Project-Based Learning of CAD/CAE Tools for the Integrated Design of Automatic Machines

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Abstract. This paper reports about project-based learning activities carried out within the course of *Design of Automatic Machines* at the *University of Genova*. This didactic experience, provided to the students enrolled in the second-level degree in Mechanical Engineering, aims at providing the knowledge of those methods and tools required to optimally design functional parts of automatic machines, here including the mechanical architecture and the actuation subsystem. Lecture hours are equally devoted to the introduction of theoretical concepts and to lab exercises, which leverage on the extensive and advanced use of dedicated CAD/CAE software tools (i.e. *PTC Creo*). In particular, the projects are related to the in-depth study of automated packaging systems, initial (sub-optimal) design solutions being provided by an industrial partner with years of practice in the sector. After a description of the educational goals, the presentation discusses the phases of the activity and the main methodological aspects. In addition, the adopted tools for the design and simulation of the developed systems are discussed in detail.

Keywords: CAD/CAE tools · Design parametrization · CAD-based shape optimization

1 Introduction

Nowadays, Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) software have unquestionably become indispensable tools on a world basis, whose advanced knowledge is necessary for young engineers taking their first steps into the competitive industrial scenario. CAD/CAE environments are indeed extensively used in several fields, including aerospace, automotive, earth-moving machines and automated plants (such as automatic machines for packaging) [1]. At the current state-of-the-art, these virtual prototyping technologies allow to simulate mechanical and mechatronic systems, starting from the geometrical and parametric representation of parts, the study of complex devices during their motion (i.e. multibody analysis), the verification and, possibly, optimization of their structural behavior (stresses and deformations). In the current literature [2, 3], it is claimed that modern CAD/CAE may soon become so advanced to simulate mechanical systems with a degree of reliability comparable to physical testing, although with the obvious advantage in terms of cost

F. Cavas-Martínez et al. (Eds.): *Advances on Mechanics, Design Engineering and Manufacturing II*, LNME, pp. 798–809, 2019.
https://doi.org/10.1007/978-3-030-12346-8_78

saving and capability to virtually test the performance of several design variants in a time efficient manner. In addition, most of the commercial CAD software available on the market (such as *SolidWorks*, *Catia*, *SolidEdge*, *Siemens NX*, *PTC Creo*, etc.), can provide this set of capabilities in a single, integrated environment.

Within this framework, the objective of the present paper is to provide an overview of the CAD/CAE teaching activities carried out at the *University of Genova*. Basically, two design tools are widely employed in the engineering curricula:

- *Bentley Microstation*, taught during the first level degree in Engineering. Despite its capabilities, the practical use of this tool is currently narrowed to the generation of 2D drafting for simple mechanical parts and schemes;
- *PTC Creo*, which is employed as the first 3D CAD tool introduced to students and it is presented during the last year of the first-level degree and, more in depth, during the second-level degree. *PTC Creo* enables an integrated approach in the design of a machine subsystem, and comprises a standard parametric CAD interface, a basic but effective multibody suite (*Creo Mechanism*), a suite for finite element analysis (*Creo Simulate*), and a built-in optimizer (*Creo Behavioral*), that can seamlessly operate on all the virtual prototype parameters (e.g. shape of parts, material properties, dynamic/kinematic variables, information about part structural behavior).

For what concerns the specific course named *Design of Automatic Machines* (i.e. the main topic of the present paper) advanced skills in the use of *Creo* are taught by means of a Project-Based Learning (PjBL) activities [4–7].

As for basic terminology, Problem-Based Learning (PBL) can be defined as an approach managing the learning process in such a way that students are stimulated to autonomously achieve solutions. Teachers and pedagogues have always reckoned the effectiveness of this method. Today, many authors differentiate between PBL and PjBL [8, 9]: the distinction is mainly based on the acknowledgment that PBL is defined by open-ended and not-well-structured problems that provide a context for learning. On the opposite, PjBL may be interpreted as an assignment or a set of tasks that the students have to perform.

PjBL is often seen a synonymous of PBL as both are student-centered methods for learning. Some experts [10] suggest indeed that PBL can only be faced in small groups and nobodies believe that PjBL can be undertaken individually. An important difference between the two approaches is that in PjBL students must generate a result in form of a report or design. In PBL, the focus is not on this kind of outcome: the tutor supervises the project and students are required to produce a solution or strategy to solve the problem. In PBL, solving the problem is part of the process, but the attention is on the problem-management, not on a clear and fixed solution. The focus in PBL is on students working out their own learning requirements so PjBL often occurs at the end of a degree program after a proper set of knowledge has been given the students the skill to face the project. PjBL can be considered as an effective mechanism for tying together several subjects under one bigger activity at the end of a course. Summing up, PjBL is a growing area of interest within engineering education, as also shown in recent literature. For instance, a description of active education methodologies can be found in [11]: in this case, engineering students have to deal with the requests of a real customer, an important aspect being the constant maintenance of a proper and professional relationship with the company itself. Another actual example of multidisciplinary didactic project is described in [12], where students and professors from different departments combine skills in the design process of new products, eventually fabricated with 3D printing FDM technology. In both cases, the possibility to interact with real problems, after an established theoretical background, shows positive results and very encouraging feedbacks from students. However, there are some barriers that inhibit the PjBL wider integration within the engineering curriculum, in fact:

- PjBL is identified as one of the most resource-intensive elements of the current engineering curriculum, often demanding tailored learning spaces, materials, tools and equipment as well as requiring significant time from faculty and support staff.
- Many engineering faculty teachers have got little confidence and knowledge in the design and application of student assessment processes in PjBL. For this reason, perhaps, many PjBL experiences are highly structured and employ a wide range of different cumulative assessment processes within a single activity, with high workload for both staff and students.

In the specific case of the course *Design of Automatic Machines*, activated since the academic year 2015–2016, the required resources are limited, as for all the practical activities are computer-based. Furthermore, the absence of heavy simulations from a computational point of view (e.g. non-linear FEM, CFD, etc.), allows to deal with all calculations in the University computer labs. The course provides 6 credits (i.e. ECTS —European Credit Transfer System), that are equally divided into hours of theoretical lessons about architectures and design aspects of automatic machines, and hours of CAE exercises. During the exercise sessions, the teachers show to the class different types of CAE-based simulations and design approaches (as described in the following). In particular, the practical part starts with a seminar given by a well-trained engineer from industry, whose role is to present a design problem related to the fascinating world of automatic machines. An initial design solution (i.e. the mechanical architecture of a machine subsystem) is shown to the students at the very beginning of the course. The students, divided in small groups of 2–4 people, are then required to go through the overall design process (here including possible design improvements achieved by the use of Creo Behavioral). The educational goals of the PjBL activities may be outlined as follows:

- To understand the chain of virtual prototyping activities ideally required before physical testing (identification of the mechanical systems architecture, motion analysis, structural analysis, actuator selection, design optimization);
- To provide methodological indications on how to go through the development process of a mechanical/mechatronic system;
- To achieve advanced specific skills in the use of modern, industrially relevant, design and simulation tools, namely: (i) parametric CAD, (ii) integrated multibody environment for motion analysis; (iii) integrated FEM environment for the structural verification of parts in the worst load-case scenario; (iv) integrated optimization routines for design improvement.

- To train the capability for analyzing/describing an engineering problem, to work in a group (and not individually), to generate and evaluate solutions under a concurrent set of design constraints, to present the results of the work (via written report and oral exposition), not neglecting a critical review of the achieved results.
- To stimulate students' creativity, practically involved, for the first time in their career, in the solution of a design problem of real interest for industry. Within the problem solving activity, emphasis is put on the comparative evaluation of design variants, which are (in most cases) directly available thanks to system parametrization.

At the end of the PjBL activity the students have potentially gained an insight of the problem, along with the knowledge of the capabilities and potentiality of the CAD/CAE integrated environment. Only at this stage, each group is required to propose a novel machine architecture and to write a detailed report about the previously assigned project activity. At the end of the course, all the design steps, comprising the new architecture and the proposed improvements, are critically discussed in an oral presentation, which represents the 50% of the final exam. The remaining part of the exam includes a written and oral test, based on the theoretical topics presented during the course.

2 Activity Organization—Problem Overview

A PjBL case study, carried out in the past year, is depicted in Fig. 1, which provides a schematic of an Automatic Machine for packaging of paper rolls with different formats.[1] The paper rolls are piled up and, subsequently, conveyed to a couple of elevators. The motion of the elevator plates is achieved by means of two slider-crank mechanisms, each driven by a brushless servomotor (not shown in the picture), which allows a very precise position control of the plates. These elevators transfer the paper rolls to the upper part of the machine, where the paper rolls envelope (a plastic film) is applied. In the current embodiment design, one elevator starts the returning (downward) stroke before the other (as clearly shown in Fig. 2), in order to allow the application of the plastic film also underneath the paper rolls. Given this case study, the PjBL activity is divided into several steps, also underlined in Fig. 1.

As previously introduced, the course starts with a seminar, in which an engineer from industry presents the design problem and provides the main specs and requirements of the automatic machine, in particular of each sub-system (e.g. elevator mechanism in Fig. 1).

Then, starting from an initial configuration presented during the seminar, the design process is organized with a sequential approach. In particular, the main steps and related CAD/CAE tools are as follows:

[1] A video showing the motion of the machine sub-systems can be found at: https://www.youtube.com/watch?v=UhUeZ3cv0DQ.

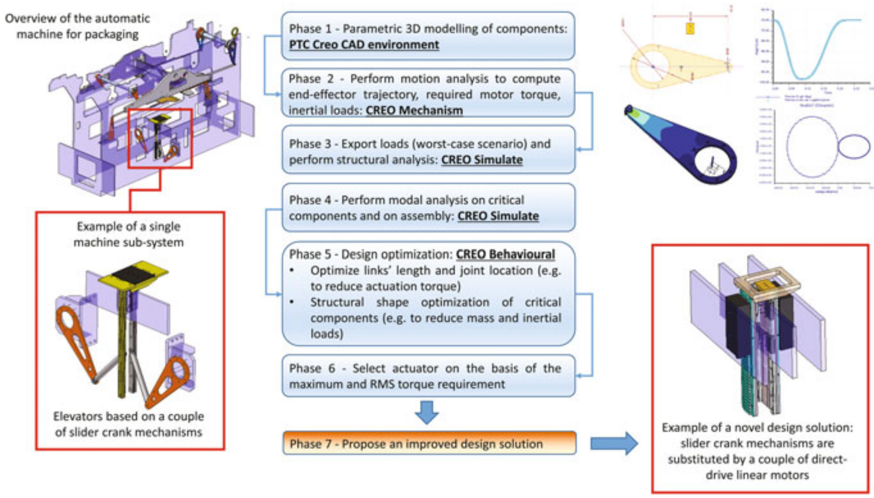

Fig. 1. Case study and design phases employed in the PjBL activity

- **Phase 1—PTC Creo CAD**: Parametric 3D modelling of (some) parts of the mechanical system.
- **Phase 2—PTC Creo Mechanism**: Motion analysis based on the end-effector's requirements, evaluation of the motor torque and of the inertial loads acting on a specific member (e.g. crank in Fig. 1).
- **Phase 3—PTC Creo Simulate**: Structural analysis for evaluating stress-strain condition on the members (e.g. crank in Fig. 1).
- **Phase 4—PTC Creo Simulate:** Modal analysis on each component and on the complete assembly in order to verify/avoid resonance during the machine working cycle.
- **Phase 5—PTC Creo Behavioural**: Shape optimization of a member based on a single objective function (e.g. stress condition).
- **Phase 6—PTC Creo Mechanism + Excel**: Selection of the actuator based on *rms* and *maximum* required torque [13].
- **Phase 7**: proposal and critical evaluation of novel design solutions.

Naturally, the design process is not completely sequential and several iterations are always necessary due to the presence of critical aspects (e.g. unacceptable stress-strain condition evaluated in Phase 3, different shapes evaluated in Phase 5, etc.), that could request the review of previous phases. As said, the last part of the learning experience requires the student to propose a novel, possibly improved, machine architecture complying with the project requirements. A possible design solution, depicted in the rightmost part of Fig. 1, is based on the use of direct-drive brushless linear motors (with obvious simplification of the system, despite increased installation cost).

3 Embodiment of the Mechanical Model and First Simulations

The initial industrial seminar ends up with the assignment of the mechanism's geometry and its detailed description, in terms of functionality of each member and related dimensions. Then, after these necessary indications, all the work-groups can deal with the case-study under the supervision of the professors. As previously said, the Phase 1 is totally dedicated at the 3D modelling of the sub-system within the PTC Creo Parametric environment. In particular, the CAD exercise is limited to the components directly involved in the simulations (Phase 2–6), since the secondary components (e.g. external structure, etc.) are provided in order to save time. Particular attention is paid to the assembly process, in order to avoid problems during all the next simulations in the *PTC Creo* integrated environment. Once the parametric mechanical model is obtained, an inverse kinematic analysis is needed to extrapolate the desired motion law at the motor shafts.

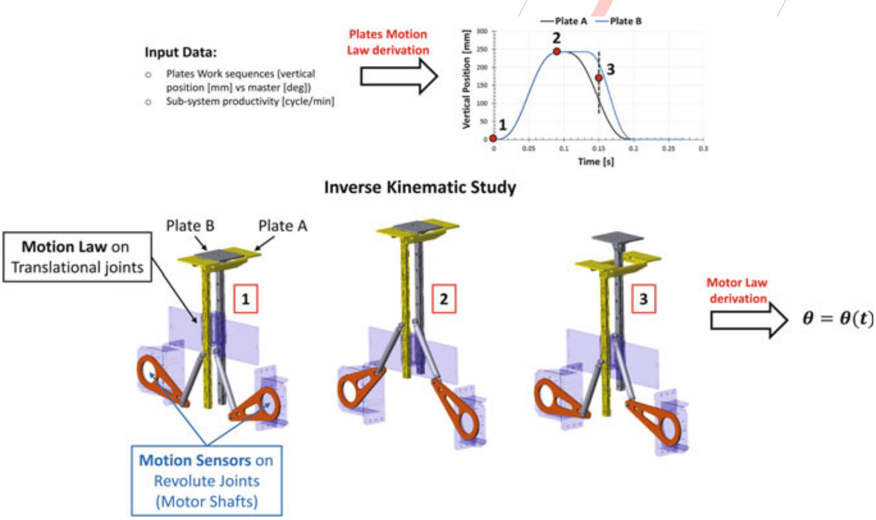

Fig. 2. Inverse kinematic: evaluation of the motion laws

The procedure (depicted in Fig. 2) starts from the motion requirements (position $[mm]$ vs master $[deg]$) assigned to the sub-system end-effectors (in this case, the two plates, Plate A and B, represented in Fig. 2). The translational motion laws, that have to be assigned in the multi-body environment (*Creo Mechanism*) in order to perform an inverse kinematic study, are evaluated on the basis of the machine's productivity ($[cycles/min]$).

Then, the final rotational motion laws ($\theta_i = \theta(t), i = 1, 2$) are evaluated through "motion sensors" on the motor shafts. The Phase 2 closes with a kineto-dynamic analysis, in which the $\theta_i = \theta(t), i = 1, 2$ laws are applied at the motor axis, while different "force sensors" are exploited for recording the inertial loads on the mechanism's components. In particular, for the reported example, the subject of the study is the crank member.

4 Structural and Modal Simulations

During the post-processing step of the previous kineto-dynamic simulation, the worst load case is automatically transferred from the multi-body environment (*Creo Mechanism*) to the structural environment (*Creo Simulate*). The integrated PTC Creo architecture allows the user to easily export all necessary information (e.g. position and module of load's vector) and to change the nature of the analysis. In the specific case depicted in Fig. 3, the crank is simulated with the FEM method in order to verify the stress-strain condition in the worst inertial load-case scenario. This approach is conservative since only the worst condition, that is a combination of single loads registered at different time-steps in the previous analysis, is tested. However, the application of the load condition in static analysis, instead of dynamic conditions, represents an important limit of the procedure. This is due to the nature of the software, that includes different simulation environments and a useful connection for data-exchange between them, even if it does not allow to perform Multi-Flexible-Body-Dynamic simulations, which is only manageable in specific CAE tools (e.g. RecurDyn [14] or Adams [15]). Once verified the correct location and direction of the load condition on the crank member, the students have to deal with the meshing step and the imposition of the boundary condition. In particular, while respecting the software's limits in terms of mesher-options, a great part of the study is focused on mesh-convergence analysis and, if necessary, on local mesh-refinement. Furthermore, the need to exclude a precise number of degree-of-freedom for the static analysis convergence represents another important issue for the boundary condition setting. The didactical purpose, at this step of the exercise, is totally concentrated in the selection of the correct constraints-set, in order to maintain coherence between the multi-body mechanism and the FEM structure from the functional point of view. The complete procedure is depicted in Fig. 3.

As it may be self-evident, Phase 3 represents the first critical point of the design process, since a re-design of the mechanical part may be necessary if the stress-strain results highlight local (unacceptable) stress concentrations or global (unacceptable) part deformations. Then, Phase 4 introduces another important aspect of the mechanism's analysis/design, proposed only from a theoretical point of view in the most part of engineering programs. The modal analyses, carried out in *Creo Simulate*, are firstly performed on each single component involved in the motion and, subsequently, on the complete assembly. Exactly like the structural analysis, also in Phase 4, the selection and discussion of the constraints-set becomes an essential step. In fact, even if the FEM solver provides feasible results for different boundary conditions, the students have to recognize the correct configuration in order to extrapolate important data in the post-processing and conclude the study.

Concerning the mechanism considered in this paper, a qualitative example of modal analysis on a single component is reported in Fig. 4, in which the crank model is initially tested in free-free configuration.

From the practical point of view, all the simulation results (natural frequencies and related modes) have to be compared to the dynamic loads acting on the component, in

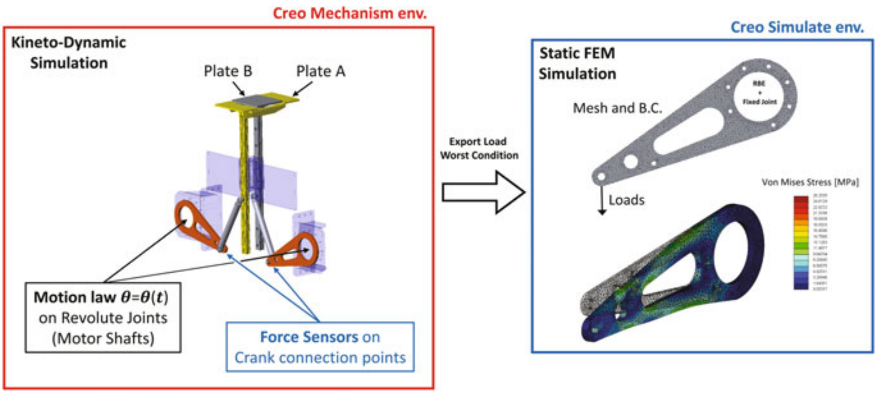

Fig. 3. FEM simulation on crank member with worst load condition

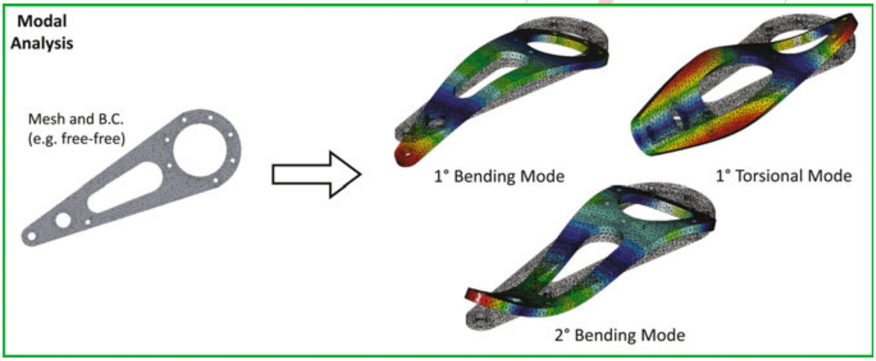

Fig. 4. Modal analysis on crank: qualitative example

order to verify the possible presence of resonances during machine's work. In most cases, after the analysis performed during Phase 3–4, the students suggest some adjustment to the CAD model, in order to correct all the detected critical issues.

5 Design Improvements and Actuator Selection

The last part of the analysis/design process, composed of Phase 5–6, exploits *Creo Behavioural* for possible performance improvements (e.g. shape optimization) and *Creo Mechanism* for what concerns the motor selection. In particular, after the previous simulation steps (Phase 1–4), the students are invited to find feasible solutions for any critical issue (e.g. Von Mises stress or motor torque exceeding acceptable limits, collisions and/or incorrect phasing due to badly designed initial trajectories, dangerous natural frequencies, etc.). Even if these problems are usually described by simple monotonic objective functions and their solution can be achieved with only basic-theoretical approach, the internal optimization toolkit is exploited in order to give to the students a complete overview of the PTC Creo environment. Considering the case study reported in this paper, a simple optimization study on the crank member can be formulated as follow:

$$\begin{aligned} &\textbf{Minimize}\, \tau_R = \tau_R(l_c) \\ &\textbf{Subject to}\, l_c \in [l_{c_{\min}}, l_{c_{\max}}] \end{aligned} \tag{1}$$

where τ_R is the reaction torque at the motor shaft and l_c is the crank's length. The results of this study, for both crank modules, are easily predictable, since τ_R increases linearly with l_c and, as a consequence, the optimal solution is the lower bound adopted.

However, this simple example allows to explain in an easy way the advantages of using a parametric CAD-CAE tool for sensitivity analysis.

Once defined the final design of the sub-system, in other words after the last geometry update as result of the iterative design process (Phase 1–5), a fast CAD-CAE based approach is applied for the servomotors selection [16]. The procedure, which exploits also Excel (or Matlab) for numerical integration during post-processing, is divided in two steps:

- Derivation of Speed-Torque curve at the motor shaft;
- Computation of the reduced moment of inertia, J_{red}, at the motor shaft.

Since the example reported in the paper is characterized by two modules (named A and B in Fig. 5), also this procedure selection has to be repeated twice. This first step can be achieved with a single kineto-dynamic simulation, where the kinematic input is a cycloidal law, that allows to investigate both negative and positive velocities. A torque sensor is placed on the same actuated rotational joint (as shown in Fig. 5), in order to record the reaction torque at each time-step.

Concerning the second step, the procedure requires two kineto-dynamic simulations (for each module), followed by a numerical integration process, which provides J_{red}, defined with Lagrange formulation:

$$J_{red} = \int_{\theta_{min}}^{\theta_{max}} J'_{red} d\theta + J(0) \tag{2}$$

where θ_{min} and θ_{max} are the lower and upper limit of the module's operative range (different for A and B), J'_{red} is the derivative of J_{red} with respect to θ and $J(0)$ is the integration constant. Once concluded the data post-processing, students have to compare different industrial manuals for the selection of the brushless actuators. The basic theory related to possible strategies for numerically computing the reduced moment of inertia, whose discussion goes beyond the purpose of the present paper, can be found in [17].

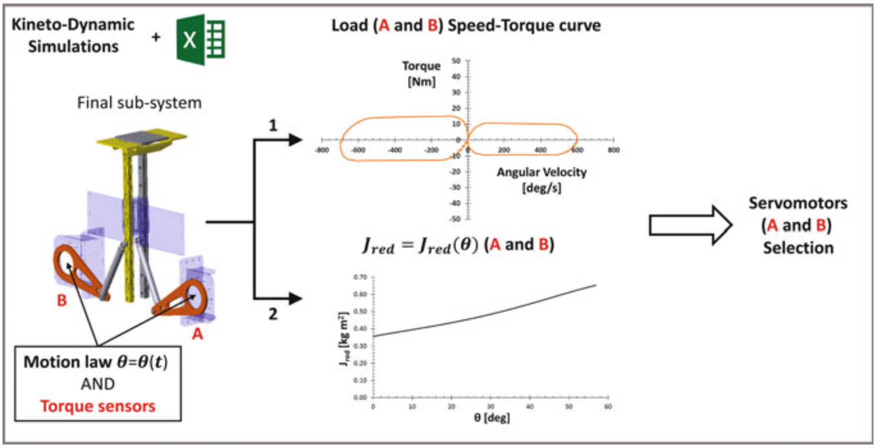

Fig. 5. CAD-CAE procedures for servomotors selection

6 Discussion and Statistics

As reported in [5], the effective development of PjBL activity in the Mechanical Engineering curriculum is outcome of several interacting factors, namely:

- The level of interest shown by the students that, on the basis of the authors' experience, is strongly stimulated by the initial industrial seminar, which underlines the real interest of industrial companies in the overall activity outcomes.
- An adequate choice of the project to be developed, that should balance between a sufficient level of difficulty and time constraints to be faced by students (due to other curricula activities carried out in parallel with the course described in the paper).
- A solid background in the most important disciplines of mechanical engineering (e.g. Industrial Technical Drawing and basic 3D CAD knowledge, Machine Design, Mechanics of Machines). In fact, the proposed PjBL activity can be hardly proposed to students at the early stages of their technical education.

The opinions of the students about the PjBL activity, collected at the end of both academic years, are summarized in Fig. 6. In particular, the statistics refers to a number of students equal, respectively, to 10 for the academic year 2015–2016 and to 16 for the academic year 2016–2017. The positive trend of the collected feedbacks stimulates to continue this kind of didactic approach.

Topic	Year	Absolutely NO [%]	More NO than YES [%]	More YES than NO [%]	Absolutely YES [%]	No response [%]
PjBL's efficacy for didactical purpose	2015-2016	0	11.11	0	66.67	22.22
	2016-2017	0	0	12.5	62.5	25
Quality of teaching and acquired skills	2015-2016	0	0	0	77.78	22.22
	2016-2017	0	0	0	100	0
Consistency with theoretical background	2015-2016	0	0	22.22	55.56	22.22
	2016-2017	0	0	25	75	0

Fig. 6. PjBL activity students' opinion

7 Conclusion

In conclusion, the PjBL activities recently introduced within the course of *Design of Automatic Machines* (Master degree in Mechanical Engineering) at the University of Genova have been here shortly presented. The first outcomes from this experience are showing a strong enthusiasm of the involved students that, for the first time in their academic career, play an active role in devising new design solutions and their optimization through well-known standard methods and advanced software tools (e.g. PTC Creo).

Considering the question "does problem-based learning work in engineering?", it is clear that there are obstacles to its implementation across a whole engineering program.

This issue is related to the nature of engineering knowledge and practice compared to other disciplines (e.g. medicine), where PBL has been widely adopted. Professional problem-solving skills in engineering require the ability to reach a solution using data that are usually incomplete, while trying to poise demands that are usually in conflict (e.g. customer requirements in terms of productivity/reliability and cost minimization). Therefore, it seems that PjBL is likely to be an effective way to introduce students to the actual issues to be faced in their future working careers and the use of PjBL as a key component of engineering programs should be promulgated as widely as possible, since any improvement to the existing lecture-centric programs that dominate engineering would be strongly welcomed by students and industry.

References

1. Leondes CT (1998) Computer-Aided Design/Engineering (CAD/CAE) techniques and their applications, vol. 58. Academic Press
2. Um D (2017) Solid modeling and applications rapid prototyping, CAD and CAE Theory. Springer
3. Pratt MJ (1995) Virtual prototypes and product models in mechanical engineering. Virtual Prototyping 113–128
4. Chua KJ (2014) A comparative study on first-time and experienced project-based learning students in an engineering design module. Eur J Eng Educ 39(5):556–572
5. Vassura G, Macchelli A (2008) Multi-disciplinary tutoring for project-based mechatronics learning. IFAC Proceedings Volumes 41(2)
6. Hall W, Palmer S, Bennett M (2012) A longitudinal evaluation of a project-based learning initiative in an engineering undergraduate programme. Eur J Eng Educ 37(2):155–165
7. Rudtsch V, Bauer F, Gausemeier J (2013) Approach for the conceptual design validation of production systems using automated simulation-model generation. Procedia Comput Sci 16:69–78
8. Prince JM, Felder MR (2006) Inductive teaching and learning methods definitions, comparisons, and research bases. J Eng Educ 95(2):123–138
9. Savin-Baden M (2000) Problem-based learning in higher education: untold stories
10. Barrows HS, Tamblyn RM (1980) Problem-based learning: an approach to medical education. Springer Publishing Company

11. Biedermann A, Lopez NM, Tierz AS (2017) Developing students' skills through real projects and service learning methodology. In: Advances on mechanics, design engineering and manufacturing. Springer, pp 951–960
12. Thomnn G, Morais F, Werba C (2017) How to teach interdisciplinary: case study for Product Design in Assistive Technology. In: Advances on Mechanics, Design Engineering and Manufacturing. Springer, pp 931–939
13. Isermann R (2005) Mechatronic systems fundamentals. Springer, London
14. www.functionbay.org. Accessed: 25 Feb 2018
15. www.mscsoftware.com/product/adams-maxflex. Accessed: 25 Feb 2018
16. Giberti H, Cinquemani S, Legnani G (2011) A practical approach to the selection of the motor-reducer unit in electric drive systems. Mech Based Des Struct Mach 39(3):303–319
17. Berselli G, Balugani F, Pellicciari M, Gadaleta M (2016) Energy-optimal motions for servo-systems: a comparison of spline interpolants and performance indexes using a CAD-based approach. Robot Comput-Integr Manuf 40:55–65