Design and Analysis of an Undergraduate Computational Engineering Degree at Federal University of Juiz de Fora*

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Abstract. The undergraduate program in Computational Engineering at Federal University of Juiz de Fora, Brazil, was created in 2008 as a joint initiative of two distinct departments in the University, Computer Science, located in the Exact Science Institute, and Applied and Computational Mechanics, located in the School of Engineering. First freshmen began in 2009 and graduated in 2014. This work presents the curriculum structure of this pioneering full bachelor's degree in Computational Engineering in Brazil.

Keywords: Curriculum Structure, Computational Engineering, Undergraduate Program

1 Introduction

This work presents the curriculum design of the undergraduate program in Computational Engineering (CE) at Federal University of Juiz de Fora (UFJF), Brazil. The creation of the CE program at UFJF was based in an international trend of creating undergraduate engineering programs with an interdisciplinary background that aims to prepare students to work with formulation, analysis, implementation and application of mathematical models, numerical methods and computational systems to solve modern scientific and engineering problems. These multiple skills are a way of inserting students in new areas of the job market that are dedicated to innovation and technological developments to solve a great diversity of problems.

The CE program at UFJF, due to its intrinsic interdisciplinary nature, was proposed by two distinct units: School of Engineering and the Exact Sciences Institute. The Graduate Program in Computational Modeling, which offers master and doctoral degrees, is also offered by these two units. With a close proximity to

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the graduate program, the CE program also offers the students to be in contact with a rich scientific research environment. In this way, the students get used to ask and search for new solutions, and to verify and compare them to others, which is certainly an advantage in the job market.

The CE program is offered on a full-time basis. In fact, all CE students are first admitted to the Exact Sciences (ES) program. The ES program was designed in a way that it shares a common core with many distinct programs: Computer Science, Computational Engineering, Electrical Engineering, Mechanical Engineering, Statistics, Physics, Mathematics and Chemistry. An ES student has the opportunity to have contact with these distinct disciplines and, after this first contact, choose the one that he/she is more identified with. Up to 20 ES students can be admitted to the CE program per year, after they finish the third term of the ES program. Another 20 students can enroll at the CE on the very first term of the ES program. This choice is for students that, during the admission process, are confident to proceed directly to CE.

The ES program can be taken as a kind of minor program in which the students receive a full bachelor's degree in ES. After students have concluded the ES program, which occurs after six terms, they are officially admitted in the CE program (or in another program they have chosen).

The fulfillment of requirements to obtain the CE degree should occur, following the suggested curriculum, within 10 terms, including the 6 terms to conclude the ES program. The maximum time allowed for its conclusion is the double of the expected completion time, i.e., 20 terms. The CE program requires at least $3,800$ hours of courses and activities, in line with the Brazilian law on engineering undergraduate programs.

The remaining of this paper is organized as follows. Section 2 presents the multiple aspects that have been taken into account during the CE curriculum design. Section 3 presents the CE curriculum and discusses some of its main aspects. Section 4 presents the impact of the proximity of the graduate and undergraduate programs. Section 5 presents other CE programs and Section 6 presents our conclusions.

2 Curriculum Design

The CE curriculum was designed in order to give a basic formation in a new area of knowledge that has been in consolidation during the last decades, gathering specializations from different fields of engineering and sciences. This interdisciplinary education is present not only in the core courses, but also in a large amount of elective ones.

The advanced topics of the CE curriculum are open, depending on the choices of the student. In other words, the curriculum is flexible to adapt to a variety of students: those that want a breadth or a in depth view of some area. Furthermore, some courses covering themes such as computational modeling, numerical methods and parallel computing are also included for junior and senior students. It is also recommended that junior and senior students choose courses from other

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sorts of engineering available in the School of Engineering, such as electrical, electronics, telecommunications, mechanics, environmental, among others. The objective is to allow students to improve their skills in modeling problems from other disciplines. In the specific case of our undergraduate CE degree, a large number of courses in structural and computational mechanics fields are available.

Also, a large number of laws in Brazil had to be observed during the CE curriculum design, such as: a) requirements for bachelor's degree; b) minimum requirements for engineering programs; c) syllabus, grading policy; and d) obligation to include in the curriculum some disciplines, such as Afro-Brazilian and native indigenous history and culture, the Brazilian sign language, and environmental education.

2.1 Objectives and Competencies

The main objective of the curriculum is to prepare the students to be able to formulate, analyze, implement and apply mathematical models, numerical methods and computational systems to solve distinct scientific and engineering problems. To achieve this purpose, many abilities must be developed during the CE undergraduate program:

- Ability to use knowledge from mathematics, physics, computer science, engineering and modern technologies in the development of products and services. The following courses contribute to this goal: Calculus I, II and III; Differential Equations I; Physics I, II and III; Physics Lab; Fundamental Chemistry; Chemistry Lab; Sciences Lab; Calculus of Probability; as well as courses in the area of mechanics and computing;
- Ability to project, implement, test and maintain software for the development of products or services. Algorithms; Data Structures and Data Structures II; Object-Oriented Programming; Programming Lab I and II; Software Modeling; Databases and Software Engineering are courses related to this goal;
- Ability to take advantage of existing techniques and technologies, and to develop and propose new ones. Introduction to Computational Modeling; Transport Phenomena and Mechanics are courses related to this goal;
- Ability to understand the impacts of products and services in the environment. The course Ecology and Environment Preservation is related to this goal;
- Ability to apply the knowledge from numerical methods to solve scientific and engineering problems. The following courses contribute to this goal: Numerical Calculus; Introduction to Computational Modeling and Introduction to Discrete Methods;
- Ability to interact and communicate with engineers and other professionals during the development of projects. Internship; Multidisciplinary Project; Undergraduate Thesis; and the presentation of projects and practical activities in some courses contribute to this goal;

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- Ability to keep himself/herself updated with the latest technological trends. This topic is always addressed in courses, specially in Introduction to Computational Engineering and Multidisciplinary Project;
- Ability to act with ethics and integrity in his/her professional activities, evaluating the impacts of his/her professional activities for the society and the environment. Introduction to Computational Engineering and Ecology and Environment Preservation are courses related to this goal;
- Ability to supervise, coordinate, plan, specify, project and implement activities compatible with his/her academic degree. The conclusion of all courses in curriculum contributes to this goal. More specifically, Multidisciplinary Project and Undergraduate Thesis evaluate if the student successfully achieved this ability.

A set of core competencies has been chosen to compose the curriculum. They include, as mandatory courses for all CE students, the following areas: mathematics, science, programming, computer science, numerical methods, and applications (applied and computational mechanics). These competencies were included as mandatory courses for all CE students. Also, a large number of completely unconstrained elective slots are available for students that want to develop, based on their own interests and goals, new skills.

3 Curriculum

The curriculum is divided into eight basic components, following UFJF's and ES's rules, as well as laws in Brazil about Bachelor's degrees: a) core courses, which are composed of mandatory courses for all CE students; b) mandatory activity, which is an activity (i.e., there is no grade associated with it, the student is either approved or reproved) mandatory for all CE students; c) elective courses, which is a pre-selected list of courses on advanced topics, and students can choose some of them to attend to; d) elective activities, which is a pre-selected list of activities, such as attend to a conference, workshop, short-term courses and other related activities, as well as additional hours in internships and other hands-on training experiences inside or outside UFJF; e) optional courses, which can be any course in any area of knowledge that was not listed as an elective course; f) a mandatory internship; g) a multidisciplinary project; and h) undergraduate thesis. Except for the undergraduate thesis, for all other components one hour corresponds to 60 minutes of lecture class time, activities or internship, so the time spent by students in homeworks and outside class study is not considered. For the undergraduate thesis, the number of hours necessary to develop and implement a computational model, as well as to write the text that describes it, is estimated. Tab. 1 presents how the total number of hours are divided in these distinct courses and activities. Again, the proposed CE curriculum had to follow some rules and laws in order to define the amount of time for each type of course.

In the proposed curriculum students play a fundamental role in their education through the choice of elective courses that allow to have a breadth view on

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Table 1. Distribution of the academic load by its basic components. A total of 3,800 hours is required for obtaining the CE Bachelor's degree.

Core Courses	2,520 hours
Mandatory Activity	30 hours
Elective Courses	420 hours
Elective Activities	120 hours
Optional Courses	300 hours
Internship	170 hours
Multidisciplinary Project	60 hours
Undergraduate Thesis	180 hours

multiple areas or a in depth view of some area of their particular interest. In fact, the mechanism allows students to trade engineering depth for breadth within a single department (for example, computer science) or breadth among other disciplines (for example, electrical, mechanical and environmental engineering). To achieve this goal, a large number of unconstrained slots are available as elective and optional courses. Although a huge amount of courses can be chosen as optional, the following topics are suggested to those students that may be lost with so many options: a) scientific method; b) communication and expression, including foreign languages; c) administration; d) economy; e) humanities, social and environmental sciences. Nevertheless, some students prefer to choose other courses from biology, mathematics, physics, or geology by themselves.

The core courses in the CE curriculum, presented in Tab. 2, presents the student to fundamental topics of mathematics, physics, programming, numerical methods and structural and computational mechanics, as well as substantial breadth and depth in some topics related to Computer Science, such as digital circuits and computer organization, computer networks, and operating systems. As one can observe, the core courses are scattered across all the curriculum. Some of the courses in the CE curriculum are shared with the ES program, specifically those from the first till the fourth term. Moreover, the focus on structural and computational mechanics is due to the fact that the department in the School of Engineering that supports the program is the Applied and Computational Mechanics Department.

The core courses are approximately distributed in the following way, as Tab. 3 shows: 19% in Mathematics, 17% in Physics and Chemistry, 14% in Programming, 21% in Computer Science, 12% in Numerical Methods, 12% in Applied and Computational Mechanics, and 5% in other disciplines.

Fig. 1 illustrates the basic components of the curriculum, describing how they are distributed along the terms. The term is composed by 15 weeks, so the maximum number of hours a student spend per week in classes is 28 hours, in the third, fourth, fifth and sixth terms. Recall that the elective activities are not courses, but external activities such as conferences, short-term courses, and hands-on training experiences. In order to conclude the ES bachelor, it is required that some of the core courses, and all the optional courses and elective activities are concluded. The number of terms suggested to conclude the ES bachelor is

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Table 2. CE core courses.

Year	First Semester	Hours	Second Semester	Hours
1	Calculus I Algorithms Programming Lab Introduction to Physical Sciences Lab Fundamental Chemistry Chemistry Lab Analytic Geometry and Linear Systems	60 60 30 30 60 30 60	Calculus II Data Structures Programming Lab II Introduction to Computational Engineering Physics I Physics Lab I Structures and Transformation Lab Introduction to Statistics	60 60 30 30 60 30 30 60
2	Calculus III Object-Oriented Programming Physics II Calculus of Probability I Graphical Representation and Geometric Modeling	60 60 60 60 60	Differential Equations I Data Structures II Physics III Linear Algebra Mechanics Numerical Calculus	60 60 60 60 60 60
3	Transport Phenomena Introduction to Computational Modeling Graph Theory Digital Circuits Fundamentals of Structural Mechanics Mechanics of Materials	60 60 60 60 60 60	Computer Organization Software Modeling Solid Mechanics I Structural Mechanics Operational Research	60 60 60 60 60
4	Analysis and Project of Algorithms Introduction to Discrete Methods Databases Operating Systems	60 60 60 60	Formal Languages and Automata Theory Computer Networks Introduction to the Finite Element Method	60 60 60
5	Ecology and Environment Preservation Parallel Programming	30 60		

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Table 3. Distribution of core courses by disciplines.

Discipline	Hours
Mathematics	480
Physics/Chemistry	420
Programming	360
Computer Science	540
Numerical Methods	300
Applied and Computational Mechanics	300
Other	120
Total	2,520

six, and for this reason these activities are distributed till the sixth term. Also, due to the fact that elective activities are usually related to advanced topics, they should be attended by junior and senior students. This is a suggestion, since students are free to attend the courses in a distinct way.

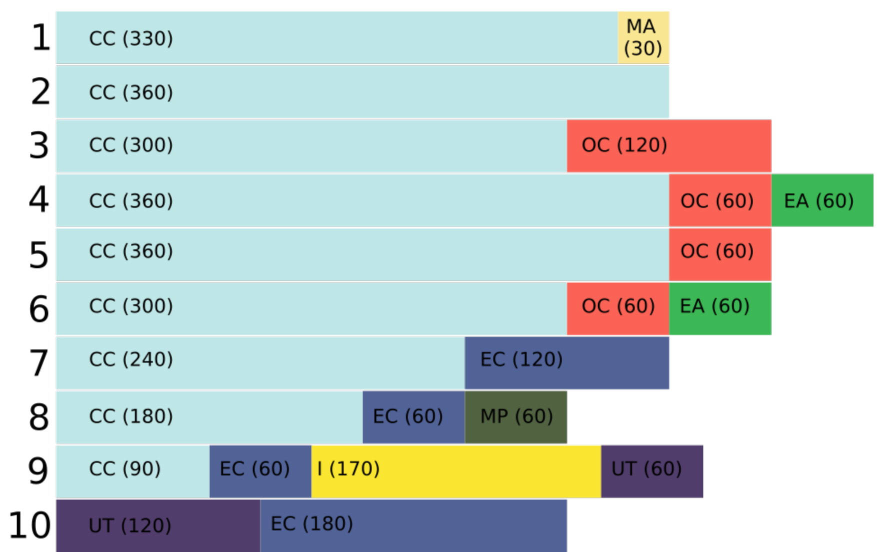

Fig. 1. CE curriculum: basic organization. CC represents core courses, MA mandatory activity, EC elective courses, EA elective activities, OC optional courses, I internship, MP multidisciplinary project and UT Undergraduate Thesis. Each line represents an academic term. Within the parentheses are represented the hourly loads of each components of the curriculum along the term.

Also, as one can observe from Fig. 1 and Tab. 1, the key attribute of the CE curriculum is its flexibility. In the curriculum 840 hours, or 22% of the hours required for obtaining the CE Bachelor's degree, are of free choice of students. If

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we consider that the theme of the Undergraduate Thesis is usually also chosen by students, the total number of hours in which they decide what to study increases to $1,020$, or about 27% of the total. Students have probably thousands of courses to choose as optional, and about 50 to choose as elective ones.

Such a huge number of courses available to choose are exciting for some focused students, but may represent a problem for others. Although the student can count not only on the head of the CE program for advise, but also on other professors and senior colleagues, a group of professors, responsible for the conception, consolidation and continuous updating of the curriculum, decided to group the elective courses into three distinct groups, called thematic groups. These groups are the following: Numerical Methods and Optimization; Applied and Computational Mechanics; and Applied Computational Systems. The idea of the groups is only to guide students in their choices. For example, if a student would like to focus on Numerical Methods and Optimization, he/she can consult the list of elective courses that are related to this topic. Students inclined to be generalists can explore a wider range of courses in these three topics. Examples of courses that are offered as electives are: Numerical Solution of Differential Equations; Scientific Visualization; Fluid Mechanics; Mechanics of Materials II and III; Computational Modeling of Aeroelastic Phenomena; Advanced Topics on Geometric Modeling; Image Processing; Applying Image Processing to the Solution of Engineering Problems; Introduction to Number Theory; Computational Intelligence; Queue Theory; Non-Linear Programming; Artificial Neural Networks; Computer Graphics; Computer Architecture; Evolutionary Computing; Distributed Systems, among many others.

3.1 Multidisciplinary Project

The Multidisciplinary Project has the objective of applying all the knowledge that students have acquired along the program to model a problem proposed by the professors, i.e., a capstone project. Basically all the modeling phases must be observed by students: first, they have to create a real system, perform some experiments and acquire, using sensors, cameras or other instruments, experimental data. Then they have to use a mathematical model to describe the phenomenon under study, and use numerical methods to implement it. Simulations are performed and their numerical results are compared to the experimental ones. Some adjustments may be necessary in this process. Some visualization tools may also be used to present the numerical results. Two professors teach this course, one from the Computer Science Department, and another from the Applied and Computational Mechanics Department. This is done in order to guarantee the multidisciplinary nature of the class. Students are divided in groups to implement the tasks, and each group works on a different task.

The approach used by professors in the course involves a discussion of common issues in the modeling area, such as conceptual models that can not be used to make predictions; the use of projects developed by third-party, and the lack of full control over their operation; the lack of documentation to describe the implementation of a model and its impacts; and especially on the difficulties of

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fitting parameters and validating models in order to obtain reliable results and predictions.

With respect to project themes, students are led to think, as a way of contextualization, in a complex problem for which the computational modeling is important. Then the student has to associate it with a simpler problem, which one could perform simple laboratory experiments, without the need of sophisticated tools. This is not only due to budget restrictions, but above all the idea that creativity is also necessary for a multidisciplinary training.

The choice of the project theme may take some time, and in the meanwhile some theoretical classes are offered as a way to review important concepts and applications. From this point onwards, materials and methods are proposed by students and the dynamic of meetings changes, so that they assume the leading role. Teachers encourage interaction between groups by asking for systematic presentations of each group's progress, and allowing opinions and suggestions from others, and most of the time they are taken into account.

Students have to describe technical problems and results in a final written report. In addition to the presentation of the reports in classroom, students are also encouraged to produce a video describing the entire project, which is also used to assess their work. Recently, a channel of the course was created in YouTube to store these videos. It is expected that the channel can help other students interested in computational modeling as well as to disseminate the CE program.

4 Participation of Students in a Interdisciplinary Research Environment

An additional advantage of the CE program at UFJF is its proximity to the Graduate Program on Computational Modeling (GPCM). Almost all researchers at GPCM are also professors in the CE program. This proximity is not only important to present the students to the state of art in the research fields of many distinct areas, but also to attract them to work on research.

UFJF funds scholarships to undergraduate students to work on research. This funding program in known as Iniciação Científica (scientific initiation), and offers scholarship from CNPq (the Brazilian Research Council), FAPEMIG (Research Council of the Minas Gerais State) and UFJF. Many of the CE undergraduate students work on interdisciplinary research topics conducted by professors of the GPCM. This research activity may be used by them as an Internship. Also, during the research activity it is usual for students to attend to conferences, workshops, etc., which can be used as part of elective activities. Finally, some of them publish works on conferences, workshops and even in scientific journals, as main authors or coauthors. Part of this research can be presented as the Undergraduate Thesis. As a result, almost all of the CE students choose to enter in a graduate program after graduating. In fact, some of the senior students attend graduate classes while they are finishing the undergraduate, reducing the time to obtain a master degree. Since in UFJF it is mandatory to hold a B.S.

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degree to be admitted in a graduate program, this is only possible because they finish the ES program after 3 years.

5 Other CE undergraduate programs

The SIAM list of undergraduate CSE programs [5] identifies only twelve programs that offer bachelor degrees on Computational Science and Engineering. For sure, this number is out dated. A simple search in the web returns a much large number of colleges and universities that offers distinct types of CSE degrees, and some works[13, 6] present an additional list of programs. Basically it is possible to identify distinct ways to structure these programs[6]:

- Full Bachelor degree in CSE;
- Full Bachelor degree in Computational Finance, Computational Physics, Computational Mathematics or Applied Mathematics;
- Emphasis or Concentration in CSE;
- Minor program in CSE.

American University[1] offers a full B.S. in Computational Science, and students can choose distinct application areas, including biology, chemistry, computer science, economics, environmental studies, finance, mathematics, physics, psychology, and statistics. Hood College[4] offers a full B.S. in Computational Science with concentration in four distinct areas: chemistry, ecology, molecular biology and physics. Its Senior Project in Computational Science seems to be very similar to the Multidisciplinary work described in this work: the student uses computational knowledge and skills to investigate a given problem. The same concept is present in the B.S. in Computational Science offered by the Florida State University[2]: in the Practicum in Computational Science course, students are required to work on an ambitious project in computational science. Stanford University[7] offers a full B.S. in Mathematical and Computational Science, and tracks on biology, engineering and statistics are available. The University of Queensland [9] offers a Computational Science and Computer Science Dual Major as part of the Bachelor of Science program. This is similar to the ES undergraduate program, that allow students to have one or more majors in the programs that are part of the ES. Many students that obtained a B.S. in CE have also obtained a B.S. in Computer Science. Many other universities offer full bachelor programs in the CSE field[11, 12, 3, 10, 8].

The undergraduate CE program at UFJF shares common features with these bachelor programs, including mathematics (specially Calculus), programming, and numerical methods. Most CE programs require a capstone project and an industrial internship. Finally, an application area is usually present in most of CE programs. From a design point of view, CE program at UFJF can be distinguished from the other CE programs in the following way: a) strong emphasis on mathematics and sciences, which corresponds to 900 hours of lecture class time; b) inclusion of courses that are typical of Computer Science, such as Computer Organization, Databases, Computer Networks and Operating Systems, to show

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students how computer systems work, and how these systems should be used to improve performance of applications; and c) the proximity to the graduate program, which helps to attract students to an undergraduate research experience.

6 Conclusions

In this work we presented the curriculum of the undergraduate program in Computational Engineering at Federal University of Juiz de Fora, Brazil. This 5 years full bachelor degree has the focus on mathematics, sciences (physics and chemistry), programming and numerical methods. Moreover, the curriculum also focuses on structural and computational mechanics due to the fact that the department in the School of Engineering that supports the program is the Applied and Computational Mechanics Department. Another key attribute of the CE curriculum is its flexibility: up to 27% of the hours required for obtaining the CE Bachelor's degree are of free choice of students. The program is evaluated frequently by the Brazilian Government, and in its last evaluation it achieved the maximum grade (5 in a scale from 1 to 5).

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