Feedback on Innovative Pedagogy for teaching Systems Modeling

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Abstract: This paper presents a feedback on a new core course on "Systems modeling – Model representations and analysis" of the new curriculum of CentraleSupélec. Dedicated to all the first year students, this course stands as the main prerequisite for an important part of the curriculum. Thus its fruition is essential. Multiple challenges have been overcome: (i) propose a high level academic program for more than 800 engineering students with initial heterogeneous levels in systems modeling; (ii) make the course easy-understandable and attractive for students, while allowing interactions students-to-students and students-to-professors; (iii) guarantee the consistency with the entire curriculum; (iv) manage the time constraints imposed by the course schedule.

Keywords: Challenges for control engineering curricula, pedagogy in control engineering.

1. INTRODUCTION

A flourishing industrial development relies undoubtedly on tomorrow's engineers. To support it, the university system has to adapt to the industrial commitment by offering more and more engineers with better knowledge and multidisciplinary skills that will facilitate their insertion into the industrial world. To this aim, the engineering universities/schools have to face the somehow contradictory constraints of increasing their number of graduates while ensuring a high quality and nearly individual follow-up of their training. CentraleSupélec is one of the most prestigious French 'Grandes Écoles', i.e. a graduate engineering school with a selective entrance exam, offering a three-year curriculum preceded by two years of intensive higher education in mathematics, physics, industrial science, foreign languages and communication, and a national and very selective competition. This particular French organization of the bachelor and master education is called up in Fig. 1.

CentraleSupélec is one of the first top-ranking institution among these engineering high schools. Graduates from CentraleSupélec are internationally recognized as multidisciplinary "engineer-entrepreneurs" [1] able to develop innovative responses to major technological, economic, social and environmental challenges. Their training has therefore to be very inclusive and to encompass engineering (high-level scientific and technical skills), entrepreneurship, management and research domains. In close connection with its industrial network, CentraleSupélec has built a new curriculum within a program-based framework offering an overall coherence between all the teaching activities and coming with numerous novelties in the scientific program, the semester structure and the pedagogical approaches. The main steps of the first two years of this curriculum progressively cover modeling of complex systems, information-based analysis (e.g. signal processing), functional modeling, control engineering and optimization.

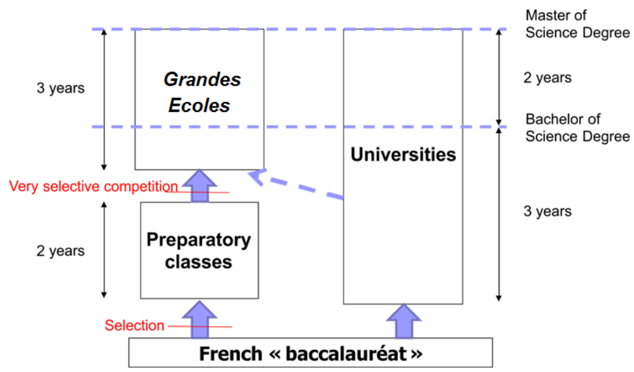

Fig. 1. Organization of bachelor and master degrees in France

Systems modeling plays a crucial role to represent a complex system and to analyze interactions between its components or with other systems. The course on "Systems modeling – Model representations and analysis" which takes place during the first year of this three-year curriculum was developed considering the specificities and the requirements of the new curriculum of CentraleSupélec and has taken into account part of the recommendations

[1] www.centralesupelec.fr/en

issued from the Panel Session "The control curriculum for the 21st century" (2018). Considerable efforts have been done in order to ensure the coherence with the other modules of the curriculum, to motivate the students and to provide them the necessary background in dynamical model representations and analysis. Indeed, after completion of this course, students should to be able to: (*i*) select a relevant model type to represent the behavior of a system with an appropriate trade-off between the model representativeness and its complexity; (*ii*) evaluate the performances of the model in regards to adequate criteria that depend on the modeller's objectives (domain of validity, predictive ability, control etc). This vast objective is particularly ambitious because it requires that the module combines three parts that are rarely taught in a same course: continuous-state models, discrete-event models and methods for identification and analysis of these two families of models [2] . These three parts are connected by their interactions within the modeling process which is introduced to the students. (*i*) First, the most appropriate representation of a complex system has to be selected: a continuous-state model (continuous-time or discrete-time) or a discrete-state model; (*ii*) Then the model parameters has to be identified using experimental data that can be noisy and the model structure has to be assessed; (*iii*) In parallel, the model properties have to be analyzed (equilibrium points stability, uncertainties propagation and sensitivity analysis for continuous-state models, properties of discrete-event models). Thus, setting up this new course implied gathering in a same course, taught by a unique pedagogic team that had to share their expertises, different pieces of knowledge that originate from a wide variety of disciplines: automatic control, numerical optimization, statistics, probabilities, etc., with the challenging task of giving the students a valuable grasp on the links between these components through the general modeling methodology. To tackle these points as well as the problem of maintaining a good degree of interactivity even at a scale of 800 students, several novelties were tested in the course on "Systems modeling – Model representations and analysis" in relation to the pedagogical approaches (e.g. 201 mini-projects proposed and peer reviewed by the students) and tools (e.g. interactive questions using Kahoot! (2013)).

The remaining part of this paper is organized as follows. Section 2 focuses on the theoretical notions taught during this course. The pedagogical approaches are presented in Section 3, while the feedback on the mini-projects and the main challenges are discussed in Sections 4 and 5, respectively. Finally, concluding remarks and current work are presented in Section 6.

2. SCIENTIFIC FOCUS

The theoretical content of the course is split in 3 parts:

(1) *Modeling of continuous-state systems* (50%) Both continuous-time and discrete-time systems are modeled in a state-space representation. Starting from a non linear model, a linearized model around an equilibrium point is proposed and its stability is further analyzed. Secondly, a transfer function framework is proposed for dynamical systems modeling, introducing basic concepts on Fourier, Laplace and z transforms. The stability of transfer functions is analyzed. Both frequency (Bode diagram) and time responses (impulse response, step response with a focus on 1st and 2nd order systems) are taught in this part.

(2) *Modeling of discrete-state systems* (20%) Mainly based on Cassandras and Lafortune (2008), untimed discrete-event systems (untimed automata and untimed Petri nets) are first presented and analyzed. Then timed automata (with gards and invariant conditions), timed Petri nets and hybrid discrete-event systems are introduced. Finally, timed stochastic automata are proposed based on the prerequisites from the course on "Convergence, Integration, Probability & Partial Differential Equations".

(3) *Parameter identification, sensitivity analysis and evaluation of models* (30%) Both frequency domain and time domain based identification methods are presented. Linear and non linear least square methods are also taught. Among the criteria allowing to evaluate the predictive ability of a proposed model, this course considers the Mean Squared Error of Prediction (MSEP) and the associated method to estimate it based on a cross-validation scheme. A criterion for model selection that penalizes model complexity to avoid over-fitting, namely the Akaike Information Criterion (AIC), is also introduced. Finally, the useful methods to deal with factor uncertainty are presented. Two main approaches can be used for uncertainty modeling: parametric (parameter estimation of a given probability law) or non-parametric (histograms, kernel density estimation) techniques. Then three approaches are introduced for uncertainty propagation: deterministic error propagation, variance combination methods and Monte-Carlo simulations. The last course component consists in being able to assess the respective contributions of the different uncertain factors to the output uncertainty, by means of global sensitivity analysis based on the Standardized Regression Coefficient (SRC) or Sobol indexes deriving from variance decomposition.

A plenary lecture on "The diversity of model functions and types in history and today" (Varenne (2018)), introducing some concepts from epistemology for a better understanding of current and future trends in modeling practices of complex systems (e.g. big data, predictive modeling, etc.) along with their advantages and weakness, completes this course.

3. PEDAGOGICAL APPROACH

3.1 Module general organization

The course "Systems modeling – Model representations and analysis" is composed of 10 lectures of 90 minutes each, 9 Matlab-based tutorials of 90 minutes each, one plenary lecture of 90 minutes and one application-based tutorial of 3 hours. The approx. 800 students were split into 8 series of approx. 100 students each. The 3 professors

[2] In the previous curricula of CentraleSupélec, only continuous-state systems were analyzed in the course "Signals and Systems" (see Antoine et al. (2014)), while the discrete-state representation, the uncertainties propagation and the sensitivity analysis were taught for the first time in 2018 - 2019 to the first year students of CentraleSupélec.

duplicated the lectures: the lectures in English (with approx. 100 students at a time) and in French (one class with approx. 100 students and one class with approx. 200 students) were taught twice in order to keep a reasonable size allowing interaction during the lectures. To this aim, interactive questions were asked during the lectures, using the Kahoot! (2013) application. Both slides and a handout (Stoica Maniu et al. (2019)) were realized for the lectures.

During the tutorials, the students were split in 24 classrooms of approx. 34 persons. The tutorials attractiveness was increased by using Matlab to simulate and analyze the behavior of the proposed models. Thus the same notion was often presented through two complementary ways: theoretical derivations and analytic resolutions of exercises, or numerical simulations. This duality increased the understanding level of students, since some students felt more comfortable with one approach and others with the other one. A large effort has been made to study only examples derived from real-life applications (often considering some simplified problems for sake of pedagogical approaches and to obtain exercises doable in a 90 minute tutorial). To this end, these 9 tutorials dealt with:

- Tutorial 1: Modeling and stability analysis of a robot arm, to illustrate the state representation approach;
- Tutorial 2: Modeling and behavioral analysis of a vehicle weighting system, dedicated to the use of the Laplace transform and continuous-time transfer functions;
- Tutorial 3: Modeling and analysis of a product storage system, as an example of discrete time systems that can be studied with the help of z transform and discrete-time transfer functions;
- Tutorial 4: Modeling of a blood test laboratory by means of synchronized Petri nets;
- Tutorial 5: Modeling of a diabolo throwing to illustrate the use of hybrid system automata;
- Tutorial 6: Modeling of event arrivals in a discrete event system to have a focus on stochastic automata and the methods available to simulate them;
- Tutorial 7: Identification of an industrial furnace and of the flexibility modes of a bridge;
- Tutorial 8: Identification of a prostate cancer tumor model by means of non linear square methods;
- Tutorial 9: Analysis of the dynamical properties of swords, with the main focus being on uncertainty and sensitivity analysis.

For instance, Fig. 2 presents the problem that is handled in the first tutorial (with straightforward notations) and the kind of simulation students can obtain with the help of Matlab / Simulink to illustrate the concepts of equilibrium points and stability.

In order to illustrate and apply the modeling approaches presented during lectures, a specific tutorial of 3 hours on modeling approaches on real-life problems development was proposed. The students registered to one specific tutorial derived in several versions depending on the field (e.g. quantum Physics, mass or heat transfer, AC/DC converters, biotechnology, electromagnetism). The main objective of these tutorials is to illustrate a modeling methodology: starting from reference and sophisticated model of a real-life application, the idea is to define some realistic assumptions to get a simplified model and then validate the obtained model by means of simulations and to characterize its region of validity. Depending on the chosen application, students may have to use some specific software for the simulations.

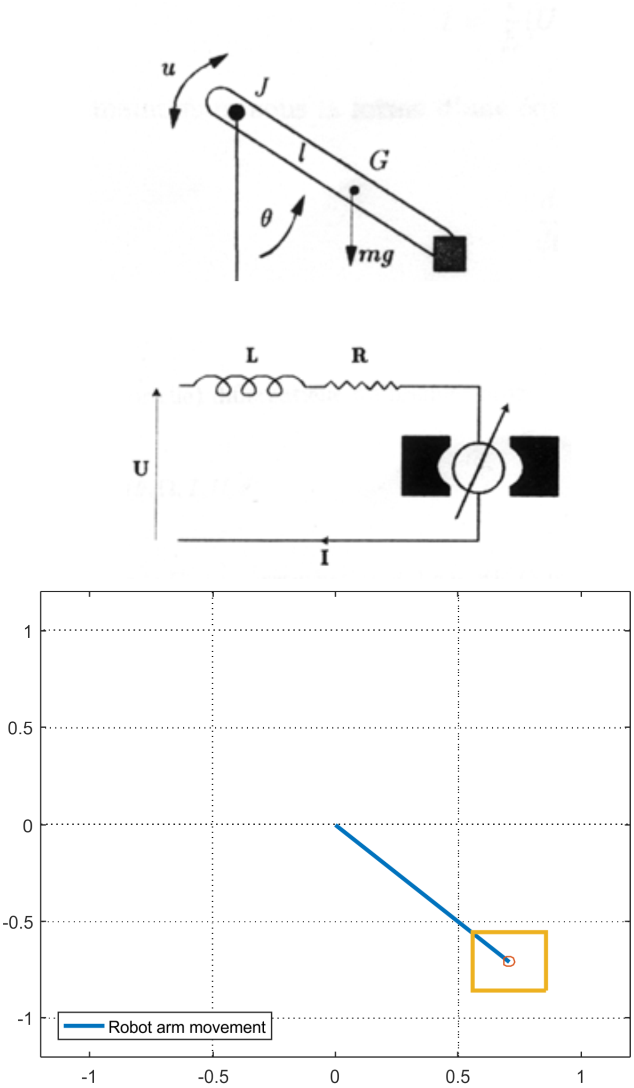

Fig. 2. Illustration of the complementarity of theoretical and simulation parts of the tutorials: Definition of the robot arm problem and Matlab framework for simulation (tutorial 1)

All in all, the ratio of tutorials in the module achieves 50% allowing a large part of exercises and real-life examples.

3.2 Student project related to the module

An important challenge raised by this course was to set up a process to make the students practice the modeling approach on a more complex project than what can be tackled in the limited time of a practical session. Indeed, gaining experience by practising the modeling process seems mandatory in a course with the objectives stated in Introduction. But how to deal with a project-based pedagogy in a group of 800 students? A two-fold peer-reviewed procedure was imagined. Students were randomly organized in groups of 4 or 5 persons that had to work on the two successive following tasks:

(1) *Subject proposal*: Each team had to propose a subject for a modeling project. It consisted in a one-page long description of a system or a process, with a few lines describing some modeling objectives. It had to be accompanied by a 5-6 pages long document, taken from the scientific literature, that could play the role as starting point for a modeling work. The aim of this document was to provide a detailed description of the system, some parameter values and some preliminary models.
(2) *Project development*: The subjects were then randomly assigned to another team that had to realize it. The group had to develop a model for answering the proposed questions, provide a simulator, and a short report, including a representative experiment to be tested in order to illustrate the relevance of the simulator with respect to the model description (equations, diagram, assumptions, etc.) and the physical intuition on the modeled system. The recommended time to be dedicated to the project was 8 to 10 hours of personal work.

A peer review was realized via Edunao (2014) in order to evaluate both the subject and the development of the projects. The team proposing the subject evaluates the results obtained by the team who realized the project and vice-versa. Several pedagogical goals were achieved via the different phases of these projects:

(1) Team working;
(2) Grasping the diversity of methods and application fields of the systems modeling when searching papers in the open literature for writing the subject;
(3) Practicing the iterative process consisting in: going from a real system/process to a set of equations or to an algorithm; implementing a simulator and testing it; interpreting/evaluating the behaviour of a model given some expected objectives of the model; challenging some of the assumptions (structure of equations, parameter values, etc.) when realizing the project itself;
(4) Analyzing a system modeling approach and the model proposed by a different team via the peer assessment (based on several evaluation criteria).

In addition, the 201 subjects have been of remarkable scientific wealth and have allowed the teaching staff to get an impression of the areas of interest of their students. Here are some examples of the proposed projects, illustrating the students' large inventiveness. Proposed projects originated from many fields (e.g. robotics, energy, health, financial modeling, nature, sociology, etc.):

- Modeling of the propagation of forest fires;
- Modeling of an ant colony;
- Modeling the take-off, flight and landing of a plane;
- Modeling of a wind turbine;
- Modeling of an anti-noise acting headphone;
- Modeling electric guitar pickups;
- Modeling the spread of a virus on smart phones;
- Road traffic modeling;
- Modeling of a photo-voltaic panel.

Due to the synchronisation with the entire course schedule, the subjects of the mini-projects focused only on the first two parts: modeling of continuous-state or discrete-state systems. During the mini-projects, the students used either Matlab/Simulink or Python (Python Core Team (2015)).

In order to maintain interactivity and increase students' motivation, a Questions & Answers Forum via Edunao (2014) was maintained by the 3 professors in charge with this course.

4. EXPERIENCE FEEDBACK ABOUT THE 201 MINI-PROJECTS

In this experience feedback, several points deserve to be highlighted.

Regarding the project, a main difficulty was the uneven level of difficulty of the subjects written by the student teams. To attenuate this problem that had been anticipated, the teachers provided examples of typical subjects. This was an important resource to the students in order to better position their subjects and the expected format. Another advantage was that these example subjects were available as back-ups in case some teams would not had submitted their subjects (this case did not occur). They were also useful to be given to the few teams (2 over 201) that found the subject they received too difficult to be handled in the allocated work time. Note that, in such case, the instructions given to the students were to first try to reformulate the objectives of the modeling work within the same application field (and therefore they would also give a lower mark to this point in the peer-assessment of the team that had written their subject). A total change of subject was thus only allowed in very special cases, for instance when the proposed application field required a high expertise of the domain to be properly appropriated (e.g. some finance-related projects).

Another point of vigilance related to the project was the uneven level of requirement of the different student teams in the peer-assessment process. To deal with this problem, the teachers detailed as precisely as possible a grid of the evaluation criteria. As illustration, Table 1 presents the criteria for the project assessment. Particular weight and attention were given to criterion 6: to fill this row, the evaluating students had to run a simulator provided by the team (the programming language was freely chosen by each team). They were asked to check whether it fulfilled three conditions, on a typical experiment that the students were asked to describe in their report: (i) that the simulation does not crash, (ii) that the simulation is in agreement with the model as described in the report, (iii) that the simulation is in agreement with the physical process or system to be modeled. This criterion had the advantage to be factual and objectively assessed. In a meta-evaluation step, the teachers finally checked a (selected) sample of assessments. The students were warned in advance that they would get penalties if their evaluation were found too far from the teachers' ones. Lastly, a questionnaire was available to the students asking whether they were satisfied with the assessment they had received, so that the teachers could verify those that asked for re-assessments. The same questionnaire also asked whether some students should be awarded a 'bonus', in

Criterion	0 pts	1 pts	2 pts	3 pts
1. Report layout	The report looks like a draft, illustrations are misrepresented or misused, without captions, without numbering, not cited in the text, etc.	An effort is made on the layout, but it is not enough	Some details are missing (e.g. format of bibliographic references)	Good use of space, figures are representative for project results, labelled, numbered, quoted in the text, bibliographic references are well formatted and quoted in the text
2. Pedagogic quality of the writing	Little effort in writing the report, difficult to understand, report too short, seeming sloppy, or on the contrary too many details without it being possible to identify the important points	Lack of clarity in the report, its reading requires effort, important points are poorly highlighted	Report clear and understandable overall but some gaps; important points appear, but without analysis or hindsight	Pleasant to read, educational, facilitating the understanding of the work done, highlighting important points and analyzing them with hindsight and critical thinking
3. Re-formulation of modeling objectives	Poorly formalized problem, unclear or uninteresting objectives	A slight work of positioning the objectives that could have been further developed	The objectives are correctly reformulated and the changes compared to the initial subject are justified; these objectives define an interesting modelling work	An important work has been done on formalizing and positioning of objectives; the project is much more ambitious than in the initial subject
4. Assumptions made, approach, proposed final model and its validity range	no rigour, assumptions not explicit	Approach correct overall but some assumptions are not very clear, some simplifications are not justified, validity range is not clarified	Good approach but one element is missing	All 4 points are well-addressed: the assumptions are relevant and well explained, the steps of model development are well presented, the final model is relevant and its validity range is tested
5. Team competences acquired on the subject	The understanding of the subject remains very approximate; our classmates seem to have little or misunderstood the subject	Comprehension seems approximate	The team has a good knowledge of the content	Very good knowledge of the content and satisfactory understanding of the modelling concepts presented
6. By testing the simulator on a typical experiment, we find that the simulator is in "agreement" with the model presented in the report and with the reality of the physical phenomenon	No simulation possible or the simulation returns a bug (does not return a result) or no typical experience defined in the report	Simulation returns a result, but it seems incorrect	The simulation returns a result that matches the description of the model given in the report	The simulation is in accordance with the model and also in accordance with the reality of the modelled phenomenon
7. (Optional) One additional criterion to be proposed if needed	(to be filled by students)	(to be filled by students)	(to be filled by students)	(to be filled by students)
Free comments				

Table 1. Criteria grid for project peer-assessment

order to take into account, when they were too large, some important differences of students' involvement in the team work.

5. CONTEXTUAL DIFFICULTIES FOR THE COURSE SET-UP

The main challenge was to succeed the implementation, within a very short period, of a complex course on systems modeling, both from the scientific program and pedagogical points of view. Several constraints were related to: a first occurrence of a new course, a large number of students, a large team of tutorial supervisors, a need of adapted tools (e.g. pair assessments tools, registering tools), the coherence with the entire new curriculum of CentraleSupélec, the synchronization of the lectures between the professors and between the two occurrences of a lecture given by the same professor. Providing a high quality handout appreciated by the students demanded a lot of efforts from the teaching team [3]. The implementation of the mini-projects and registration procedure to the specific tutorials have been time demanding and energy consuming. In order to improve these processes, there is a

[3] Notice that the 3 involved professors have 50% of their time for teaching and 50% for research.

need of adapting existing tools (e.g. Galtier et al. (2016)) and creating new ones.

The key of success of this course relies on the mutual help and investment of a newly created teaching team, interested in proposing and applying new pedagogical approaches for the engineering students' benefit.

6. CONCLUSION AND PERSPECTIVES

6.1 Conclusion

This paper proposed a feedback on a new course on "Systems modeling – Model representations and analysis" at CentraleSupélec. From a scientific point of view, three main assets were realized. (*i*) This course offers the necessary framework allowing to choose the right model typology well-suited to the model objective (simulation, optimization, control etc.): discrete/continuous state (or time), deterministic/stochastic, mechanistic (based on physical laws)/data-driven (based on measured data), frequency/time based model. (*ii*) It provides analytic and numerical approaches to analyze the reliability of the developed models with respect to uncertainty propagation, sensitivity analysis, selection of a model with regards to certain specifications. (*iii*) Simulations and, more particularly, comparison with experimental data are developed. Writing the handout of this multi-disciplinary course was a common work realized by the pedagogic team: this time-consuming task was precious to homogenize the teachers' expertise and pedagogy, to homogenize notations (e.g. H was classical notation commonly used for transfer function in control or for Shannon entropy in uncertainty analysis), and to strengthen the links between the different parts of the course.

6.2 Potential improvement directions

Future work focuses on the scientific, pedagogical and organizing aspects.

In their feedback about this course, the students were globally satisfied (75% found that the course objectives were attained). They appreciated the project although some would have preferred to choose their team mates, which will be allowed in the next occurrence. Some of them pointed out that the links between the different parts of the course could be reinforced: this remark was mainly due to the fact that the tutorials were too independent. It will be improved by adding a last general tutorial mixing the different modeling approaches on a same case-study, as it was done in the written exam problem.

This experience allows to highlight some important requirements for developing a peer-assessment platform: easy creation of groups of students (imposed or by auto-inscription, depending on the course policy), anonymity of the submissions and evaluations procedures, direct access to online feed-backs and marks given by the students, ease of meta-evaluation by teachers with possibility to highlight the potentially problematic assessments by the students. Hopefully, the peer assessment tool proposed by Galtier et al. (2016), Galtier (2016), Peeramid Project (2017) will release a new version taking into account most of these constraints, allowing to simplify the procedure with respect to the actual solution based on Edunao (2014).

Another point that will be improved in the future is to provide more strict guidelines concerning the model development and analysis in the projects. Indeed, some students chose to explore complex model formalism or to calculate systems control while they did not have yet the needed knowledge. With the teachers' help they could handle it and make rapid progress, but the project was thus very time-consuming. A solution will be to impose a restricted set of modeling approaches that can be used and to specify that a stability analysis has to be performed as well.

Lastly, several difficulty levels of the tutorials will be proposed in the future, allowing us to better take into account the heterogeneity of the students' comprehension level. Some notions of uncertainties propagation and sensitivity analysis will also be illustrated for a discrete-state model. Matlab onramp Matlab (2014) and Simulink onramp Matlab (2018) will be part of the prerequisites of this course. A handout in English will also be available in the future.

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