Integrating Engineering Workflow at Early Stages of Higher Education

The French Example

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***Abstract*— In this paper, we share our experience in using an innovative approach of teaching Engineering Science established by the French Ministry of Education for the French national preparatory classes for grandes écoles. The engineering science curriculum has moved from theoretical-based teaching into an engineering workflow-based style that considers engineering skills as an integrated part of the learning outcome. The approach makes use of simulation tools and experimentation on real systems. We will show how this new approach not only enhanced students' learning and confidence in their skills but also how it successfully impacted the selection process for getting into engineering schools.**

Keywords—engineering workflow; modeling; simulation; design; experimentation; analysis.

I. INTRODUCTION

Attaining an engineering degree in France involves five years of study:

- Two years of curriculum either integrated in the engineering schools or held outside the school in independent entities called preparatory classes for grandes écoles (CPGE).
- Three years of curriculum covering different disciplines and held at engineering schools called grandes écoles.

This paper focuses on the recent reforms of the French education system in the engineering science curriculum of preparatory classes. These reforms motivated an innovative teaching approach that uses simulation tools and experimentation on real-world systems, with the goal of attracting youngsters to pursue engineering education and to better prepare them for careers in industry [1]. These changes became effective with the 2013-2014 academic year. Note that these changes occurred in France after 20 years of traditional curriculum. This program is not only one course held in one school—it is the common curriculum for all French national preparatory classes. It counts for five tracks in the first year, covering more than 9000 students from public and military schools, and more than three tracks in the second year, with about 8000 students, according to the Union of Professors in Industrial Science and Technology (UPSTI) reports [2].

In the past, teaching in preparatory classes was mainly theoretical—dedicated to mastering the concepts in mathematics, physics, engineering science and/or other disciplines according to the chosen track, and preparing for the highly competitive exam to enter grandes écoles. The Engineering Science curriculum has moved from theoretical-focused learning into engineering-workflow focused as an integrated part of the learning outcome. It aims at preparing students to master these six skills aligned with the industrial engineering workflow: conceive, model, analyze, experiment, solve, and communicate.

Existing initiatives, such as CDIO and other research work [3], [4], [5] have been focusing on improving students' learning and getting them introduced progressively to engineering workflow through a project-based learning curriculum, where students work in groups to enhance their collaborative and communication skills. Others focused more on problem-based learning, letting students work on an open problem to get them more motivated. Unlike these methodologies, the approach we present here is not project-based learning or problem-based learning. It is similar to any standard lab module where the problem is well defined, the number of hours by subject is limited, and each student works with only one other student. The approach is innovative in terms of the teaching methodology used to master the six skills, as the learning outcome aligns with the industrial workflow. This is achieved by having students work in labs equipped with simulation tools and multi-domain real systems. The students adopt the engineering workflow by evaluating the deviations among: (a) the desired performances of the system based on the specifications, (b) the measured performances of the system obtained from experimentations, and (c) the simulated performances of the system provided by the simulation model. For progressive learning, the approach can first be used on a simple system and then be easily leveraged for more complex systems.

However, the requirements for the tools are high—they need to be graphical, able to model and simulate simple as well as complex systems, and connect easily with didactical and industrial hardware.

In this paper, we present our innovative approach and share our experience in applying it using MATLAB and Simulink, first on an elementary system using low-cost hardware, and then on a more complex system using physical modeling tools. We also show how this new approach not only enhanced students' learning and confidence in their skills and industrial future, but also how it successfully mapped engineering schools' needs and expectations in hiring students, thus greatly impacting the selection process for getting into engineering schools.

II. ENGINEERING SCIENCE CURRICULUM

A. Description

The SI (Science de l'Ingénieur) curriculum is covered by five tracks in the first year (MPSI, PCSI, PTSI, PCSI/SI, and TSI), and three in the second year (PSI and TSI2). Note that M, P, C, and T stand for mathematics, physics, chemistry, and technology. The 2013-2014 academic year counted more than 9000 students following this program in the first year, and about 3000 students in the second year **[2]**. The curriculum is composed of lectures, tutorials, and labs, with a number of hours varying from one track to another. For example, PCSI and PSI tracks count one lecture, one tutorial, and two lab sessions per week, whereas PTSI and PT cover two lectures, six tutorials, and two-and-a-half lab sessions. No changes in the lectures or tutorials were made after the reforms. Both remain theoretical, and the tutorials are exercises on theoretical concepts that the students have to solve. The changes took place only in the lab sessions.

B. Before the Reforms

Before the reforms, these sessions were in the form of two-hours-per-week lab sessions where students had to solve problems. Some of the lab sessions used modeling and simulation tools and experimentation on real systems. Others were theoretical, similar to tutorials with no experimentation or simulation. It was not mandatory to have such tools, and students were not evaluated on the practical aspect in any exam. They were evaluated only on their ability to correctly replicate the results. Also, they were not evaluated on their thinking, reasoning, or communication skills.

Similarly, the highly competitive exam that allows students to be admitted to engineering schools, was in the form of written and oral tests, both focusing on testing students' learning of the concepts. This was a disadvantage to students who had good practical and communication skills. The curriculum does not develop any other skills to better attract and prepare students for an engineering and industrial career. Thus, the changes were also implemented in the exam, evaluating students on the six skills, as well as on their ability to ask the right questions during the workflow and adapt quickly to systems and situations that were different from what they saw in class.

III. ENGINEERING WORKFLOW-BASED TEACHING APPROACH

The six engineering skills that students develop are design, model, analyze, experiment, solve, and communicate (Figure 1. a). Students acquire these skills to align with the different phases of the V-Cycle industrial workflow **[6]** that details all phases for the industrialization of a system from setting up specifications to validation. The main phases are: specifications, design, coding and implementation, integration and verification, and validation (Figure 1. b)**.**

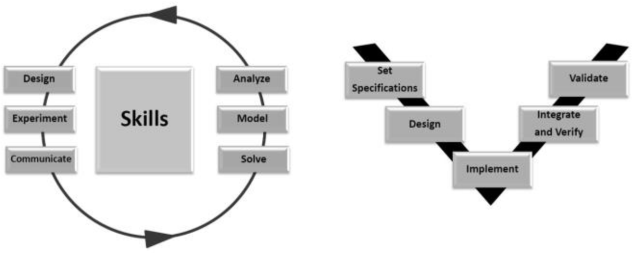

Figure 1. a) Engineering skills b) V-Cycle workflow

In order to complete these phases, students work in labs equipped with simulation tools and multidomain real systems. They adopt the engineering workflow by evaluating the deviations among: (a) the desired performances of the system based on specifications, (b) the measured performances of the system obtained from experimentations, and (c) the simulated performances of the system provided by the simulation model.

In the **specification phase**, students analyze the needs and get to know what the expected or desired specifications are.

In the **design phase**, students model, simulate, and experiment on the real system. Then they compare the experimental data to the simulated ones. Next, they validate the model by analyzing the differences. After that, they use the model to design the system to achieve the desired specification. Then they compare the behavior of the model to the real one after the design, improve the model and solve the problem to reduce the deviations. Once validated, this model is used to tune the design to meet the desired performances. This means minimizing the deviations between the designed model and the desired specifications.

The **coding and implementation phase** consists of translating the algorithm designed and tested in simulation into a program that can be directly implemented into the real system. The **integration and verification phase** represents the implementation phase of the algorithm on the real system and testing.

Finally, in the **validation phase**, students analyze the deviations between the desired performances and the real ones in order to validate that the real system meets the required performances specifications.

Note that at the end of the session, students must explain how they achieved all the steps and communicate it through a short presentation.

IV. NEEDS FOR IMPLEMENTATION

As stated before, the methodology requires modeling and simulation tools, as well as hardware for experimentation. It sets high demands on the simulation tools used because it requires a graphical environment for modeling, simulation, and design of both simple and complex multidomain systems. The tools must also be able to connect easily to hardware so that students can experiment, acquire data, and easily illustrate the deviations between simulations and experiments.

Additionally, the core objective of the engineering curriculum is to study complex multidomain systems. However, for the sake of the students' progressive learning, the approach first needs to be adopted with simple systems, and then it should be easily leveraged to be applied to more complex systems. This creates additional constraints regarding the tools to be used. The complex systems studied are equipped with multidomain technologies, such as mechanical, electrical, and hydraulics.

It is important to use a model that represents the different multidomain parts, enabling students to recognize these different parts. A complex system usually comes with a lot of different measurement points. Therefore, to allow students to compare the experimental and simulated data, the model needs to have the same data points as the real system.

This is why the revised program integrated physical modeling as the new tool to represent such systems. Consequently, in addition to the previous requirements, the simulation tools need to include multi-domain physical modeling and simulation functionalities that allow for a comprehensive model representing the behavior of the multidomain system.

In the next two sections, we describe the pedagogical activity we delivered to first-year PCSI students at Lycée des Eucalyptus of Nice. In Section V, we describe the method that was first used to design a controller of a simple DC motor. For that example, we chose the LEGO Mindstorms NXT motor. In Section VI, we show how it can be easily leveraged for use with a more complex system such as the automatic pilot of a boat, a multidomain system available in most of the preparatory classes labs. For both activities, the simulation tools used are MATLAB and Simulink.

V. APPLICATION ON ELEMENTARY EXAMPLE

The objective is to design a PID control for the angular position of the DC motor through the workflow presented in the previous section. For that example, we chose the LEGO Mindstorms NXT motor. Students need computers with MATLAB and Simulink, the LEGO Mindstorms Brick and one LEGO Mindstorms motor equipped with an encoder to measure the angular position (Figure 2).

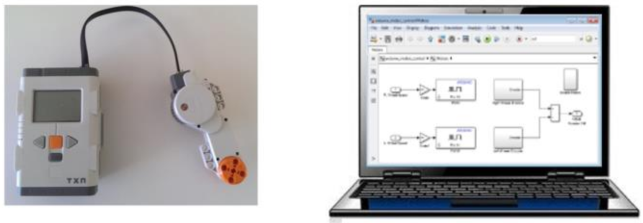

Figure 2. Equipment needed for the pedagogical activity

In the specification phase, students analyze the objectives, the requirements, and the desired specifications such as cost, stability, rapidity, and precision of the system response.

In the design phase, students derive the first-principle model of the DC motor and simulate it. They also experiment on the LEGO motor to acquire the encoder measurements and compare the resulting simulated behavior with the real one. In this phase, students are given the correct parameters of the motor which allows students to validate the model immediately.

After that, students use this model with proportional feedback gain to simulate the behavior of the closed-loop response. They do the same with the real system, and again they compare the closed-loop simulated behavior to the real response. They analyze deviations between them due to the presence of saturation and dead zone in the motor that are not taken into account in the model. Students make changes in the model to take these into account and then compare and validate the improved model with the real behavior.

The students now use the validated model to design a PID control that meets the desired specifications. Finally, they test the designed controller on the real system and verify that the real performances also meet the desired ones.

Simulation tools such as MATLAB and Simulink that connect easily and immediately with low-cost hardware such as LEGO Mindstorms [7], Arduino [8], Raspberry Pi [9] and others, enable students to go from the model to the real system without any learning effort. This makes the coding and implementation phase very easy for students because no skills need to be developed for this purpose at this stage of the curriculum.

VI. APPLICATION FOR COMPLEX SYSTEMS

In this section, we present how the approach can be easily applied using a physical model of the automatic pilot of a boat, which is a system available in most of the preparatory classes labs. It is a multidomain system including different technologies, such as mechanical, hydraulic, and electronics. The system is also equipped with different sensors that provide a number of measurement points. It is connected with MATLAB and Simulink for data acquisition and monitoring.

A physical model of the system representing and integrating these different parts and measurement points was developed with MATLAB and Simulink. Students use this model to simulate and understand how changing a physical parameter influences the behavior of the system. They compare the behavior with the real system on the same data points available for experimentation. Using a 3D animation of the solid movement, students can visually interpret and compare the two behaviors (Figure 3).

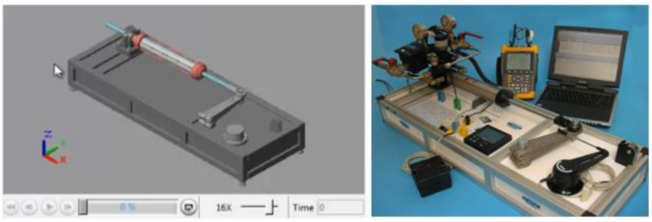

Figure 3. 3D representation of the mechanical structure of the automatic pilot

They can also easily design and integrate the controller into the model, simulate the controlled behavior, and analyze it with real performances

VII. RESULTS AND CONCLUSION

In this section, we share with teachers and students the results and experiences in delivering and presenting such an approach.

Through this approach, students are initiated into what an engineering job would be like. They develop high-level skills in modeling, engineering thinking, and communicating. They are also evaluated on the different skills that provide students with the opportunity to show off their other capabilities. We noticed that students are much more comfortable and confident in their skills as well as in the model, as they compare it and validate it on the real system before using it for design. Moreover, they can transfer these skills to their own projects, in future studies, and during their career. They also developed critical thinking and the ability to adapt quickly to new situations, which makes them better prepared for a job in the industry.

In addition to being proven in the industry, using simulation tools such as MATLAB and Simulink that offer all the functionalities for easily implementing this innovative approach, helps students be more prepared for their industry career.

However, as this approach integrates physical modeling—a new concept for these classes—it requires that teachers as well as students learn this new concept of modeling, as well as master the simulation tools that come with it. This is why we developed an entire book on getting started with physical modeling tools that is free and downloadable for teachers and students. We also developed free downloadable lab modules and lab activity examples to train teachers in class. In order to help teachers better reuse the pedagogical activity described in this paper, a 45-minute online webinar detailing how to conduct this activity is available for teachers to attend.

As previously mentioned in this paper, the new approach not only enhanced students' learning and confidence in their skills, but it also successfully impacted the selection process for getting into engineering schools. The grandes écoles so appreciated being able to hire candidates with such skills that they changed the weighting score for the engineering science exam to be the highest, which means that it holds more importance than the scores for the mathematics and physics exams. In the future, we will be able to track how these modified weights changed the profile of the students selected by the grandes écoles.

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