THE “INGENIA” INITIATIVE FOR PROMOTING CDIO AT TU MADRID: LESSONS LEARNED FOR ENHANCED PERFORMANCE

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ABSTRACT

The implementation of the “Bologna process” has culminated at ETSII-TU Madrid with the beginning of the Master’s Degree in Industrial Engineering, in academic year 2014-15. The program has been successfully approved by the Spanish Agency for Accreditation (ANECA) and includes a set of parallel subjects, based on the CDIO methodology, denominated generally “INGENIA”, linked to the Spanish verb “*ingeniar*” (to provide inspired or creative solutions), also related etymologically in Spanish with “*ingeniero*” (engineer). INGENIA students live through a complete development process of complex products or systems linked to different engineering majors at ETSII-TU Madrid. All subjects within the INGENIA initiative have an analogous structure and aim at the promotion of similar professional outcomes, linked to the ability to design, implement and operate engineering systems, also focusing on teamwork and communication skills, and trying to systematically promote student creativity and their interest in social and ethical aspects of engineering for a sustainable World.

In this study we present a complete development of the INGENIA initiative, the main results from the first implementation from 2014-2015 academic course and the principal challenges and difficulties faced, when trying to systematically promote CDIO and to encourage a shift from traditional teaching-learning methodologies to student centered approaches. Present analysis is carried out focusing on the main drivers of change: students, teachers, environment and resources, taking into account opinions from the Managing Board at ETSII-TU Madrid, which have been systematically gathered by means of comprehensive surveys and personal interviews. Key aspects, including: student motivation, coordination between teachers and subjects, supervision of projects under a tight schedule, promotion of topics for all industrial engineering areas, rapid prototyping resources for reaching the implementation and operation stages, among others, are discussed and the more relevant lessons learned and proposals for improvement are put forward. We also provide an analysis about the impacts of such proposals for improvement on the second implementation from 2015-2016 academic year in which the INGENIA initiative is performing with even better results and involving more than 250 students, almost doubling the numbers from the first implementation.

To our knowledge, the INGENIA initiative constitutes the first integral application of the CDIO methodology to the field of Industrial Engineering in our country.

KEYWORDS

CDIO as Context, Integrated Curriculum, Integrated Learning Experiences, Active Learning. (Standards: 1, 3, 7, 8).

INTRODUCTION

Student motivation and active engagement to their own learning process is a key success factor in Higher Education, especially in Science and Engineering paths, as recognized and highlighted in several studies (Prince, 2004, Hmelo-Silver, 2004), reports and declarations, such as the Bologna Declaration and the subsequent related declarations from Prague, Berlin, Bergen, London, Leuven and Budapest-Vienna, aimed at the implementation of the European Higher Education Area (EHEA). Making students drivers of change is perhaps the most effective part of a global strategy, for the promotion of a wide set of professional skills in Engineering Education (Shuman, et al. 2005, Díaz Lantada, et al. 2013). Problem- or project-based learning (typically PBL) methodologies clearly tend to motivate students to participate and become involved in their own learning process and constitute an excellent way of analysing whether students have acquired basic concepts taught in the theory classes and if they are capable of applying them in real situations. These PBL experiences have proven to be effective in primary, secondary and university education and in scientific-technological, bio-sanitary, humanistic and artistic contexts. In consequence, most technical universities, before awarding the engineering degree, almost always include the standard final degree project as part of the studies, which, basically, is a PBL learning experience. In direct connection with the promotion of project-based learning methodologies worldwide, even though its holistic approach to engineering education development goes far beyond project-based learning, the CDIO™ Initiative (www.cdio.org) is probably the most ambitious approach. The CDIO™ Initiative is focused on the establishment of an innovative educational framework for producing the engineers of the future, by means of providing students with an education stressing engineering fundamentals by means of "Conceiving - Designing - Implementing – Operating" (CDIO) real-world systems, processes and products (Crawley, et al. 2007). Throughout the world, CDIO Initiative collaborators are adopting CDIO as the framework of their curricular planning and outcome-based assessment. CDIO also promotes collaboration and sharing of good practices among engineering educational institutions worldwide.

The main purpose of present study is to detail current actuations at ETSII – TU Madrid oriented to a more systematic integration of CDIO experiences within our program 6-year integral program of Industrial Engineering (Grade + Master's Degree), paying special attention to the "INGENIA" initiative, which was implemented for the first time in academic year 2014-2015. Main results from the first implementation, together with the principal challenges and difficulties faced, when trying to systematically promote CDIO and to encourage a shift from traditional teaching-learning methodologies to student centered approaches are presented. Key aspects and good practices, based on the experience of the Managing Board at ETSII-TU Madrid, are discussed and proposed.

THE "INGENIA" INITIATIVE: INTEGRATED PROMOTION OF CDIO INITIATIVES

The ETSII – TU Madrid (www.etsii.upm.es, see Figure 1) has been promoting student-centred teaching-learning activities, according to the aims of the Bologna Declaration, well before the official establishment of the European Area of Higher Education (Vera, et al. 2006). In the last years we would like to highlight the Innova.Edu educational projects, funded by our centre during the academic years 2004-2005 and 2005-2006, which helped to promote several project-based learning activities in different subjects and to set common practices among our teaching staff for activities in the field of "conceive, design, implement & operate". Additional educational innovation projects, funded by our University since 2007, have helped us to establish supplementary best practices for promoting student motivation, to implement novel subjects linked to project-based learning, to enhance our faculty teaching skills, to improve our assessment and evaluation plans, among other innovations. Such improvements have led to the Accreditation of our Industrial Engineering program by ABET (www.abet.org) in 2010.

Figure 1. ETSII – TU Madrid Campus, main hall and collaborative learning environments.

The level of commitment of our teachers with these educational innovation activities is noteworthy, as the teaching innovation experiences carried out in last ten years have led to the foundation of 17 Teaching Innovation Groups at ETSII – TU Madrid, hence leading the ranking of teaching innovation among all TU Madrid centres. The historical background was previously reviewed and presented at 10th International CDIO Conference, held in Barcelona in 2014 (Díaz Lantada, et al. 2014), and discussed at the Rejkiavik European Regional Meeting in 2015, which eventually led to our ETSII – TU Madrid joining the International CDIO Initiative, as first Industrial Engineering School of our country to fulfil the required criteria.

In any case, it is important to highlight that, at ETSII – TU Madrid, we are deeply concerned about students' involvement in their own learning process and implicated in strategic actuations for the promotion of project-based learning activities, linked to real products and systems, as drivers of curricular planning, of continuously evolving teaching-learning methodologies and processes, and of an outcome-based assessment. We have been working towards providing an integrated support framework for driving the aforementioned PBL actuations, searching for common principles, based on the "conceive – design – implement – operate" guidelines and standards. The implementation of the **"INGENIA" Initiative** has been the key for achieving standardized and complete CDIO experiences (from the conceptual stage to the operational phase) and for providing the 100% of our students with the opportunity of living the whole development process of a product or system, as detailed further on.

In short, the implementation of Bologna process has culminated at ETSII – TU Madrid with the beginning of the Master's Degree in Industrial Engineering, in academic year 2014-15. The program was successfully approved in 2014 by the Spanish Agency for Accreditation (ANECA), with the inclusion of a set of subjects based upon the CDIO methodology denominated generally "INGENIA", an acronym from the Spanish verb "*ingeniar*" (to provide ingenious solutions), also related etymologically in Spanish with the word "*ingeniero*" (engineer). INGENIA students experience the complete development process of a complex product or system and there are different kinds of subjects (and projects), within the initiative, covering most of the engineering majors at ETSII – TU Madrid. Students choose among the different INGENIA subjects (and projects), depending on their personal interests. It is important to note that the INGENIA subjects are compulsory for all students enrolled in the first year of the Master's Degree program at ETSII – TU Madrid (a two-year program with 120 ECTS after a four-year Grade in Industrial Technologies with 240 ECTS). The subjects (with a similar CDIO orientation but offering different topics and projects) are 12 ECTS equivalent, which correspond to a student workload between 300 to 360 hours, distributed along two semesters with the following structure: 120 hours of supervised work plus between 180 to 240 hours of personal student work, organised usually in teamworks. Professor supervised part of the subjects is divided into 30 hours dedicated to adapt basic theoretical knowledge derived from other subjects to those directly related with the project, and a second set of 60 hours is devoted to practical work in the lab, with professor supervised sessions. Students also receive two seminars of 15 hours; one oriented to transversal outcomes, in particular, workshops on teamwork, communication skills and creativity techniques, and the other one about social responsibility issues such as environmental impact, social, political, security, health, etc. The distribution of these lectures, practical sessions, seminars and workshops, is distributed along the 28 weeks of the two semesters of the first year, resulting in 5 hours per week of lectures or practical sessions in the regular schedule of students (Lumbreras et al. 2015).

Hours/week	THIRD SEMESTER	ECTS	Hours/week	FOURTH SEMESTER	ECTS
	Final Master's Thesis	6		Final Master's Thesis	6
6	Curricular configuration	9	6	Curricular configuration	9
2	3 specialization subjects (Automation & Electronical, Chemical, Electrical, Energetic, Materials, Mechanical, Construction, Org.)	3	2	3 specialization subjects (Automation & Electronical, Chemical, Electrical, Energetic, Materials, Mechanical, Construction, Org.)	3
2		3	2		3
2		3	2		3
2	1 subject on Industrial Installations	3	2	1 subject on Industrial Management	3
2	1 subject on Industrial Technologies	3	2	1 subject on Industrial Technologies	3

Hours/week	FIRST SEMESTER	ECTS	Hours/week	SECOND SEMESTER	ECTS
4	INGENIA (first part)	6	4	INGENIA (second part)	6
2	2 subjects on Industrial Management	3	2	2 subjects on Industrial Management	3
2		3	2		3
2	2 subjects on Industrial Installations	3	2	2 subjects on Industrial Installations	3
2		3	2		3
2	4 subjects on Industrial Technologies	3	2	4 subjects on Industrial Technologies	3
2		3	2		3
2		3	2		3
2		3	2		3

Figure 2. Program structure (Master's Degree in Industrial Engineering).
120 ECTS program with at least 20% devotion to project-based learning activities.

Placing the INGENIA subjects in the first year of a 120 ECTS program is indeed interesting, as additional 12 ECTS are devoted to the final degree thesis normally during the second year. Therefore, at least 20% of the whole Master's Degree is devoted to project-based learning aimed at the complete development of engineering products and systems. Program structure is detailed in Figure 2 and the integration of CDIO activities can be easily appreciated (INGENIA subjects in pale blue and Final Master's Thesis in pale green). In addition, the INGENIA subjects are helping us to complement our competence-based strategy, in accordance with CDIO Standards 1, 3, 7 & 8, by placing special emphasis on several professional skills difficult to obtain in more traditional teacher-centred activities, such as conventional master classes and expert talks. Main perceived outcomes include the promotion of: students' ability to apply knowledge of mathematics, science and engineering, students' ability to design experiments and interpret data, students' ability to design engineering systems and components to meet desired goals, students' ability to communicate effectively and to work in multidisciplinary teams, or students' ability to use modern resources, in accordance with the ABET professional skills our program pursues (Shuman, et al.

2005). Table 2 includes the different CDIO topics (or subjects) taught within the INGENIA scheme for the academic year 2014-2015, covering several disciplines.

Table 1. CDIO topics of the INGENIA subjects for the last couple of academic years.

Different INGENIA Subjects	Product / system developed & objective
Formula Student	Students take part in the complete development project of a competition car, from the conceptual design, to the final competition.
Engineering design: Machine development projects	Students live the whole process of creating an innovative machine, from the conceptual design stage, to the final trials with real prototypes, searching for design improvements.
Development of daylife products / household goods	Students live the whole process of designing innovative products, from the concept step, to final simulations and trials with prototypes.
Smart systems engineering	Students experience the process of designing a smart system, using state-of-the-art engineering resources and taking account of the whole life-cycle. (A set of co-operative drones in current year).
Development of electronic devices	Students live the whole process of creating a new electronic product, oriented to improving daylife in our ETSII-TU Madrid, from the concept, to the prototyping stage and trials.
Development and management of industrial construction projects	Students experiment with information management and project planning resources applied to a real industrial construction project, (a beer-factory in the first two implementations) .
Development of electricity supply networks	Students live the development project of an electricity supply network, from an initial renewable energy source to population.
Biomedical engineering design	Students experience the process of creating an innovative medical device, from the conceptual stage, to the final trials with prototypes.
Finite-element and testing in machine elements (new 2015-2016)	Students design, model, manufacture and test machine elements for the automotive and aeronautic industries.
Development of video games (new 2015-2016)	Students live through the whole development process of a video game, from specifications, to implementation and testing.

Some of the proposals for the INGENIA subjects evolve from previous experiences, but most of them are novel initiatives consequence of the progressive involvement of our teaching staff in student-based teaching-learning methodologies for the promotion of integrated learning experiences (7th CDIO Standard) and of active learning (8th CDIO Standard). The topics from Table 2 cover most specializations of our Master's Degree in Industrial Engineering and we believe that all of them are interesting, although continuously improving the offer is a key-point. As additional reflection, the proposed two-semester structure for the INGENIA subjects is very appropriate, as the "conceive" and "design" phases are adequately carried out during the first semester and the "implement" and "operate" stages are tackled in the second semester. A whole academic year is ideal for maturing the development process of complex products and systems and is helping us to improve several prior experiences, limited to design and simulation activities, with the benefits from obtaining final prototypes and carrying out operational trials.

SYSTEMATIC DETECTION OF CHALLENGES AND DIFFICULTIES ALONG THE WHOLE IMPLEMENTATION PROCESS OF COMPLETE CDIO EXPERIENCES

Once the INGENIA Initiative, inspired by the CDIO approach, has been running for almost two complete academic years, we have decided to gather main challenges and difficulties linked to the whole implementation process of such a methodology for the promotion of complete CDIO experiences. The implementation of these experiences has been divided into different phases, including: planning and preparation, assignment and organization, project development (the actual CDIO experiences, which students live) and assessment. A survey has been prepared, highlighting some possible key aspects linked to the aforementioned phases. Eventually relevant aspects, ordered along the implementation process, include:

I) Planning and preparation of complete CDIO experiences

a. Designing projects that properly reflect how the subject evolves
b. Designing stages that will ensure progressive learning
c. Designing the assessment system to be used
d. Preparing a sufficient number of different questions
e. Preparing questions of equivalent difficulty
f. Choosing appropriate support tools
g. Implementing manuals and help examples
h. Implementing software support tools
i. Planning projects to fit the time allocated to the subject
j. Searching for a realistic approach ("real" projects) but feasible for students

II) Student organization and assignment of projects

a. Explaining to students the "PBL" methodology to be used
b. Students' acceptance of "PBL" methodologies as something positive
c. Decision between group and individual projects
d. Choosing the number of students per group
e. Group training process
f. Assigning projects (should students be unable to propose them)
g. Choosing projects (should students be able to freely propose them)
h. Acceptance of projects by students / teachers
i. Consideration of alternatives to "PBL" methodology, if appropriate
j. Project coordination and timescales compared to other experiences in other subjects

III) Development of the projects (the actual CDIO experiences lived by students)

a. Setting milestones throughout the process
b. Taking action to adapt students' starting-out levels
c. Tutorials throughout the process
d. Coordinating the development with other experiences in other subjects
e. Motivation and follow-up to avoid deviations in the results
f. Motivation and follow-up to avoid deviations in the timescales
g. Student access to learning resources
h. Student access to laboratories
i. Student access to software tools
j. Carrying out practice to back up the "PBL"

IV) Assessment

a. Setting a diagnostic assessment system to find the starting-out level
b. Setting an adequate system to evaluate knowledge
c. Setting an adequate system to evaluate skills
d. Setting an adequate system to evaluate generic competencies
e. Setting an adequate system to individualise group experiences
f. Detecting and controlling unacceptable conduct (copied projects, "parasite" students…)
g. Public presentation of results as a supplement to assessment
h. Use of other conventional assessment methods to supplement (final exam, test…)
i. Use of questionnaires to assess the progress of the experience and possible improvements
j. Use of questionnaires to evaluate students' work load

Such phases and eventual key processes have been implemented in form of survey, in order to evaluate their: i) relevance for the overall success, ii) difficulty of taking them into account, iii) maturity of implementation. Their connection with the main drivers of change (professors, students, environment and resources) is also evaluated within the survey. The degrees of relevance, difficulty, maturity and connection with drivers of change have been assessed from 0 (none) to 10 (extreme). The survey has been filled by members of the Managing Board at ETSII – TU Madrid, which have been involved in the conception, design, implementation and assessment of the INGENIA Initiative, as a multidisciplinary set of subjects with a similar approach for the systematic promotion of the CDIO methodology.

Main results regarding the most relevant processes are summarized and discussed below. In fact, some of the most relevant ones for the overall success are perceived as quite easy to handle, while some others still need special attention for an improved maturity, as will be pointed out in the lessons learned section. Figure 3 shows the relevance of the different phases linked to the whole implementation process of CDIO experiences and related relative importance of main drivers of change, as obtained directly from the survey results. It is interesting to note that the “development” stage, which corresponds to the actual development of projects by the students, is considered to be the most important. The “planning” stage, which corresponds to the strategic definition, orientation and preparation of the actual course, follows as the second most relevant phase. The “assignment” stage, which is linked to dividing students into groups and to assigning the topics and projects to be developed, and the “evaluation” stage, linked to students’ presenting their results and to the final course assessment, are considered also quite relevant. In any case, there is not a single stage with an outstanding figure, when compared with others.

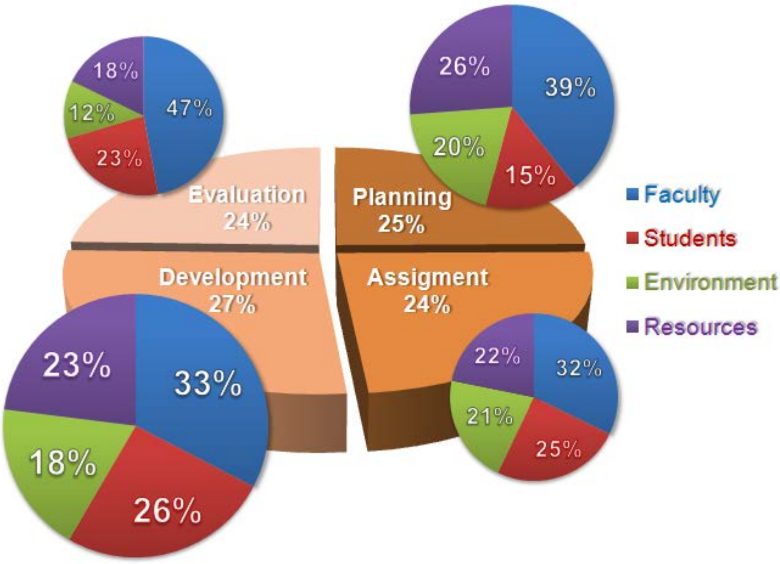

Figure 3. Relevance of the different phases linked to the whole implementation process of CDIO experiences and related relative importance of main drivers of change.

Regarding the drivers of change, it is interesting to note that in all stages professors (and their motivation and implication) have been perceived as the most relevant driver of change, not just in the planning, assignment and evaluation phases, but even in the development stage. In future studies we should also consider students’ opinions, but we believe that the provided results are quite objective. Clearly the motivation of professors is a key for shifting from teacher-based to student-based Higher Education and for “re-thinking Engineering Education”, as proposed by the CDIO Initiative.

Figure 4 presents the 12 more relevant aspects, which have received an assessment of “importance” above 9.25/10, within the different phases of the whole implementation process of CDIO experiences. Their “importance”, “difficulty” and “maturity” mean values are presented and can be compared with the mean values of all aspects presented in dotted lines. The more relevant aspects, including: adequate explanation of the PBL methodology, definition of milestones and tutorials along the process, are in fact quite easy to implement and very mature in our CDIO-related experiences.

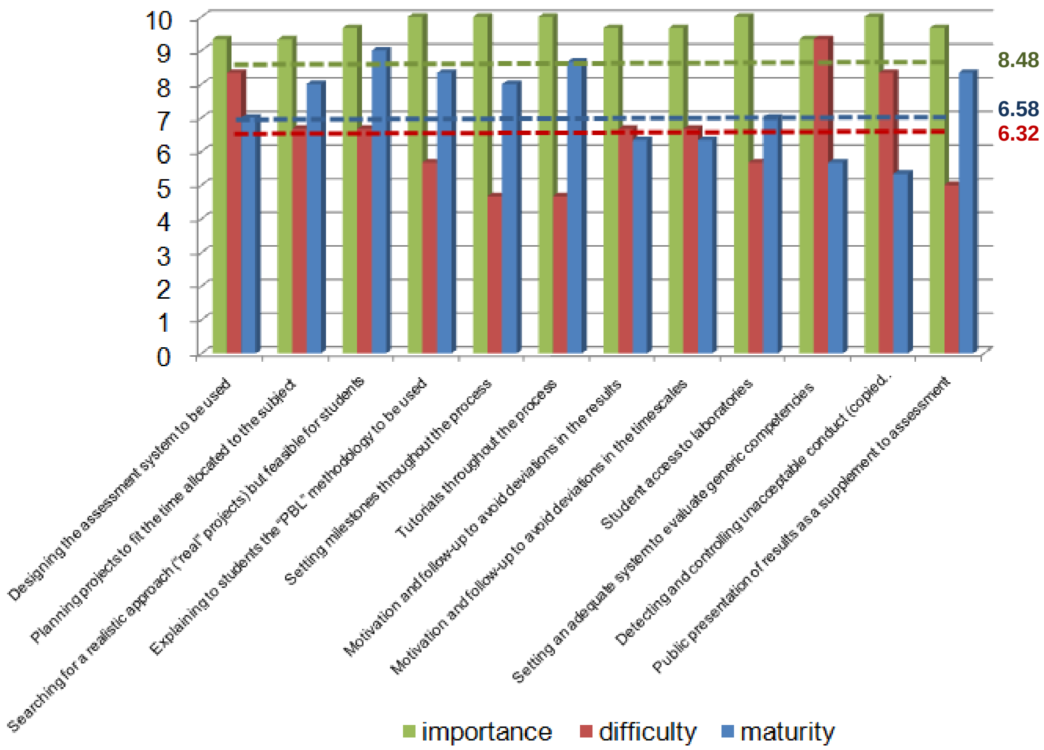

Figure 4. Importance, maturity and difficulty of the 12 more relevant aspects connected to the different phases of the whole implementation process of CDIO experiences. Mean values are presented and compared with the means of all aspects (dotted lines).

MAIN LESSONS LEARNED, GOOD PRACTICES AND FUTURE PROPOSALS

Although the gathered results can be additionally discussed (hopefully *in situ* with colleagues attending the Turku CDIO Conference) and even if deeper analyses are possible, we would like to summarize here some main lessons learned, good practices applied and future proposals in mind.

First of all, an adequate concentration, collaboration, communication and co-motivation between teachers and students during the development stage are fundamental good practices for the implementation of successful CDIO experiences. The planning phase, in which the professors are the clear main characters, is also of remarkable importance. Above all, the impact of the human factor (students and teachers) is much higher than the impact of the material resources and environment for the expected success of novel CDIO experiences.

In consequence, really interesting and formative CDIO-inspired courses can be implemented, counting with the efforts and motivation of students and teachers, without requiring many additional resources. This leads to highlighting the CDIO approach, not just as the preferred methodology for “re-thinking Engineering Education”, but also as a key towards the concept of “Engineering Education for all”, as it may well enable the performance of integrated learning experiences and the overall promotion of student motivation, without requiring vast investments, which may not be possible in the public universities of developing countries.

Regarding the future, we would like to expand the study to count with the opinions from students and colleagues, both at ETSI Industriales – TU Madrid, and even at other universities and centers involved in the International CDIO Initiative, so as to find other possible relevant aspects, which may not have been considered.

CONCLUSIONS

Present study has detailed the complete development of the INGENIA initiative, the main results from the first implementation from 2014-2015 academic course and the principal challenges and difficulties faced, when trying to systematically promote CDIO and to encourage a shift from traditional teaching-learning methodologies to student centered approaches. Present analysis has been carried out focusing on the main drivers of change: students, teachers, environment and resources, taking into account the opinions from the Managing Board at ETSII-TU Madrid, which have been systematically gathered by means of comprehensive surveys and interviews. Key aspects, including: student motivation, coordination between teachers and subjects, supervision of the projects under a tight schedule, promotion of topics for all industrial engineering areas, rapid prototyping resources for reaching the implementation and operation stages, among others, have been discussed and the more relevant lessons learned and proposals for improvement have been also put forward. We have also tried to provide an analysis about the impacts of such proposals for improvement on the second implementation from 2015-2016 academic year in which the INGENIA initiative has been performing with even better results and involving more than 250 students. We truly hope that present summary of key aspects and possible good practices, for the systematic promotion of active methodologies within a whole plan of studies and based on the CDIO approach, may be useful for colleagues desiring to carry out similar experiences.

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