# REDESIGN OF AN ENGINEERING CURRICULUM BASED ON FOUR INTEGRATED LEARNING PROJECTS

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**Abstract**
École Polytechnique de Montréal is currently redesigning all its programs to prepare its future engineers to the realities facing the industry of the 21st century. Based on the CDIO initiative, the Mechanical Engineering curriculum is now articulated around four major design projects, which constitute a cohesive chain of learning experiences.

For the first year project, a general design methodology is taught but the students apply only specific parts of this approach. In the second year project, the complete design methodology is used; prototypes are built and tested in a team competition. The third year project is an individual assignment where students have to demonstrate autonomy and initiative when solving an engineering project. The fourth year project is team based over two semesters and focuses on the design and implementation of a complex design exercise. During this final year project, the students are supervised by engineers working in industry and are evaluated on skills such as team communication, project management and technical know-how.

This paper describes some of the most important issues of the implementation of the CDIO based program. The overall objective to foster multidisciplinary team-based experiences through integrated learning projects is also discussed in this paper.

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## Introduction

École Polytechnique de Montréal is one of the largest engineering schools in Canada with 3700 undergraduate students and 1700 postgraduate students distributed in 11 different engineering programs. All the undergraduate programs are currently being redesigned to meet the expectations of the 21st century industrial world.

This global revision project comprises a number of requirements which need to be met by all engineering programs. These include a program specific first year (instead of a first year common to all disciplines), project based learning activities in each year, and more emphasis on "soft skills", e.g. communication and management skills. The objective is to include these new requirements within the various curricula while maintaining the strong scientific content which has been the hallmark of École Polytechnique since its foundation in 1873. For the Mechanical

Engineering program, the CDIO initiative was evaluated and was found to fulfill all the global requirements set out by the Academic council and more. It offered the advantage of a clearly defined implementation process and a proven international benchmark to work with.

In the next section, the paper first describes the evolution of the CDIO implementation before detailing, in the third section, the contents of the new mechanical engineering curriculum. The fourth section outlines the premises for a multidisciplinary team-based learning experience, which will hopefully be offered to all fourth year students within the next 2 years pending governmental approval.

## The CDIO initiative and its implementation framework at École Polytechnique

Until the early 1990s, a majority of the mechanical engineers freshly graduated from École Polytechnique would join large manufacturing firms, where senior engineers would mentor the new recruits to develop their engineering knowledge and expertise in a professional context. The traditional role of the university was therefore to provide its students with the necessary theoretical and background knowledge in engineering, while employers would train new recruits internally to develop their know-how and professional skills.

Nevertheless, in the past 15 years, the profile of companies recruiting junior engineers in the manufacturing sector has changed rapidly. Indeed, graduates are now mainly employed by small and medium size companies, where engineers are expected to be completely operational as soon as they are recruited. The recent effects of globalization have also imposed new constraints upon industrial practices; engineers are nowadays working in highly distributed teams, where new communication and collaborative tools, such as videoconferencing or digital product technologies, are key to success. This section will therefore present how the Mechanical Engineering curriculum at École Polytechnique has evolved within this context.

### *The Mechanical Engineering curriculum prior to 2004*

The department of Mechanical Engineering at École Polytechnique has always benefited from a solid reputation amongst prospective students and future employers. The program covers a wide range of specialized disciplines and the number of students enrolled has always been very stable. The employment rate is high and graduates find work rapidly. However, the enrollment was declining steadily in the last 3 years.

Until 2004, the various engineering curricula followed the same core characteristics:

- A common first year, comprised of courses in mathematics, physics, materials, drafting and a common introduction to Design and the engineering profession,
- Three years of specialization in each engineering discipline including a backbone of compulsory engineering topics which define the essence of each program with an individual capstone engineering project in Fourth year,
- More specifically in the Mechanical Engineering program, which is taken by an average of 200 students per year, a large number of options and independent courses which enable students to create their own educational profile particularly in their last two years, including aeronautics, astronautics, mechatronics, AEC, automotive, railway engineering, design and analysis and finally manufacturing,

- The programs all offered the possibility of a voluntary internship that could last from 4 to 16 months and also international exchanges in 140 institutions around the world for one or two semesters.

The mechanical engineering program was therefore chosen by an average of 200 students entering their second year of studies. This relatively large class has enabled the department to offer a vast number of elective courses and options; a strength that the new curriculum needed to preserve. Although the program offered very flexible educational profiles, an important number of students was found to avoid the various sequences of studies recommended by the department. The reasons were essentially related to the workload imposed by teachers in a highly modular program, where each course was considered independently. In this context, it was easy for both students and professors to loose track of the overall curricular objectives, leading to excessive workloads in certain topics. Furthermore, it is also important to note that a majority of students now work part time (54% in 2003) in order to finance their studies.

***The CDIO implementation framework***

Since the curriculum review started before the committee was aware of the CDIO initiative, the implementation process had to be adapted to meet a very tight schedule. The project started at the beginning of 2004 and the redesigned curriculum had to be completed by the end of that year for a first year implementation in September 2005. The process did not start with a complete survey of the stakeholders. To speed up the implementation of CDIO within the new curriculum's framework, a survey of the professors only was used to design the first year of the curriculum. Based on previous surveys from MIT and other CDIO collaborators, we came to the conclusion that the results from the professors are to a first degree a good approximation of the stakeholder's survey.

To implement the first year, a subset to the CDIO syllabus outcomes, presented in Table 1, was thus selected. In Table 1, the numbers in the left hand column relate to the CDIO syllabus outcome number [] and the numbers in the right hand column represent the results based on Bloom's taxonomy with a maximum of five as generally used within the CDIO initiative. Numbers in parenthesis are the average for the rows below them (sub-outcomes). Efforts were concentrated on four major outcomes, those most important for the first year implementation and those that received the highest scores from the professors, namely "engineering reasoning", "personal skills", "communications" and "designing".

Table 1. The subset of the CDIO syllabus outcomes selected for the first year of the new curriculum implementation

| Outcome number | Description of the CDIO syllabus outcome and related *sub-outcomes* | Bloom's taxonomy results |
|---|---|---|
| **2.1** | **Engineering reasoning** | **(4.02)** |
| | *Problem Identification and Formulation* | 4,7 |
| | *Modeling* | 4,6 |
| | *Estimation and Qualitative Analysis* | 3,5 |
| | *Analysis With Uncertainty* | 3,1 |
| | *Solution and Recommendation* | 3,9 |
| **2.4** | **Personal skills** | **(3.44)** |
| | *Initiative and Willingness to Take Risks* | *3,3* |
| | *Perseverance and Flexibility* | *4,0* |
| | *Creative Thinking* | *4,1* |
| | *Critical Thinking* | *3,8* |
| | *Awareness of one's personal knowledge, skills and attitudes* | *3,1* |
| | *Curiosity and Lifelong Learning* | *3,2* |
| | *Time and Resource Management* | *2,9* |
| **3.2** | **Communications** | **(3.66)** |
| | *Communications strategy* | *2,9* |
| | *Communications structure* | *3,8* |
| | *Written communication* | *4,3* |
| | *Electronic/Multimedia Communication* | *3,0* |
| | *Graphical Communication* | *4,4* |
| | *Oral Presentation and Inter-Personal Communications* | *4,5* |
| **4.4** | **Designing** | **(4.06)** |
| | *The Design Process* | *4,6* |
| | *The Design Process Phasing and Approaches* | *3,9* |
| | *Utilization of Knowledge in Design* | *4,8* |
| | *Disciplinary Design* | *3,8* |
| | *Multidisciplinary Design* | *3,8* |
| | *Multi-Objective Design (DFX)* | *3,5* |

**The new Mechanical Engineering curriculum at École Polytechnique**

The various actors involved in the development, review and implementation of the new Mechanical Engineering program agreed upon a set of common values to achieve their goals. These can be described as follows:

- *Professionalism:* work ethic, integrity, rigor, honesty, and autonomy.

- *Attentiveness:* to the requirements of the society, to public safety, to the protection of the workforce, to the respect of the environment and built heritage.
- *Openness:* to others, to difference, to team work and to innovation.

Of course, these fundamental values must be taught to the students, but they must also be respected and applied by the teaching and administrative staff.

***Key aspects of the new program***

The fundamental values aforementioned were clustered in three areas of competence that need to be developed through the new curriculum, namely "scientific and technical knowledge", "professional skills", and "personal skills". The aim is to provide a cohesive learning strategy where students can gradually acquire a solid understanding of the environment in which complex product are developed. Although scientific and technical knowledge have always been strengths in the program, the weaknesses highlighted in the survey called for an improved approach to integrate professional and personal skills in the new curriculum so that graduates have the opportunity to become leaders in their field of expertise. To achieve this goal, the revision committee focused on the development of integrated learning projects.

In practice, this means that courses have been grouped to form cohesive chains of learning experiences within typical disciplines of the Mechanical Engineering domain. This approach fosters the development of a clear set of learning objectives and enables a high level of continuity between courses across the four-year program. The chains of learning experiences have been articulated around four design projects where students can apply their scientific and technical knowledge while progressively acquiring professional and personal skills. These integrated learning projects offer a unique opportunity for the teaching staff to evaluate the students and to provide sustained teaching support on more practical aspects of the engineering profession.

To achieve the goals of the new curriculum, a number of practical measures have been put in place for each one of the three areas of competence endorsed by the CDIO initiative:

- *Scientific and technical knowledge*. Four specific Mechanical Engineering courses are offered to first year students; within this introductory package, a specific course on "mechanical systems and product modeling" is taught in the very fist term of the syllabus. For the following years, the curricular objective is to maintain the same level of scientific and technical knowledge throughout the program.
- *Personal and interpersonal skills*. The integrated learning projects are ideal situations where students need to develop their communication, collaborative, leadership, and project management skills in order to succeed. To support this initiative some human sciences courses are offered in the program, in conjunction with the design projects. For each project type, specific personal skills are targeted; this has enabled the revision committee to associate some relevant human sciences courses to the new curriculum. As an example, a teamwork and leadership course is associated with the first design project and a project economics course is offered in parallel with the 4$^{th}$ year design project.
- *Professional (CDIO) skills*. The new curriculum is organized around 4 integrated learning projects (one each year) described in the following section. In order to stimulate professional skills and experience, a compulsory 4 months internship program has been introduced along with an increase in the number of laboratory sessions for some of the taught courses. For

most of the more applied courses and projects offered in the curriculum, industrial collaborators are strongly encouraged to supervise and participate in the training process. This approach, previously tested in graduate courses offered in the department, has proven to enhance motivation and spark genuine interest from the students on more practical issues that engineers face on a day-to-day basis.

***The four integrated learning projects***

The integration projects form a cohesive chain of learning experiences, going from a well circumscribed scope early in the program to a capstone project in the fourth year fostering autonomy development by the student as he/she progresses through the curriculum. The series of projects are thus designed as a progression in each year, going from well defined and precise design tasks to open ended projects.

The vision is to foster multi-disciplinary experiences with other engineering disciplines in the last year. The integration process of the projects is carried out at two levels. First, a general design methodology is taught and used throughout all four projects. Secondly, the projects always take place in the winter term and therefore courses directly related to the project are offered in the preceding fall term and during the project, in the winter term. Professors teaching these subjects participate in the project definition and project assessment, and this approach thus reinforces the subject knowledge and integrates it to a practical realm.

**The first year project.** This first project, offered in the second term of the first year, provides essentially an introduction to the engineering profession and a design methodology and experience with integration to a few fundamental courses such as statics, strength of materials and product modeling. This project is preceded also by a teamwork and leadership course in the first term, which is taught in an experiential format. The introduction to the profession comprises a number of seminars given by practicing engineers. The students also have a chance to present the results of their tasks orally throughout the term and also to evaluate the various presentations made by the other teams. A general design methodology is presented to the students, who are called to apply specific parts of the methodology (1-build a functional requirement document, 2-present a complete solution of a simple problem with a 3D mock-up and 3- analyze a simple solution with the material selection and the final dimensions of the various parts) to design problems using some of the fundamental knowledge that they have already covered. The students are shown how to use a project logbook where the students consigned their ideas, analyses, comments and hypotheses, which are supervised by the professors throughout the term. The aim is to use this type of logbook in all four projects. The concepts of project management are also introduced and the planned activities must be clearly shown in the project logbook to show the various tasks carried out by each student all along the term.

**The second year project.** In the second year design project, the complete design methodology is employed with precise objectives and constraints. The projects are completed over one term in teams of four or five students, which lasts 13 weeks. The students must conceive physical prototypes that are built and tested in a team competition at the end of the term. The students must seek to optimize a precise performance equation, which is used to evaluate the prototypes during the competition. All solutions are possible but the requirements, the performance and the test environment need to be well defined in advance. The project planning is also covered in this second project.

**The third year project.** The third year project is an individual project where students have to demonstrate autonomy and initiative when solving a complex design problem. The projects can be carried in industry or in a research laboratory environment. A faculty member supervises each project. The main objective for this project, which will start in the coming year, is to based evaluation of each project on the Critical Thinking principles as presented by the Engineering Reasoning guide written by Paul, Niewoehner and Elder [1]. An introductory seminar has already been presented to the students in the program. This approach to the analysis of documents teaches the students to ask eight fundamental questions about any report or initiative: the engineering purpose, the question at hand, the point of view, the assumptions, the engineering information, the concepts used, the inferences and the implications. A recent article related to this product development topic [2] suggests that there is a strong link between Critical Thinking and Design. The student will be asked to plan his work in detail covering the complete project and the later can be used by the project supervisor to check the proper progression and planning of the individual project.

**The fourth year project.** The fourth year project is team based and focuses on the use and management of collaborative product development technologies. As already described in [3], this capstone project attempts to simulate the industrial reality in an academic environment. First developed for the aerospace industry in 1999, the objective is to apply this approach to all final year projects within the new curriculum. The complexity of the task is high, and project resources, schedule, risks and road map must be properly managed. The project road map describes the sequence of the important design decisions, which are planned to arrive at a proper design.

During this final year project, some fifteen students work on the redesign of an aircraft pylon to allow the retrofit a new engine to the existing fuselage. The students are supervised by engineers working in industry and are evaluated on skills such as team communication, project management and technical know-how. To accomplish their task, they dispose of a dedicated workspace, which offers a teaching laboratory, meeting rooms, and access to Digital Mock-Up (DMU) and Product Lifecycle Management (PLM) technologies. The three industrial partners supervising the project – Bell Helicopter Textron Canada, Bombardier Aerospace, and Pratt & Whitney Canada – provide the team with a complete heritage design information package, which includes technical standards, existing CAD parts and assemblies, and certification regulations. This year, the scope of the project was further expanded to include the manufacture of a full size demonstration prototype. The students and professors from one aerospace professional high school and one technical college manufactured the parts and assembly. The technical college was located 500 km from Montreal and it forced the students to work at a distance from their supplier.

The introduction of this new requirement was a real success; the students learned to deal with subcontractors for the manufacture of the parts, and experienced the complexity of synchronizing design and manufacturing activities based on concurrent engineering practices.. Figure 1 and Figure 2 illustrate the achievements of this year's team; the students developed a digital prototype using PLM and DMU tools (Fig. 1) and then carried out the necessary manufacturing tasks to build a full size demonstration pylon in aluminium (Fig. 2). Important parts of the flying prototype are designed in titanium due to the high temperatures environment of the pylon. The bleed air and fire extinguishing systems were also designed by the students but are not shown in the figures. The students also have to plan the manufacturing of the first flying prototype and prepare a production proposal and retrofit procedures for 200 pylons.

A second project of this type is also being offered, which is related to the transportation industry. This year, the students had to develop a new high performance three wheel electrical vehicle. For the first time, students from the industrial design school were involved in the project and they worked closely with the team to design the vehicle shell and the ergonomics of the vehicle. The experience was a success for all students.

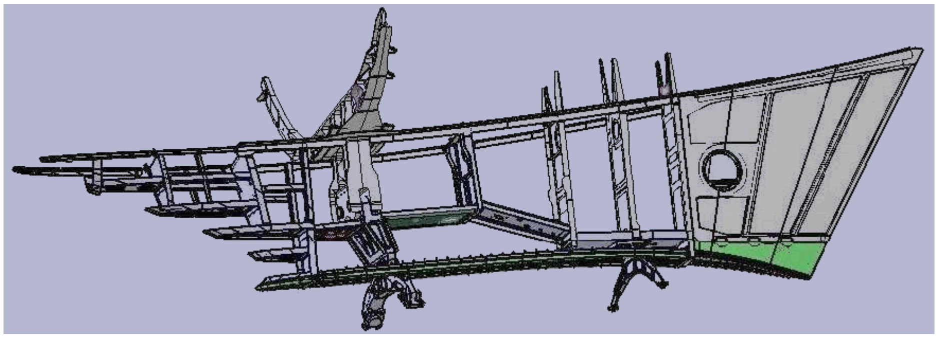

Figure 1: The digital prototype of the pylon showing the primary structure (top view).

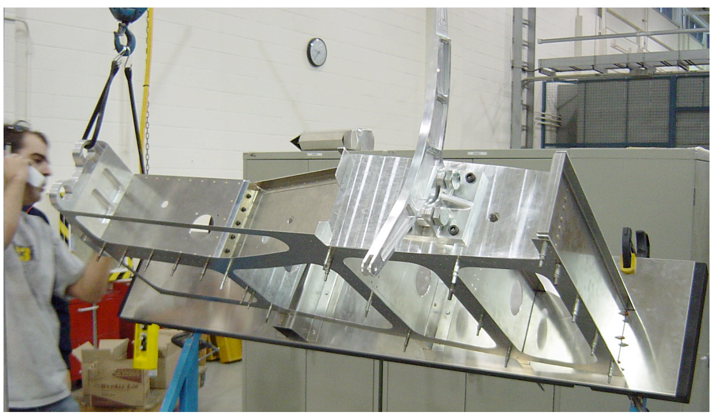

Figure 2: Assembly of the primary structure of the full-scale demonstration prototype.

***Current status of the implementation***

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The new curriculum is currently in its second year of implementation and the results are promising. The student enrollment has progressed significantly and we feel that our students are receiving a much-improved education. The complete stakeholders survey has been completed including the technical subjects, like the surveys of Queen's University of Belfast in Ireland and Queen's University of Kingston, Canada. These results are currently being used to finalize the detailed levels of the outcomes in the fourth year of our implementation. The CDIO initiative has been an important contributor to the development of our new program and it will help us to prepare the coming accreditation visit, which will take place in the fall of 2008.

**Towards an integrated learning project for a multidisciplinary team-based experience**

Since 2005, École Polytechnique has been working to promote a new Chair in “product and process design” associated with the CDIO initiative to go beyond the curricular reform presented in the previous sections of this paper. The Chair aims to propose a unique design training curriculum with the following strategic goals:

- The creation of common design projects with the collaboration of the Industrial Design School of Montréal (ÉDIN) and the HEC Montréal School of Business and Management. These design projects aim to foster interdisciplinary collaborations and provide a rich environment to support an efficient innovation cycle.
- The collaborative development of customized courses related to product design, process design and multidisciplinary work.
- The industrial involvement to drive and co-supervise multidisciplinary projects.

Concurrent product development strategies [4] and the industrial implications of globalization [5] require engineers to be capable of working and taking full advantage of this new environment. For educational institutions, this effectively means training student engineers to work in multidisciplinary teams using tools that enable collocated and distributed collaboration. To fulfill this goal, the new “product and process design” Chair will offer a number of industrial team-based projects where the participating students will experience the complete design process. Indeed, the three partner institutions bring together three key areas that are typically involved in the development of new products, namely industrial design, engineering and business.

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**Conclusion**

The new mechanical engineering program and, more generally, the overall review of the various curricula offered at École Polytechnique reflect current expectations placed upon engineers working under the new industrial constraints of this century. The revision process described in this paper has helped to rally the various actors involved around a unifying vision of modern mechanical engineers; the department aims to educate professionals competent in the development of complex products and systems with strong leadership skills. To achieve this goal, the new curriculum has been revised around the CDIO approach where “scientific and technical knowledge”, “personal and interpersonal skills” and “professional (CDIO) skills” are the core values that will help nurture the students to become successful engineers.

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**Biographical Information**

***Clément Fortin*** is Professor at École Polytechnique de Montréal (Canada) and the current Director of the Mechanical Engineering department. He was the Mechanical engineering program chair from 2004 until 2005 and has been involved in the CDIO initiative since 2004. His research interests include product and manufacturing process development, engineering change management, virtual environments for product development, and computer aided tolerancing.

***Bernard Sanschagrin*** is Professor at École Polytechnique de Montréal (Canada) and is responsible for the first year design project. He also coordinates the complete design-implement project chain in the new program. He has many years of experience in the teaching of design and has research interests in the area of polymer processing.

***Guy Cloutier*** is Professor at École Polytechnique de Montréal (Canada) and he is now the Mechanical engineering program chair. He is particularly involved in the integration of the personal and interpersonal skills within the curriculum and his research interests are in the area of machine-tools kinematics error corrections.

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***Greg Huet*** is Research Associate at École Polytechnique de Montréal (Canada). He completed his PhD thesis within the Design Information and Knowledge team at the University of Bath (UK) in 2006. Greg is currently working on a number of research projects involving the use of new PLM tools to support collaborative engineering activities. His research interests also include design review activities, information and knowledge management strategies, engineering change processes, and design research methodologies.

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