

TEN YEARS OF CDIO EXPERIENCES LINKED TO TOY DESIGN

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ABSTRACT

Toys are deeply rooted to the natural learning process of children, as they investigate for themselves learning cause effect relationships and the relevance of boundary conditions, and to the development of their personality and social skills, as they observe and interact with other children and adults when playing. Learning through play, promoted by pioneers as Montessori, Piaget and Steiner, is among the most powerful teaching-learning strategies and currently forms part of high-quality curricula worldwide, mainly from early childhood to high school. Our experience shows that it can be also successfully applied to higher Education and that living through the complete engineering design process of real toys, following the CDIO scheme, is an excellent strategy for making engineering students face real industrial challenges while they design, dream, play and learn.

A decade ago we started to set the foundations towards the European Area of Higher Education, which should promote active learning in contexts more linked to professional practice. To this end, several courses in our Industrial Engineering Degree began to incorporate project-based learning activities, although initially with a more limited scope than that of the integral CDIO approach, as fundamental part of the teaching-learning process. In our course on “Design and manufacturing with polymers” we opted for including capstone collaborative projects linked to designing real plastic products and the related mass-production tools. We decide to propose students to design toys and the related injection molds, which constitute great examples of complex engineering systems, using state-of-the-art industrial methodologies and resources. The topic of “toy design” has proven to be motivating for students and teachers and has helped us to re-invent the course in every edition. Our course has served as application example of the benefits of student-centered teaching-learning strategies at ETSII-UPM along the implementation of the “Bologna process”, which has culminated with the beginning of the Master’s Degree in Industrial Engineering, a programme that devotes more than a 20% of activities to project-based learning following the CDIO standards, in which the detailed course continues as part of the Mechanical Engineering major. Here we present a summary of the course evolution during the last decade and analyze its main teaching-learning results.

To our knowledge, this “complete toy design experience” constitutes one of the first integral applications of the CDIO methodology to the field of Industrial Engineering in our country and stands out for ten years of continuous improvements. Around 500 students have taken part in these projects from our “Design and manufacturing with polymers” course at ETSII-UPM and more than 200 real toys, together with the related injection molding mass-production tools, have been designed during the last ten years. The most outstanding designs have been manufactured and tested every year for letting students live the whole CDIO cycle.

KEYWORDS

CDIO implementation, Case studies & best practices, 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, 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 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 is an excellent way of analysing whether students have acquired the 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.

Project-based learning following the CDIO approach can be also linked to “learning through play” methodologies, in which toys may play a fundamental role. In fact, toys are deeply rooted to the natural learning process of children, as they investigate for themselves learning cause effect relationships and the relevance of boundary conditions, and to the development of their personality and social skills, as they observe and interact with other children and adults when playing. Learning through play, promoted by pioneers as Montessori, Piaget and Steiner (Davies, et al. 2002), is among the most powerful teaching-learning strategies and currently forms part of high-quality curricula worldwide, mainly from early childhood to high school. Our experience shows that it can be also successfully applied to higher Education and that living through the complete engineering design process of real toys, following the CDIO scheme, is an excellent strategy for making engineering students face real industrial challenges while they design, dream, play and learn.

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THE “DESIGN AND MANUFACTURING WITH POLYMERS” COURSE

Learning objectives and desired outcomes

Our main aim, when planning the course on “Design and manufacturing with polymers”, was to make students aware of the relevant connections between geometries, materials and manufacturing processes in real industrial design projects. Such connections are even more essential if the design projects are linked to using polymeric parts and aimed at mass-production by means of injection molding. In these projects, very special considerations have to be taken into account for an optimal in service performance of the polymeric parts, but also for an adequate cost- and eco-efficient mass-production. Therefore we planned the course for explaining such interdependent relations of the triad “geometry-material-process” and with the intention of making our students good designers of parts and of related manufacturing tools for their potential professional development in the plastics industry. We wanted them to understand these issues by means of real cases of study, adapted from previous experiences in research, development and innovation tasks performed in collaboration with industrial partners by our research groups at UPM. In addition, we wanted to introduce common theoretical and practical aspects of polymeric materials, of polymeric part design and of polymers processing, especially focusing on injection molding and on the design of molds and related injection molding tools. Since the beginning we understood that it would be beneficial for the students to acquire experience with design and simulation resources typically used in this industry (computer-aided design resources, finite element modeling tools, computer-aided manufacturing systems...), as the sector is quite relevant in our country and as companies usually pay attention to hands-on experience with specific software tools, for the incorporation of junior engineers. We thought that letting students live through complete polymeric product development experiences would allow them to apply the acquired knowledge in a practical way and would make them work in an almost professional context, very similar to what they could eventually live in an industrial environment. It proved a very enriching experience, both for students and teachers, as detailed further on.

Structure of contents, teaching methodology and historical perspective

According to the aforementioned learning objectives and outcomes, the course is divided in two inter-related parts, one linked to designing and modeling the performance of polymeric parts and one linked to designing and modeling the molds and tools required for their mass-production. The main contents of these two fundamental blocks are listed below (Table 1):

Table 1. Main contents of the “Design and manufacturing with polymers” course.

Block I. Polymeric part design	Block II. Injection mold design
Fundamentals of polymeric materials	Fundamentals of polymers processing
Fundamentals of polymeric part design	Fundamentals of injection molding
Joining methods and related design aspects	Mold design issues: Mold structures
Computer-aided design of polymeric parts	Mold design issues: Mechanical issues
Finite-element modeling of polymeric parts	Mold design issues: Thermal issues
Visco-elasticity and performance of polymers	Simulation of injection molding processes
Rapid prototyping by additive manufacturing	<i>In silico</i> assessment of final part quality

Regarding teaching-learning methodology, as previously advanced, we opt for project-based learning following the CDIO approach. Students work in groups typically of three or four students and develop a plastic product, designing the different parts, selecting the adequate polymeric materials, defining joining methods, optimizing the geometries towards mass-production, defining the mass production tools (molds and components) and *in silico* assessing final part quality. The results from the complete projects account for a 70% of the global mark of the students enrolled in a group. Individual evaluation is promoted by means of additional personal home-works (linked to analyzing plastic parts), which account for the remaining 30% of the global mark.

The subject was implemented in parallel to the adaptation of our ETSII-UPM to the EU Area of Higher Education (see Figure 1). In the first version (2005-2014) the course was designed as a 4.5ECTS-course, which implied between 112 and 135 hours of students’ personal work; in the second re-designed version (2015-future) it is a 3ECTS-course, which implies between 75 and 90 hours of students’ personal work. The re-design has supposed an increased use of in-class modeling tools and e-learning resources for more-efficient teaching practice and a reduction of the expected devoted hours to the design projects (from around 90 to around 60 hours). In following sections we will discuss this evolution and its consequences.

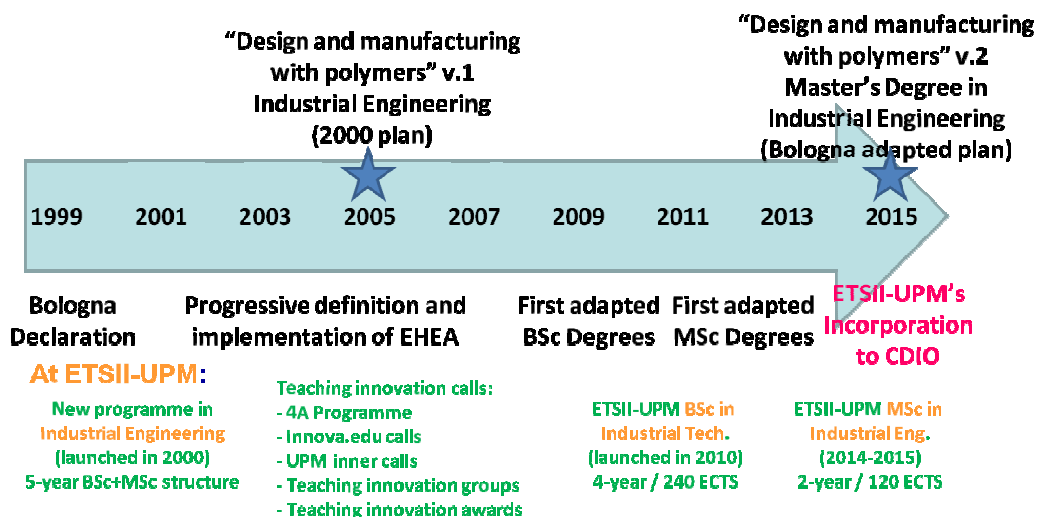


Figure 1. Evolution and implementation of CDIO activities at ETSI Industriales – UPM and the two versions of the “Design and manufacturing with polymers” course.

CDIO APPLIED TO “TOY DESIGN” EXPERIENCES

Planning of the experiences

Once the groups are formed, students decide the product they would like to design and gather information on their product and context, analyzing existing solutions together as a prior stage to the design tasks. Along the decade 2005/2006-2015/2016, we proposed “toy design” as main topic for selecting the products. Toys are fun to design but also quite demanding engineering products, if mechanical issues, material selection aspects and optimization strategies for manufacturability are adequately addressed. In addition, toys provide a nice equilibrium between the desired complexity for applying theoretical aspects along the design and feasibility for living a complete CDIO cycle in a one-semester course. In some cases, so as to promote homogeneous boundary conditions to all participant groups, monographic topics have been explored (i.e. “car design”, “plane design” or “toys inspired on the machines of Leonardo”, among others). The result of this initial stage is a list of requisites with the basic information for the project (desired toy to be designed).

From the need to the concept

The teams continue to work on the list of requirements to identify main problems and to choose the best conceptual solutions for each issue, paying attention to manufacturability, time optimization and costs reduction. Drawing sketches and using computer-aided design programs, student groups obtain a pre-design of the components and select among main connecting options. A potential set of materials is also chosen according to the initial estimations of resistance required for the different components.

From the concept to the design

Once the most appropriate solution has been chosen from the different pre-designs, the different parts must be exactly defined. Following the concepts explained in the theory classes, the students use a design approach oriented to manufacture and assembly. In order to verify that the chosen materials are suitable, the initial estimations are further analyzed with the information provided by computer-aided engineering programs, considering the triad “geometry-material-process”.

From the design to the implementation and operation

In our course, implementation and operation are related to the design of molds and to the *in silico* evaluation of mass- production by injection molding, as the investment required for the manufacture of real molds is beyond our capabilities. The use of injection molding simulation programs is fundamental, in order to check that the choice of materials and injection molding conditions are appropriate, as well as to define: i) an optimum distribution of the cavities in the mold, ii) the adequate material inlets, iii) the filling channels and iv) the eventual cooling system. Molding simulations are carried out in order to choose the optimum (theoretical) injection point or to evaluate times and temperatures obtained when filling the mold and cavities. To promote student motivation, to check ergonomics and aesthetics and to perform limited functional validations, prototypes the best toys are manufactured using additive manufacturing resources.

Assessment of students and projects

Along the projects, the groups of students interact with the professors and present their results, which involves typically a public presentation linked to the concept and design and another linked to the implementation and operation. Final project results constitute a 70% of the global evaluation, as previously mentioned. Technical quality, product viability, creativity, teamwork and communication skills, among other outcomes, are evaluated.

SUMMARY OF RESULTS: A DECADE'S PERSPECTIVE

As brief summary of results, Table 2 includes some figures related to student and teacher success, motivation and implication in the subject, as compared with subjects of the Industrial Engineering Degree before implementing student-centered activities, as a consequence of the adaptation to the European Area of Higher Education. The positive effect of shifting towards CDIO related methodologies can be clearly appreciated. It is necessary to indicate that the benefits affect not only learning and acquisition of outcomes, but also student and teacher motivation and mutual relation in a very special way, which is starting to influence the overall ambience of learning, collaboration and respect present in our novel Master's Degree in Industrial Engineering, for which the "Design and manufacturing with polymers" course was a pioneer pilot experience. Such positive aspects clearly rely on an important increase of teacher dedication outside the classroom to the CDIO-based subject, but the general impression is that such additional dedication is compensated by the highly satisfactory results. However, this approach requires more resources than more traditional plenary master classes. In any case, as the topics covered can be of special interest for several enterprises, with which we normally collaborate by means of Enterprise-University Chairs, it is possible to search for additional funding and sponsorships. Our intention is to incorporate enterprises from the product design industry into the course, as key players for proposing complex projects, for implementing student competitions and even for evaluating our students.

To further illustrate students' results within the course, Figure 2 and 3 provide examples of computer-aided designs, simulations for design optimization and prototypes for design validation; while Figures 4 and 5 show examples of injection mold design towards mass-production, with analyses linked to filling time, part quality assessment and performance of refrigeration system. Main lessons learned, future perspectives and forthcoming challenges are additionally discussed in the following Section.

Table 2. Some figures related to student and teacher motivation and implication in the "Design and manufacturing with polymers" course along a whole decade.

Control aspect	In conventional subjects before the promotion of student-centered approaches	In play-based CDIO "Design and manufacturing with polymers" course along a decade
Success ratio	45% – 75%	>95%
Student attendance to scheduled lessons	35% – 65%	>80%
Typical number of answers to debate questions	1 – 3	6 – 8
Typical number of student questions / hour	2 – 5	4 – 6
Frequency of meetings between the teachers of the same subject	2 / semester	3 / month
Num. of interactions with students outside the classroom / week	0 – 3	5 – 10
Resources needed for practical activities	0 – 100 € / student for practical sessions	300 – 500€ / group for prototyping tasks
Hours devoted by the teachers outside the classroom / class hour	0.5 – 1	3 – 4

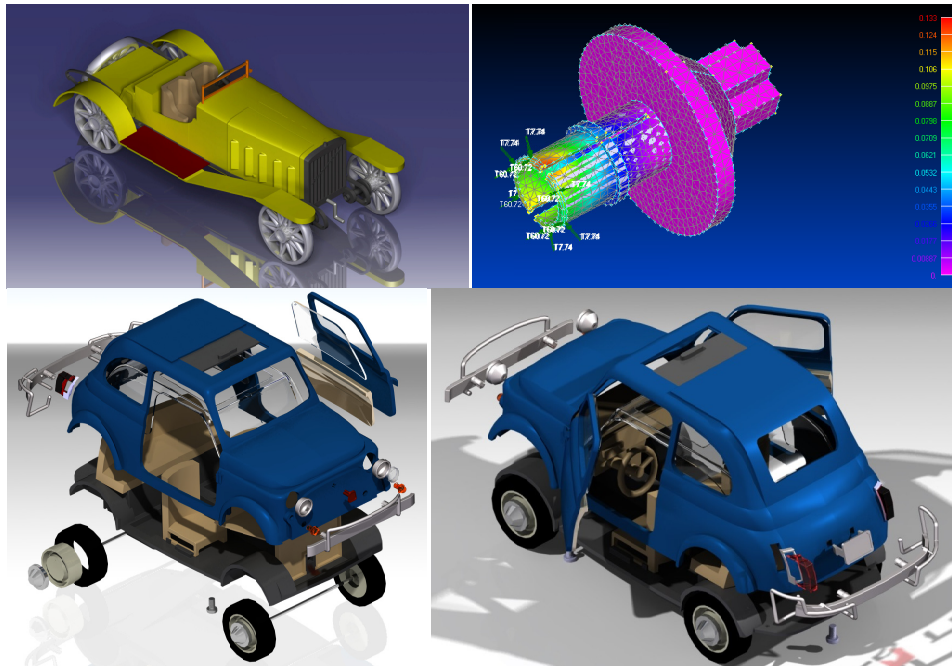


Figure 2. Examples from monographic year devoted to toy car design. Computer-aided designs and simulations for design optimization. (Students' designs).

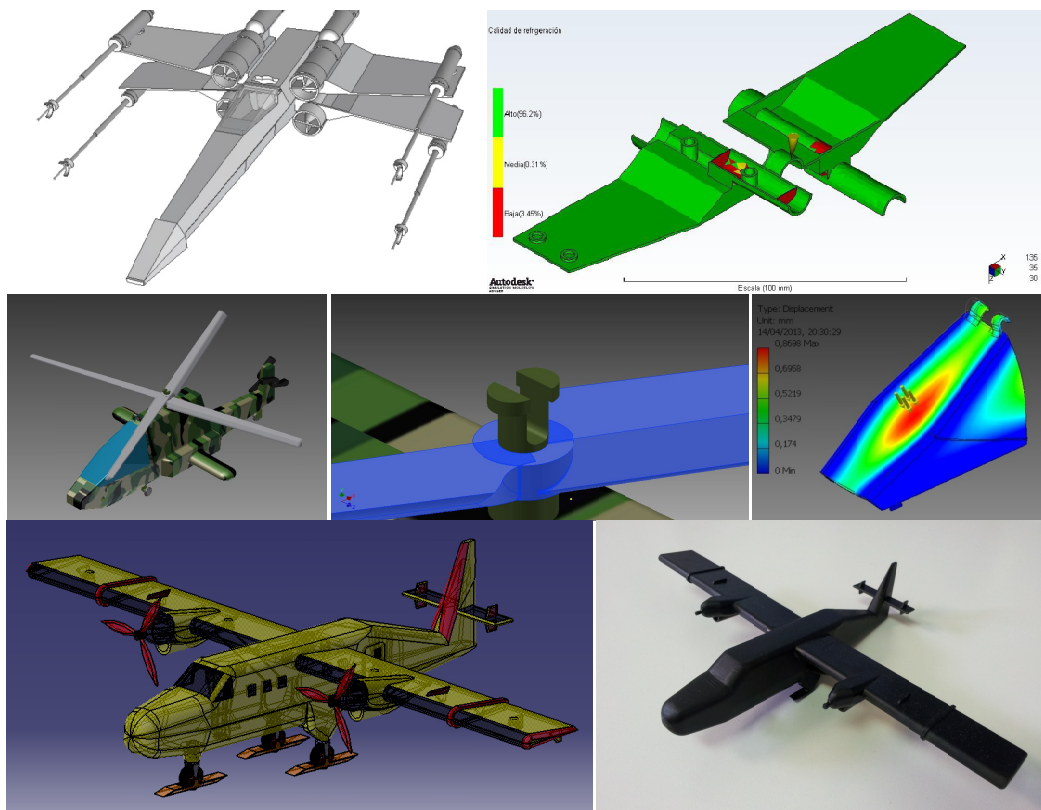


Figure 3. Examples from monographic year devoted to toy plane design. Computer-aided designs, simulations for design optimization and prototypes. (Students' designs). Prototype: UPM's Product Development Laboratory.

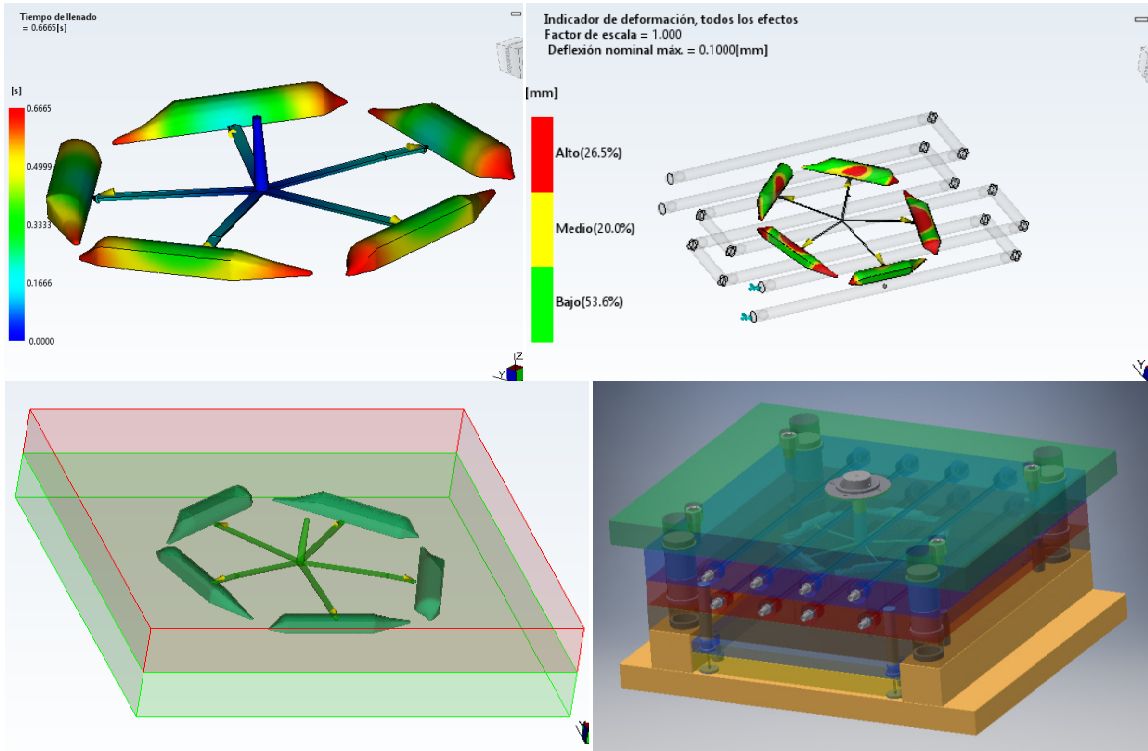


Figure 4. Examples of injection mold design towards mass-production. Filling time analysis, part quality assessment, refrigeration system design and mold structure. (Students' designs).

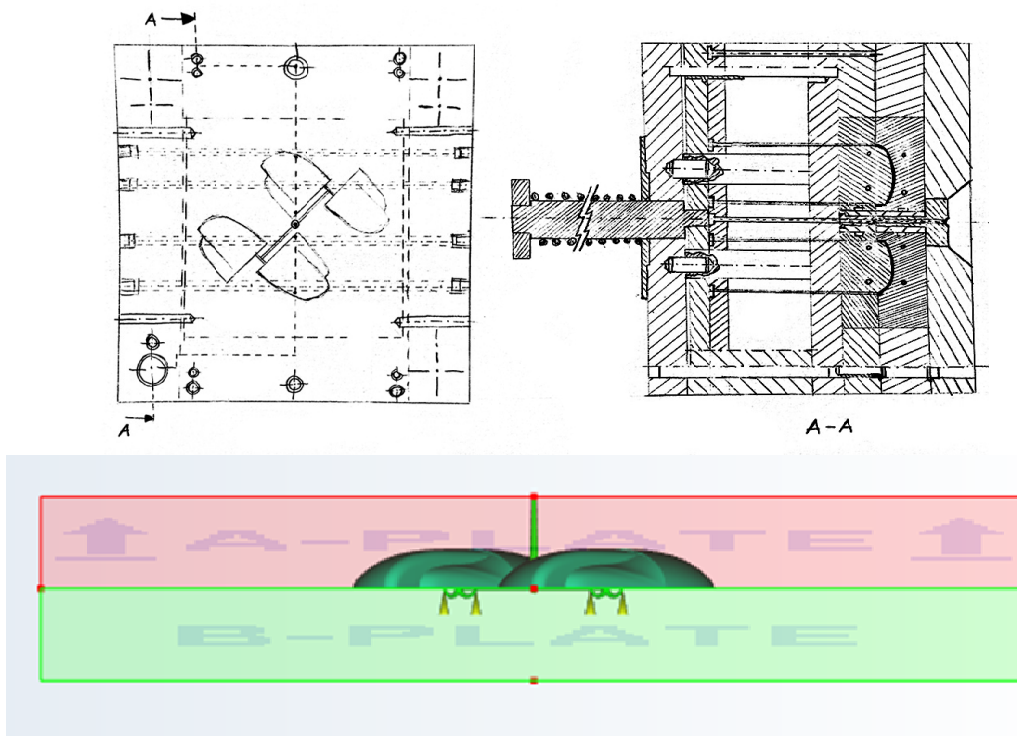


Figure 5. Mold concept and final computer-aided design of the mold. (Students' designs).

LESSONS LEARNED AND MAIN FUTURE CHALLENGES

Main lesson for the professors of the course is that implementing courses following this CDIO “play-based” approach is extremely motivating and gratifying for students, whose learning is promoted, but also constitutes a source of continuous learning and improvement for the teachers, who every year live with the students the development of novel engineering products and processes. However, in order to promote quality of results, these courses must be re-invented every year, for instance by changing the topics for projects development or by adjusting the different steps of the methodology. This helps to avoid students’ copying from companions from previous years and to provide them with a feeling of exclusivity and innovation. All this is time-demanding for teachers but enormously enriching.

Computer-aided design and engineering resources

The employment within the course of state-of-the-art computer-aided design and engineering resources, used by professionals in the plastic industry, helps to increase student motivation and to prepare them for their forthcoming professional practice, allowing them to obtain hands-on experience in relevant tools for daily engineering practice, as a complement to the technical knowledge acquired along the course.

“Fab-labs” and 3D printing hubs

Access to prototyping facilities, as a support to the *in silico* assessment of design viability, is an additional source of motivation for students and can be cost-effective indeed, if only the best designs are manufactured, which promotes healthy competition and enhances results.

e-Platforms for project management and collaborative design

Among future proposals for continued improvement, we believe that the use of e-platforms for promoting collaborative design tasks among the different groups of student may help to tackle more demanding projects and to further promote teamwork skills. If adequately implemented and used, they can help to promote approaches linked to “Engineering Education for all” (Díaz Lantada, 2016).

Collaboration between academia and industry

Regarding additional challenges, we would also like to explore the possibility of transforming the course into a whole-year subject with a larger amount of credits (i.e. 12 ECTS) for letting students live through an even more complete CDIO cycle, in which they could reach the mold manufacture stage and produce series of products to validate the whole approach and check the expected quality. Eventually we could link the design projects with real needs from the local industry, for instance aiming at the complete development of plastic parts for the automotive or aeronautic sectors, in which a polymeric component would be required to fit into a pre-existing assembly of parts of different materials and obtained with different processes. This would provide students with more complex specifications and let them work in an even more real professional environment.

CONCLUSIONS

We have presented a CDIO-based “complete toy design experience” within our course on “Design and manufacturing with polymers” and main results from implementation and evolution along a whole decade at ETSI Industriales – UPM. This experience constitutes one of the first integral applications of the CDIO methodology to the field of Industrial Engineering in our country and stands out its being linked to a “learning through play” approach. Around 500 students have taken part in these course and more than 200 real toys, together with the related injection molding mass-production tools, have been designed during the last ten years. The impact in the professional development of students and in teachers’ perspective about their own professional practice at University is noteworthy. This constitutes one of the longest running CDIO experiences in the field of product design and manufacturing.

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BIOGRAPHICAL INFORMATION

Dr. Andrés Díaz Lantada received his M.Sc. and Ph.D. degrees in Industrial Engineering (Mechanical Engineering major) from Universidad Politécnica de Madrid in 2005 and 2009 respectively. He is currently Associate Professor Professor in the Department of Mechanical Engineering at ETSI Industriales – UPM. He is Editorial Board Member of the International Journal of Engineering Education and CDIO contact at UPM. He received the “UPM Young Researcher Award” and the “UPM Teaching Innovation Award”, both in 2014, and the “Medal of the Spanish Academy of Engineering to Young Researchers” in 2015.

Dr. Juan de Juanes Márquez Sevillano received his M. Sc. and Ph.D. degrees in Industrial Engineering (Mechanical Engineering major) from Universidad Politécnica de Madrid in 1993 and 1998 respectively. He is currently Associate Professor in the Department of Mechanical Engineering & Manufacturing Engineering at ETSII-UPM. He has been visiting professor in the George W. Woodruff School of Mechanical Engineering at Georgia Institute of Technology in 1996, 2005 and 2009. He has led several research and educational innovation projects and he is Head of the Educational Innovation Group of Manufacturing Engineering at UPM. He received the “UPM Teaching Innovation Award in 2013”. He is currently Vice-Dean for Student Affairs and International Relations at the School of Industrial Engineering at ETSI Industriales – UPM.

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