered by 20 teachers. Among the responses, content related to Computer Assisted Manufacturing (CAM), Finite Element Analysis (FEA), Building Information Modeling (BIM), and working in teams and with projects may be highlighted. If we look at table 3, precisely CAM and FEA are contents that are shared with CAD to a high percentage and that we had not included in the survey in annex 1, in order to simplify it.

Question 4 was answered by 33 teachers. In general, these contents were taught on degree and master's courses in engineering, above all in mechanical engineering. Course content was mainly taught on CAD courses, although also on CAD/CAM and CAD/CAE courses.

Question 5 was answered by 15 teachers. From the observations and commentary made available, we would like to highlight three, with which we are totally in agreement and that are corroborated by our own results. The first makes reference to the need for 3D printing to form an integral part of CAD courses. This second is linked to the students who on occasions only think of learning to operate CAD software, forgetting the fundamental objectives of CAD, which are to resolve problems of design and engineering. The third observation is that CAD is not easy to teach, which is, in our opinion, because there is no one single way of resolving the problems, there are many methodologies and it is not clear which to use at any one time.

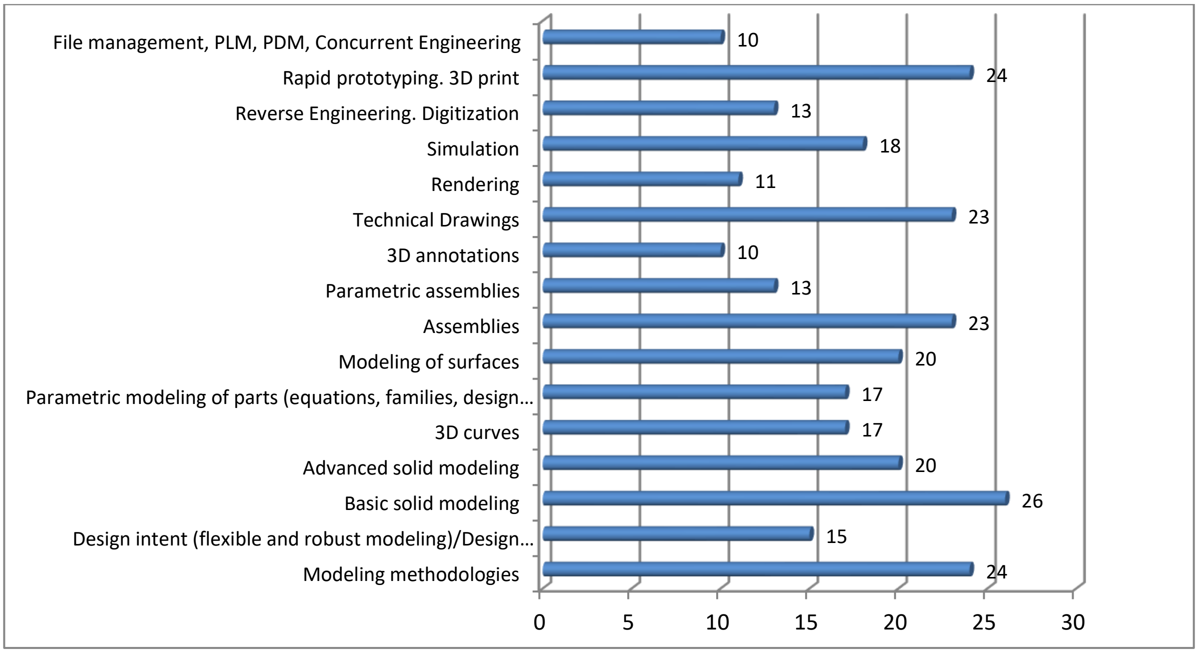

Figure 4: CAD concepts ticked by teachers.

In summary, there is a high agreement between the results of the exploratory analysis of section 6 and the replies from the experts under that section of the survey. The contents that are taught in the large majority of universities are: modeling methodologies, solid modeling, assembly, technical drawing and product representation, and rapid prototyping (3D printing). The contents that were taught at some although not at other universities were: surface modeling, parametric modeling and simulation. The contents taught least at the universities were: 3D annotations, rendering, and file management (PLM, PDM, concurrent engineering).

7 CAD-RELATED NEEDS IN INDUSTRY

A survey completed by Ye [38] in different industrial sectors indicated that 74% of those surveyed stated that CAD learning at universities was inadequate. One of the principal training objectives in engineering is to prepare engineering students, so that they may have a successful professional career in the real world. CAD is a key communication tool among engineers and Ye [38] highlighted that greater knowledge of CAD is needed in: top–down/bottom–up design methodology, parametric modeling technology, feature-based modeling technology, and part family design. CAD knowledge is also needed, but to a lesser extent, in: concurrent engineering, collaborative design (e. g. design revision), PDM, PLM, and Creative design (in which design knowledge and reutilization of design is incorporated). For Ault [3], firms have no clear norms of the design strategies that they should follow. There are two design tendencies: one is that modeling should be easy without thinking of subsequent modifications; and, another that modeling should be done considering easy modification of existing models. The right approach will probably be to apply both forms of thinking and, depending on circumstantial factors, lean towards one or the other.

The next CAD paradigm is not at present known, but Horváth [18] stated that there would be no major changes to CAD with respect to the next generation of computing paradigms. This affirmation is based on the reticence recently expressed by the automotive industry and the developers of industrial CAD systems to consider radical changes for the enlargement of the CAD environment with new technologies. Both industries have similar strategies and prefer incremental developments and improvements in CAD, more than radical innovations and abrupt changes; maintaining the kernel of geometric modeling, the structure of the modeling and the representation. Up until 2005, various improvements were introduced in CAD, such as for example: feature-based modeling, freeform surface modeling, assembly modeling, realistic visualization of CAD models and PLM. Since 2006, up until the present, the evolution of CAD has reached a ceiling [18]. Current improvements to CAD have been introduced through the integration of new vertical CAD applications, which have served to integrate Knowledge-Based Engineering (KBE) in new CAD applications, such as for example Reverse Engineering (RE) applications, rapid prototyping and 3D impression, and KBE tools for solving kinematic mechanisms [32]. The integration of KBE in CAD improves collaboration between design teams, improves re-design methods, and the automatization of the principal components of the product life cycle.

The market at present demands attractive products, as well as functional and easily manufactured products [20], for which reason the different stages of the product design process need to be coordinated in an interdisciplinary way. Tools such as CAx and CAD, CAM, CAE, and PLM are inseparable from the product development process in industry [21][19]. In addition, these tools together with the modern manufacturing technologies of Rapid Prototyping (RP) make necessary the modular and collaborative use of all of them for the development of products in the industry. The new CAD courses, for Wang [36], should be linked to CAM courses, in which the different aspects of the product life-cycle in industry should be taken into account. Digital manufacturing is proposed as a key aspect in the new courses, understood as a set of integrated processes: design, CAD modeling, analysis, CAM simulation, and product manufacturing (for example, in a 3D printer). The other aspect that Lukaszewicz [21] proposed is to define a set of design rules for parts and assemblies in CAD so that the designs are modifiable. It reveals the need for training our students in those rules. Otto [27], Barbero [4], Mandorli [22], and Jackson [19] have all pointed out some of those rules. The Strategic Automotive product data Standards Industry Group (SASIG) has developed a guide to improve Product Data Quality (PDQ), in which both geometric and non-geometric problems are identified, as well as relevant recommendations [34]. For example, the problem of a gap existing between two adjacent faces of a surface or when they are overlapping (G0 discontinuity) is mentioned in the guide, which recommends regenerating both faces using a curve that is a common boundary.

Ye [38] made it clear that the most important aspect of CAD is to be able to start and to finish a small assembly (even of three parts) with the in-context design methodology. However, the surveys of the firms also revealed that CAD is only a tool for engineers and it will not do their job for them, nor will it make them better engineers, but it is there to help them with their tasks. We would be in agreement with that reflection, if the CAD packages only had design modules of parts by solids and surfaces and assembly modules. However, current CAD packages have integrated modules in CAD, which serve to resolve engineering problems, such as, for example, kinematic module analysis, calculation of trajectories, assemblies, ergonomics, finite-element analysis, machining, mold designs, bending and stamping of sheet metal... The majority of these modules are part of some type of engineering process, such as mechanical engineering, and incorporate knowledge that is specific to their branch of engineering.

8 CONCLUSIONS

It has been confirmed that there are various forms of designing the same pieces in 3D, for which reason it is necessary to introduce into the learning process a set of both positive and negative rules; that the use of a set of good practices within strategic learning is a good method of learning how to model in 3D; and that when students start to design devices they usually employ context methodology, in other words a combination of top-down and bottom-up methodologies.

In various articles, we have been able to confirm the importance of teaching the concept of design intent at university, so that the 3D models are flexible and robust, as a lot of time may subsequently be saved in the modification and reutilization of these 3D models.

In another set of articles, we have detected some of the needs of CAD in the industry, such as for example better knowledge: in top-down and bottom-up design methodologies, in parametric modeling, in concurrent and collaborative engineering, and in systems of information exchange between CAD modeling in different software packages. It is clear that starting and finishing a model is of most importance in CAD, even though it may only consist of three parts.

The students also preferred to learn the concepts through a set of exercises based on good practice, within strategic learning (not by commands); they preferred a final course assignment that they could choose, rather than theoretical exams, which they find more motivating. Having introduced the concept of design intent from the very beginning of the course and in the evaluation criteria, through the modification of a parameter of a part, has had great acceptance among our students, which lends itself easily to the inclusion of concepts of flexibility and robustness in the design. The students at our university prefer to spend more time on surfaces, kinematic simulation, and in-context methodology, at the cost of restrictions in sketches and basic solid modeling.

Through the exploration completed in the 50 leading universities, the basic pillars of 3D modeling are: modeling methodologies, solid modeling, assemblies, and the drafting of technical drawings. Among the vertical applications, the rise of 3D printing may be highlighted. The use of 3D printers in CAD learning means that thinking, designing, and manufacturing any device in Universities is easy. Education is done better through creative processes. Students of mechanical engineering learn by doing, experiencing a level of understanding that only occurs through creativity.

The results of the exploratory analysis of section 5 and the responses to section 6 of the survey from the experts are in concordance with the contents that are taught in the at the leading universities of the ranking, which reaffirms the validity of our study of CAD-related contents.

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APPENDIX

CAD contents survey

Knowing the CAD contents in the high-ranking universities

1. **1. University name**

____

2. **2. Mark the CAD contents that are taught at your university**

Tick all that apply.

- [ ] Modeling methodologies
- [ ] Design intent (flexible and robust modeling)/Design reusability
- [ ] Basic solid modeling
- [ ] Advanced solid modeling
- [ ] 3D curves
- [ ] Parametric modeling of parts (equations, families, design tables, etc.)
- [ ] Modeling of surfaces
- [ ] Assemblies
- [ ] Parametric assemblies
- [ ] 3D annotations
- [ ] Technical Drawings
- [ ] Rendering
- [ ] Simulation
- [ ] Reverse Engineering. Digitization
- [ ] Rapid prototyping. 3D print
- [ ] File management, PLM, PDM, Concurrent Engineering

3. **3. Indicate other CAD contents that are taught at your university**

____
____
____
____
____

4. **4. Indicate those degrees and courses in which these contents are taught at your university**

____
____
____
____
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5. **5. Observations and comments**

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