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Can Open-Source 3D Mechanical CAD Systems Effectively Support University Courses?*

LUCA DI ANGELO[1], FRANCESCO LEALI[2] and PAOLO DI STEFANO[3]
[1] Department of Industrial and Information Engineering, and of Economics, University of L'Aquila, via G. Gronchi 18, 67100, L'Aquila, Italy. E-mail: luca.diangelo@univaq.it
[2] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, via Vignolese 905/B, Modena, Italy.
E-mail: francesco.leali@unimore.it
[3] Department of Industrial and Information Engineering, and of Economics, University of L'Aquila, via G. Gronchi 18, 67100, L'Aquila, Italy. E-mail: paolo.distefano@univaq.it

Most universities have introduced 3D CAD education and training in their engineering courses in recent years so as to respond to the actual needs of the industrial world for high-skilled design engineers. It is well demonstrated that the effectiveness of such courses depends on teaching an effective design approach rather than training for the use of specific commercial CAD tools. Since open-source CAD software has emerged in many fields as a promising alternative to commercial off-the-shelf systems, the present paper investigates the possibility for universities to adopt open-source instruments to effectively support their educational goals. Open-source 3D CAD systems are quantitatively evaluated by an original Compliance Index which considers the design tools typically used to model and draw industrial products and their weights in accomplishing the design tasks. The results obtained for the evaluation of a set of open-source CAD systems are presented and critically discussed.

Keywords: 3D CAD; Open source 3D CAD; Software evaluation; CAD teaching.

1. Introduction

The use of 3D CAD systems is an established practice in industry due to its proven effectiveness in improving design quality, cutting design costs and shortening the development time of new products and processes. Although CAD systems have completely fulfilled the vision projected for them during the late 1950s in the academy and industry, many challenging research issues are still open, since CAD systems also represent well-known key enablers for improving physical, human and social capital in the engineering field [1, 2].

The wide and deep penetration into industry of 3D CAD systems, in particular, has evolved skilled draftsmen into designers with extended capabilities in 3D visualization and creativity, in numerical engineering characterization and virtual experimentation (e.g. thermal, mechanical, vibrational, kinematic, dynamic, etc.), and in communication [1].

Such evolution has had a so direct impact on the competitiveness of companies, that training of engineers and education of engineering students have become a strategic topic in the last years [3–5].

Companies commonly organize tailored courses and training sessions in collaboration with the leading global vendors in order to achieve a deeper knowledge on specific 3D CAD-based software for specific fields of application, according to the professional profile and level of expertise of their users [4]. Such approach, however, is not completely satisfactory, since produces very well-trained CAD users but, often, does not take care of neither the design thinking [6–8] nor the linguistic basics [9] needed to fully exploit CAD performance.

Universities have taken up the challenge posed by the new technologies and have introduced stand-alone 3D CAD courses focused on specific topics, such as geometric modelling or product documentation, or oriented to more extensive applications such as computer graphics and engineering design [8].

Focusing on university education and training in engineering design, also according to the guidelines established by the American Accreditation Board for Engineering and Technology (http://www.abet.org), the goal is to propose educational programs, which aim at developing an ability to [10, 11]:

- apply knowledge of mathematics, science, and engineering;
- design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
- function on multi-disciplinary teams;
- identify, formulate, and solve engineering problems;
- communicate effectively;
- use the techniques, skills, and modern engineering tools necessary for engineering practice.

Then, the methodological focus is mainly on the teaching of the design philosophy (i.e. top-down or bottom-up approach), parametric modelling, fea-

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ture-based modelling, concurrent engineering, network-centric collaborative design and creative design [8, 12, 13]. The expected result is raising students' awareness of the importance of "thinking before drawing", while allowing them to work within contextualized environments prepared for them to learn about the complete development process of transforming ideas into saleable products [14, 15]. Moreover, many authors underline the importance of exploiting teaching through the adoption of an extended approach, based on project management [16–18], integration of different design tools [19–21], preparation of tailored IT-based didactic material [15, 20, 22], and assessment or self-assessment methods and tools [23–25].

According to this view, the specific 3D CAD system used for university education may be considered just a tool for implementing such a complex methodological approach [10, 14, 21, 26, 27]. The same conclusions are reached at the extended works of Hamade et al., which deal with the learning process of mechanical CAD students [23] and the subsequent analysis of the univariate and multivariate learning curve models for CAD [28]. In particular, the authors underline the influence of technical attributes [29] and willingness-to-learn [30] on the performance and competences of CAD users. Both of them are evidently more linked to the teaching method employed than to the instruments selected.

Many universities adopt 3D CAD commercial off-the-shelf (COTS) software primarily to keep a close contact with the industrial environment, the place where CAD skill and expertise are actually requested. In Spain, for instance, all the major 3D CAD COTS are used at all the industrial engineer schools [31]. In Italian universities there are over 70 bachelor's courses and more than 60 master's degree courses in the industrial and mechanical engineering areas. In every bachelor's and master's degree course, there is at least one computer-design class, where students can learn CAD-based design principles. Where the data is available, the most used 3D CAD software are Autodesk AutoCAD [32] for 2D drawing and SolidWorks [33], SolidEdge [34], Inventor [35], CATIA [36] and PTC Creo Parametric [37] for 3D modelling.

All the CAD COTS have a limited useful life anyway, since they are bound to become obsolete in time due to the constant update of operating systems and the unstoppable growth of hardware and software and the improvement of their performance in a very demanding and competitive race. For that reason, CAD COTS vendors release new versions at short intervals in order to offer new features and guarantee a state-of-the-art performance. As a consequence though, more often than not, universities are compelled to hold back updates because of the costs which hardware and software entail.

Leaving aside the question of the economic and ethical implications of adopting open-source software instead of closed software, the issue addressed in the present paper is connected to the following question: How is it possible to verify if any open-source 3D CAD system can effectively support university courses, when the teaching focus needs to be on the method rather than on the instrument itself?

In order to evaluate the performance of a 3D CAD system with respect to a given reference for the typical feature-based modelling of parts and assemblies used for educational purposes, a *Compliance Index* is introduced and applied to open-source 3D CAD systems.

The paper is structured as follows. In the next section a brief introduction to the problem of CAD selection is given. Section 3 presents the evaluation method and describes its steps. Section 4, in turn, presents the experimental results obtained for the evaluation of the degree of compliance of open-source 3D CAD systems with typical design tasks. Finally, sections 5 and 6 make some concluding remarks and sum up conclusions.

2. CAD selection in engineering education

In the last twenty years, a voluminous literature has published about the selection of suitable CAD COTS for academic programs, based on criteria which are functions of different factors.

Okudan [38], for instance, proposed the use of a multi-criteria decision-making approach to optimally select a solid modelling software by taking into account: modelling functions; environment criteria; user performance criteria; cost; innovation. In particular, the solid modelling functions to be compared were selected on the base of the objective of the Introductory Engineering Design teaching at Pennsylvania State University.

Kannan and Vinay [39] also proposed multi-criteria decision-making for the selection of CAD COTS evaluating the following attributes: functionality, capability, efficiency, communications, operating system, support, price. The same authors proposed an interesting literature survey about COTS selection through the adoption of analytic methods.

In García et al. [40] the following list of criteria for the selection of an educational solution was suggested:

- economic costs, referring to both the purchase price and the derived costs (e.g. extra features,

hardware, operating systems, graphical software, etc.);
- availability of suitable IT equipment for students;
- availability for private use, considered as availability of student licences and self-training material;
- easiness to learn: intuitive interface design, availability of help messages for each task, clarification of specific doubts, simple help manual, etc.;
- widespread use in industry.

Then the authors established a comparison between their specifically written software and a commercial CAD system by taking into consideration the opinions of a group of students, which they gathered through questionnaires.

Kallis and Fritz [27] proposed a list, which includes appropriateness for the task, industry requirements, acceptance/use in education and cost. A comparison between CAD tools for electrical engineering was also proposed by the use assigned to the different tools and the information gathered from a short questionnaire submitted to students.

Awanist and Haron [41], in order to assist companies and educators in making solid modeller selection decision, proposed a comparison of four CAD COTS in terms of the following seven performances parameters: extrusion, setup time, ease of use, speed, flexibility, feature based design, and CSG tree.

Díaz et al. [42] described a comparative study of CAD COTS starting from the assessment of the following preliminary criteria:

- design capabilities of the software package and the quality of results;
- calculation capabilities of the software package and the quality of results;
- possibility of exchanging information with other applications (and customers);
- use in industry or the "real world";
- use in research and academic work;
- licence costs and the number of licences available;
- maintenance costs;
- special offers for universities, and final application: specific or commercial software;
- learning difficulty.

Three CAD COTS were then compared in their performance in solid design, surface design, assembly and movement simulation, static FEM, dynamic FEM and thermal FEM simulation. The final assessment was carried out by students and teachers through a survey consisting of 36 questions which aim at evaluating easiness to learn, easiness to handle, versatility-possibilities, quality of results, quality/difficulty ratio and user-program relationship (interfaces).

Kostic et al. [43] proposed a comparative study of CAD COTS based on the use of different CAD also on conjunction with Web3D technologies for teaching students at an engineering course.

The selection approach based on lists of multiple attributes of common sense, experience and intuition is obviously subjective and limited to specific field of applications: its weakness has been addressed and discussed by long time [44, 45].

The present paper aims at overcoming the non-trivial task of selecting CAD, proposing an analytical index to measure the degree of compliance of open-source 3D CAD systems with respect to a given reference and to engineering education. Since the methodological approach is considered by the authors more important than the CAD tool adopted, attributes are simply defined as the existence of design tools for modelling. Tools and related weights are experimentally determined considering the typical educational tasks defined as the creation of parts, assemblies and drawings of industrial products by mechanical engineering students. Some of the most common CAD COTS are used to evaluate the robustness of the index.

3. The proposed method

The index to measure the degree of compliance of 3D CAD systems when performing a typical educational task has been called *Compliance Index* (*CI*), and is based on the assumption that, in a design-oriented approach, CAD students need to complete the assigned tasks by using the various tools available within the CAD environment. Hence, a CAD system is considered compliant with design education and training if it offers all the tools requested for modelling and drawing industrial products. Since some tools are more frequently used than others when designing different product families, the importance of tools is described by associated weights.

Considering that a product family typically depends on the field of application concerned, the compliance performance is evaluated with respect to the following topics: 3D solid modelling, surface modelling, parametric design and constraint management, feature-based design, and design-oriented approach based on the management of the history tree. The related CAD workbenches are then considered:

- *Sketching*, the workbench to create 2D geometries which are the base features of any solid model;
- *Solid Modelling*, the workbench to model solid parts;

- *Curves and Surfaces Modelling,* the workbench to model curves and surfaces;
- *Assembling*, the workbench to assemble two or more components at their respective work positions;
- *Drafting*, the workbench to create 2D views and sections of a 3D models.

The method workflow consists of three steps:

1. Analytical definition of the *Compliance Index*: for every CAD workbench, the *CI* considers the presence of tools and their weights for the design modelling purposes;
2. Experimental definition of tools and related weights for different product families;
   2.a. Selection of test population;
   2.b. Selection of product families (benchmarks);
   2.c. Identification of tools;
   2.d. Identification of the weights of the tools;
3. Robustness analysis of the *Compliance Index* with respect to CAD COTS software;

3.1 Analytical definition of the compliance index

The formulation of the *CI* is subject to three main requirements:

- the *CI* has to be CAD independent, i.e. the index has to consider and evaluate the design capabilities of CAD systems without referring to specific functions or features;
- the *CI* has to quantitatively evaluate the CAD system by assigning a numerical score, so the index represents an objective comparison;
- the *CI* has to systematically test the CAD systems, defining a repeatable and robust procedure.

Based on the previously mentioned considerations, this paper proposes the following analytical expression of the *Compliance Index*:

$$\begin{aligned} CI = & GW_{SK} \cdot CI_{SK} + GW_{SM} \cdot CI_{SM} \\ & + GW_{CS} \cdot CI_{CS} + GW_{AS} \cdot CI_{AS} \\ & + GW_{DR} \cdot CI_{DR} = \\ & GW_{SK} \cdot \sum_{i=1}^{n_{SK}} (W_{SK,i} \cdot \delta_i) + \\ & GW_{SM} \cdot \sum_{j=1}^{n_{SM}} (W_{SM,j} \cdot \delta_j) + \\ & GW_{CS} \cdot \sum_{l=1}^{n_{CS}} (W_{CS,l} \cdot \delta_l) + \\ & GW_{AS} \cdot \sum_{k=1}^{n_{AS}} (W_{AS,k} \cdot \delta_k) + \\ & GW_{DR} \cdot \sum_{h=1}^{n_{DR}} (W_{DR,h} \cdot \delta_h) \end{aligned} \quad (1)$$

where:

- subscripts *SK*, *SM*, *CS*, *AS* and *DR* refer to the workbenches *Sketching*, *Solid Modelling, Curves and Surfaces Modelling*, *Assembling* and *Drafting*, respectively.
- GW_{SK}, GW_{SM}, GW_{CS}, GW_{AS}, GW_{DR} are the global weights associated with each workbench;
- n_{SK}, n_{SM}, n_{CS}, n_{AS}, n_{DR} are the numbers of tools considered in each workbench;
- $w_{SK,i}$ is the weights associated with the *i-th* tool for *Sketching*;
- $w_{SM,j}$ is the weights associated with the *j-th* tool for *Solid Modelling*;
- $w_{cs,l}$ is the weights associated with the *l-th* tool for *Curves and Surfaces Modelling*;
- $w_{AS,k}$ is the weights associated with the *k-th* tool for *Assembling*;
- $w_{DR,h}$ is the weights associated with the *h-th* tool for *Drafting*;
- δ_i, δ_j, δ_l, δ_k, δ_h are presence/absence coefficients, whose values are equal to 1 if the corresponding tool is present and to 0.5 if the tool can be obtained with a set of tools; otherwise, is 0.

GW_{SK}, GW_{SM}, GW_{CS}, GW_{AS}, GW_{DR} are introduced because in some applications it can be useful to weigh differently the individual contribution of each of the five workbenches.

$w_{SK,i}$, $w_{SM,j}$, $w_{CS,l}$, $w_{AS,h}$, $w_{DR,k}$ are the weights considered in order to modulate the lack of a tool on the basis of its importance in the whole process of modelling for a data product family.

3.2 Experimental definition of tools and related weights for different product families

As it has been previously mentioned, the *Compliance Index* is based on the frequency of use of the tools which are typically involved in the modelling of industrial products. Consequently, the definition of the values for the weights and the coefficients of the *CI* must be firstly based on a correct selection of the tools to investigate. Since tools are not unequivocally defined in the different commercial systems nor in the teaching practice, they must be correctly identified when formulating the *CI*. For example, features which are deemed unnecessary, repetitive or are not optimized must be excluded from the analysis to avoid their impact on the final result.

The identification of tools and their corresponding weights requires the analysis of a significant data base of 3D industrial products, which have been modelled by skilled CAD users; the occurrence of a specific tool depends first on the competence of the CAD end-users and their aims in CAD modelling. Therefore, the first two steps of the experimental definition of tools and their related weights for different product families are the selection of both a population of CAD users and benchmarks.

Selection of test population
In the present research, the selected population consists of 144 among best students of the course in Computer-Aided Design at the University of L'Aquila (Italy) in the last five years. This course is taught annually to students of the first year of the degree in Mechanical Engineering. The course is divided into two main parts: the first part focuses on the learning of the principal workbenches of CATIA V5 [36] (7 weeks), while, in the second one, students are assigned the modelling and assembly of an industrial product. During the first part of the course, teachers give an introduction to each module commenting on its importance and highlighting basic concepts. Then, students practise the use of workbenches by following specific tutorials under the supervision of teachers. These tutorials guide the students step-by-step in the modelling of 3D objects, by making them use the most important tools of every workbench. After being assigned a personal project, each student models the industrial product in all its components. During class hours, teachers check the quality of the geometric models suggesting improvements where necessary.

A satisfactory degree of learning required to get into the selected population is therefore considered to have been reached when each component, which correctly matches shape and dimensions, is modelled as efficiently as possible with the sequence of tools. In absence of benchmarks approved by the international scientific community, this evaluation is performed by teachers on the base of their own experience about initial competencies required CAD users in real industry.

Selection of product families (benchmarks)
Because of the need to analyse a significant number of assemblies of industrial products which have been modelled in all its components and with the availability of operation trees, this paper examines the works of the selected population. In particular, 144 assemblies of 6977 different components have been examined. In Fig. 1 these assemblies are grouped under different categories and listed by their identification name and their corresponding quantity.

DIY TOOLS

Identification name	***quantity***
brush cutter	1
chainsaw	2
electric demoman	1
planer	1
sander	2
jigsaw	4
angular grinder	12
drill / screwdriver	4

TWO-STROKE ENGINES

Identification name	***quantity***
thermal unit	19
go-kart gearbox engine	1
carburator	2
go-kart intake silencer	1

INDUSTRIAL TOOLS

Identification name	***quantity***
industrial compressor	6
hydraulic power unit	1
gearbox	1
planetary gearbox	1
three-phase alternator	1
hydraulic pump	9

HOBBIES

Identification name	***quantity***
metronome	1
remote-controlled toy auto	5
fishing reel	5
trumpet	1
bicycle frame	1
double pedal battery	1
exercise bike	1
gearbox bike	2
typewrite	1
camera	3
air gun pistol	1
mechanical calculator	1

AUTOMOTIVE

Identification name	***quantity***
disc brake	2
automotive differential	1
clutch	3
optical automotive group	1
4-stroke engine	3
vehicle starter motor	4
turbine	4
cooling fan	1
pump	3

APPLIANCES

Identification name	***quantity***
hairdryer	3
fan	1
barbecue	1
mixer	2
coffee maker	3
electric shaver	2
robot cuisine	1
squeezer	2
tomato squeezer	1
mincer	1
cheese chopper	1
grinder	1
printer	1
air aspirator	1
electric mixer	1

MACHINES FOR AGRICULTURE

Identification name	***quantity***
agricultural milling machine	1
irrigator	1
sowing machine	1
grape crusher	2
wine press	1
agricultural bale press	1

Fig. 1. Identification name and *quantity of the analysed industrial products.*

Fig. 2. Rendering of some of the analysed assemblies.

Figure 2 shows the non-scaled renderings of some of the analysed industrial products.

Identification of tools

The third step involves sampling data about the occurrence of tools in the selected CAD models. The sample can be analysed manually or, preferably, automatically by using macros that record and collect the presence/absence of the tools.

A first experiment is carried out in order to record the representative list of the tools used by the students to model the selected assemblies, avoiding repetition. In order to analyse such a high volume of data, specific macros in a Visual-Basic programming language are implemented. These macros analyse and record the tools reported in the operation tree for the different workbenches here considered. The obtained list is analysed and modified. In particular, specific tools of CATIA, which are obtainable with a combination of classic tools (for example, multi-pad and multi-pocket), are removed from the list, while other tools which do not appear on the operation tree but which are nonetheless essential for the modelling are added (e.g. trim, corner and chamfer in the Sketching workbench).

Figure 3 shows the resulting lists of the tools obtained by analysing the 144 product assemblies. The tools for every workbench are grouped into the typical categories of CAD systems. As far as the *Part Designing* workbench is concerned, the tools to import and export models in *IGES* and *STEP* format are considered because they are important from an educational standpoint; file import permits us to add components derived from the industrial database (bearings, screws, etc.) to the assembly, while the export permits us to utilize the models for subsequent CAE analyses. As regards the *Drafting* workbench, only those tools for generating views and sections from the 3D model and for exporting the file in dwg format are considered. This is due to the fact that nowadays there are open-source 2D CAD systems which import dwg files and have all the necessary tools for the preparation of construction drawings.

Identification of the weights of the tools

The last step is the data analysis and definition of the weights of the tools. The collected data about the frequency of specific tools must be opportunely processed in order to be referable to the categories of generic tools which have been previously defined.

As regards the weights ($w_{SK,i}$, $w_{SM,j}$ $w_{CS,l}$, $w_{AS,k}$, $w_{DR,h}$) in equation (1), they are calculated as the percentage of the use of that tool in its category. In other words, the importance of the tools is measured by the frequency of its use, independently from the benchmark or the category of membership. By way of example, table 1 shows the values of the weights obtained for the *sketch-based features* category of the *Solid Modelling* workbench after analysing all 144 assemblies. All the weights are reported in the Appendix.

3.3 Robustness analysis of the compliance index

As it has been previously mentioned, GW_{SK}, GW_{SM}, GW_{CS}, GW_{AS}, GW_{DR} are introduced to weigh the contribution of the five workbenches. In the following experiment, in order to have 5 summands equal to unity in equation (1), we have set:

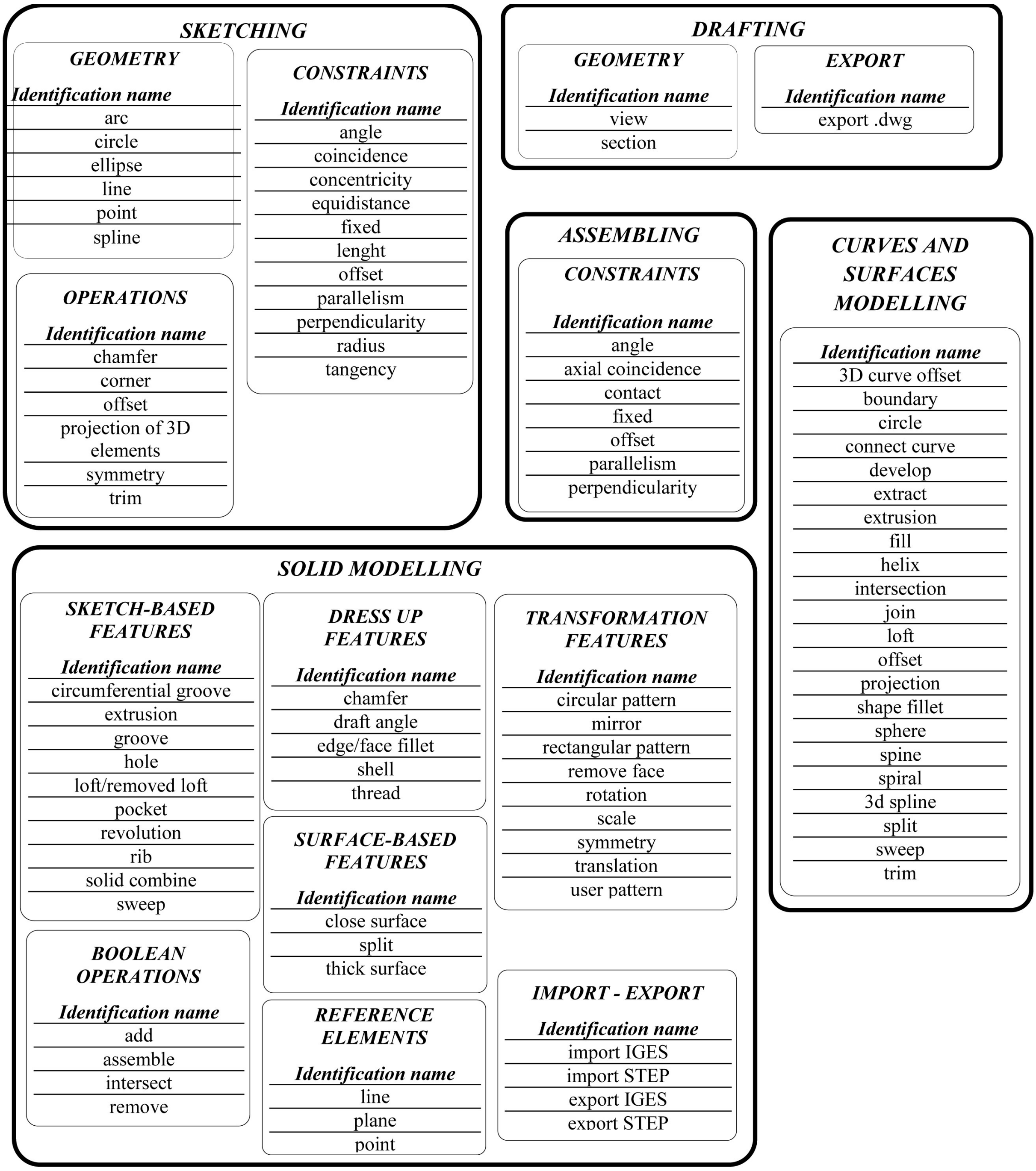

Fig. 3. List of tools obtained by analysing the 144 product assemblies for the related CAD workbenches.

- $GW_{SK} = \frac{1}{5} * \frac{1}{3} = \frac{1}{15}$, three being the categories identified in *Sketching*;
- $GW_{SM} = \frac{1}{5} * \frac{1}{7} = \frac{1}{35}$, seven being the categories identified in *Solid Modelling*;
- $GW_{CS} = \frac{1}{5}$, one being the category identified in *Curves and Surfaces Modelling*;
- $GW_{AS} = \frac{1}{5}$, one being the category identified in *Assembling*;
- $GW_{DR} = \frac{1}{5} * \frac{1}{2} = \frac{1}{10}$, two being the categories identified in *Drafting*.

The last step of the experimental plan is the robustness analysis of the method and, in particular, of the *CI*. In order to verify that the list of tools, extracted from assemblies created by CATIA V5 and used in the *Compliance Index*, is CAD independent, the *CI* has to be calculated for other similar 3D CAD software.

The method is tested by analysing the most widespread 3D parametric-variational CADs for mechanical design in Italy:

Table 1. List of the tools and corresponding weights for the sketch-based features of the Solid Modelling workbench

Identification name	**Quantity**	$w_{SM,k}$ %
circumferential groove	1485	2.66
extrusion	23637	42.29
groove	495	0.89
hole	4871	8.71
loft/removed loft	1443	2.58
pocket	18536	33.16
revolution	3090	5.53
rib	532	0.95
solid combine	28	0.05
sweep	1782	3.19

Table 2. Comparison among the Compliance Indexes for the four Commercial CAD systems here considered

	CAD systems			
	PTC-CP	**SW-10**	**I-10**	**SE–ST6**
CI_{SK}	1.000	1.000	1.000	1.000
CI_{SM}	1.000	0.987	0.987	0.960
CI_{CS}	1.000	0.950	0.828	0.828
CI_{AS}	1.000	1.000	1.000	1.000
CI_{DR}	1.000	1.000	1.000	1.000
CI	1.000	0.987	0.963	0.957

- PTC Creo Parametric (PTC-CP) [37];
- SolidWorks 2010 (SW-10) [33];
- Solid Edge ST6 (SE-ST6) [34];
- Inventor 2010 (I-10) [35].

The results, shown in Table 2, highlight that only PTC Creo Parametric has a *Compliance Index* equal to 1. This verifies that the list of tools used in the *Compliance Index* is CAD independent. The other three CAD systems present a *Compliance Index* less than 1 mainly due to the absence of modelling tools of curves and surfaces. These results are consistent with the authors' experience in the use of the above-mentioned CAD systems.

4. Results

The validated *CI* has been applied in the evaluation of open-source 3D CAD systems with a limitation on parametric, variational, feature-based and procedural CAD systems, which represent the solutions that are actually useful in design education and training.

Previously a search for and classification of open-source CAD systems available on the web has been carried out: 14 different CADs have been identified and are reported in Table 3.

Of the 14 open-source CAD systems here considered and listed in the table 3, the only one three-dimensional, parametric—variational, feature-based and procedural is FREE-CAD 0.15 (FC-015) [59]. Consequently, *FC-015* is the only software whose performances are evaluable in terms of *CI*. The Table 4 reports the comparison between the

Table 3. List, references and properties of the open-source CAD systems here considered

	3D	**Parametric–Variational**	**Feature-based**	**Implicit**
ImplicitCAD [46]	X			
NaroCAD [47]	X	X	X	
Sketch-Up [48]	X			
BRL-CAD [49]	X			
CAD-X11 [50]	X			
A9-CAD [51]				
3D Crafter [52]	X			
SolveSpace [53]	X	X		
PythonOCC [54]	X	X		
Draftsight [55]				
Medusa 4 [56]	X	X		
Q-CAD [57]				
OpenSCAD [58]	X	X	X	
FreeCAD [59]	X	X	X	X

Table 4. Comparison among the Compliance Indexes for four Commercial CAD systems here considered and Free-CAD 0.15

	CAD systems				
	PTC-CP	**SW-10**	**I-10**	**SE-ST6**	**FC 0.15**
CI_{SK}	1.000	1.000	1.000	1.000	0.914
CI_{SM}	1.000	0.987	0.987	0.960	0.864
CI_{CS}	1.000	0.950	0.828	0.828	0.268
CI_{AS}	1.000	1.000	1.000	1.000	0.716
CI_{DR}	1.000	1.000	1.000	1.000	1.000
CI	1.000	0.987	0.963	0.957	0.752

Table 5. The weights for each of the tools of the Curves and Surfaces Modelling workbench and the corresponding value of δ_l for Free-CAD 0.15

Identification name	$W_{CS,l}$ %	δ_l**—Free-CAD**
3D curve offset	0.04	0
Boundary	0.87	0
Circle	3.11	1
connect curve	1.12	0.5
Develop	0.33	0
Extract	0.62	0
Extrusion	2.49	0
Fill	1.70	1
Helix	15.88	1
Intersection	4.19	0
Join	10.57	0
Loft	0.25	1
Offset	0.17	0
Projection	1.04	0
shape fillet	1.70	1
Sphere	0.12	0.5
Spine	1.45	0
Spiral	1.20	1
3d spline	45.19	0
Split	2.57	0
Sweep	4.06	1
Trim	2.57	0

Table 6. The weights for each of the tools of the Assembly workbench and the corresponding value of δk for Free-CAD 0.15

Identification name	$W_{AS,k}$ %	δ_k**—Free-CAD**
angle	2.29%	0.5
axial coincidence	46.29%	1
contact	39.78%	0.5
fixed	3.60%	0
offset	7.48%	0.5
parallelism	0.48%	1
perpendicularity	0.07%	0.5

Compliance Indexes for the four previously mentioned Commercial CADs (PTC-CP, SW-10, SE-ST6 and I-10) and Free-CAD 0.15.

Table 4 shows that *FC-015* presents critical aspects in two workbenches: *Curves and Surfaces Modelling* and *Assembly*. As far as the first workbench is concerned, Table 5 reports the weights for each tool and the corresponding value of δ_l for *FreeCAD*. The value of the *Compliance Index* would be comparable with that of a commercial CAD if the tools of *3d spline*, *join* and *intersection* were implemented. As regards the *Assembly* workbench, on the other hand, the value of the corresponding *CI* is not satisfactory enough due to the fact that only the constraint of *axial coincidence* and *parallelism* are implemented in the analysed version (Table 6).

5. Discussions

This paper has aimed at answering the following question: can open-source 3D CAD systems effectively support university courses?

In order to find an answer, the performance of an open-source 3D CAD parametric, variational, feature-based and procedural software has been compared with a CAD COTS. In the related literature, this comparison is typically studied by submitting questionnaires to students in a class. However, and with a view to carrying out an objective evaluation, an original CAD-independent *Compliance Index* has been presented. The terms of the index have been experimentally evaluated through the analysis of 144 assemblies of 6977 different components modelled with CATIA V5 by 144 students of the course in Computer-Aided Design at the University of L'Aquila (Italy). The *CI* has been then validated through a robustness analysis.

Subsequently a search for classification of open-source CAD systems available on the web have verified that the only 3D CAD open-source, parametric, variational, feature-based and procedural software available (August 20, 2015) is *FREE-CAD 0.15*. From the results obtained when analysing *FREE-CAD 0.15* with the proposed *Compliance Index*, it has been concluded that currently this open-source CAD has not yet reached a sufficient level to replace commercial 3D, parametric, variational, feature-based and procedural CAD systems in academic courses. This is mainly because it lacks the implementation of some strategic tools in the *Curves and Surfaces Modelling* and *Assembly* workbenches.

The *Compliance Index* proposed and the related evaluation method can be effectively used to evaluate any 3D CAD available on the market in an objective way, so as to ultimately verify the compliance of the CAD instruments with the teaching of design in university courses.

6. Conclusions

A novel solution for selection 3D CAD systems based on the definition of a *Compliance Index* has been proposed, avoiding the introduction of subjective attributes. The solution is limited to open-source, three-dimensional, parametric-variational, feature-based and procedural CAD and to the educational field, since the methodological approach to teaching is considered by the authors more important than the CAD tool adopted and their industrial effectiveness. For the same reason, the *CI* does not consider the graphical interface of the software, i.e., how intuitive it is and how many operations it requires to implement a single modelling feature.

First, by a preliminary experimentation, the *Compliance Index* proved to be CAD independent. FREE-CAD 0.15 has demonstrated to be the only open-source solution capable of offering three-dimensional, parametric-variational, feature-based and procedural performance. It has been evaluated by comparing the results with those of some of the most diffused CAD COTS. Results demonstrate that the category here considered of open-source 3D CAD systems currently has not yet reached a sufficient level to substitute, in academic courses, commercial ones. Indeed, by means of the *CI* values, lacks in the implementation of some strategic tools in the *Curves and Surfaces Modelling* and *Assembly workbenches* are highlighted.

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Appendix–List of weights

		Identification name	$w_{SC,I}$ %
SKETCHER	GEOMETRY	arc	0.40%
		circle	12.65%
		ellipse	0.07%
		line	30.43%
		point	55.96%
		Spline	0.48%
	OPERATIONS	chamfer	17.50%
		corner	17.50%
		offset	15.00%
		projection of 3D elements	5.00%
		symmetry	15.00%
		trim	30.00%
	CONSTRAINTS	angle	1.04%
		coincidence	31.81%
		concentricity	2.65%
		equidistance	0.21%
		fixed	1.01%
		length	5.28%
		parallelism	15.96%
		offset	24.97%
		perpendicularity	1.05%
		radius	8.03%
		tangency	7.99%

		Identification name	w_{DR} %
DRAFT	GEOMETRY	view	25.0%
		section	25.0%
	EXPORT	export .dwg	50.0%

		Identification name	w_{AS} %
ASSEMBLY	CONSTRAINTS	angle	2.29%
		axial coincidence	46.29%
		contact	39.78%
		fixed	3.60%
		offset	7.48%
		parallelism	0.48%
		perpendicularity	0.07%

		Identification name	$w_{SM,I}$ %
SOLID MODELLING	SKETCH-BASED FEATURES	circumferential groove	2.54%
		extrusion	42.45%
		groove	0.92%
		hole	8.03%
		loft/removed loft	2.69%
		pocket	33.62%
		revolution	5.32%
		rib	0.86%
		solid combine	0.04%
		sweep	3.53%
	DRESS UP FEATURES	chamfer	4.20%
		draft angle	0.89%
		edge/face fillet	5.42%
		shell	74.70%
		thread	2.03%
	TRANSFORMATION FEATURES	circular pattern	46.71%
		mirror	0.18%
		rectangular pattern	13.04%
		remove face	1.56%
		rotation	1.01%
		scale	0.22%
		symmetry	33.63%
		translation	1.80%
		user pattern	1.85%
	SURFACE-BASED FEATURES	close surface	31.71%
		split	53.66%
		thick surface	14.63%
	BOOLEAN OPERATIONS	add	1.94%
		assemble	5.18%
		intersect	76.38%
		remove	16.50%
	IMPORT - EXPORT	import IGES	25%
		import STEP	25%
		export IGES	25%
		export STEP	25%
	REFERENCE ELEMENTS	line	37.12%
		plane	19.27%
		point	43.61%

	Identification name	$w_{SC,I}$ %
CURVES AND SURFACES MODELLING	3D curve offset	0,04%
	boundary	0,87%
	Circle	3,11%
	connect curve	1,12%
	develop	0,33%
	extract	0,62%
	extrusion	2,49%
	Fill	1,70%
	Helix	15,88%
	intersection	4,19%
	Join	10,57%
	Loft	0,25%
	Offset	0,17%
	projection	1,04%
	shape fillet	1,70%
	Sphere	0,12%
	Spine	1,45%
	Spiral	1,20%
	3d spline	45,19%
	Split	2,57%
	Sweep	4,06%
	trim	2,57%

Luca Di Angelo obtained his degree in Mechanical Engineering, summa cum Laude, in October 1999 from the Faculty of Engineering of L'Aquila and his Ph.D. in Mechanical Engineering in 2002 from the University of "Tor Vergata" in Rome. He is an Associate Professor in the Department of Industrial and Information Engineering, and of Economics of University of L'Aquila, Italy. His research interests include: computational geometry, geometric modelling of functional geometric shape, shape errors modelling, simulation and features based CAD technology. Luca Di Angelo is co-author over seventy papers in international journals and international conferences.

Francesco Leali graduated in Mechanical Engineering (2002) and attained a Ph.D. in Mechanical Engineering (2008) at the University of Modena and Reggio Emilia (Italy). He is an Associate Professor at the Department of Engineering "Enzo Ferrari" in Modena, Italy. His research interests are into the scientific field of "Design and Methods of Industrial Engineering". His main activities and publications deal with CAD-based design and simulation of products and processes, 3D geometrical product specification and industrial robotics, with a particular focus on automotive and high mechanics.

Paolo Di Stefano is full Professor of Mechanical Engineer at the Department of Industrial and Information Engineering and Economics at the University of L'Aquila (Italy) and there he is coordinator of the Master of Science Degree in Mechanical Engineering. He obtained his M.Sc. degrees in mechanical engineering from the University of Rome "La Sapienza". Prior to joining the University of L'Aquila, he held several supervisory positions in the automotive industry. His current research activities involve computational geometry, feature-based methodologies and automatic feature recognition, Computer Aided methods for biomedical, geometric inspection and product design.