STEM IN HIGHER EDUCATION: THE USE OF AN ADVANCED COMPUTING ENVIRONMENT TO DEVELOP FUNDAMENTAL SKILLS FOR UNIVERSITY CAREER AND THE WORLD OF WORK

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Abstract

According to much research, with the fourth industrial revolution the set of skills required in both old and new professions are changing. At a time when revolutionary technologies are penetrating more and more into everyday life, it is important that students, during the university courses, develop cognitive abilities (such as logical reasoning and visualization), content skills (which include ICT literacy), complex problem solving skills and technical skills (such as programming and computational thinking). One of the tools to enhance teaching and learning of STEM disciplines with technologies is an Advanced Computing Environment (ACE), a system that allows to perform numerical and symbolic computations, to make graphical representations in 2 and 3 dimensions and to create mathematical simulations through interactive components. The objective of our research is to understand if the use of an ACE in the university education of STEM disciplines allows students to develop important skills, such as problem solving, logical reasoning, mathematical reasoning, visualization, computational thinking, that will facilitate their university career and their entry into the world of work. To answer this question, we involved 48 university students in a 15-hour laboratory on the use of an ACE. The students were enrolled in degree courses in various STEM disciplines (Energy Engineering, Chemical Engineering, Physics, Mathematics Engineering, Computer Engineering, Aerospace Engineering, Biomedical Engineering, etc.) and they attended different years of bachelor’s and master’s degrees. During the laboratory, the students learned the functionalities of an ACE and used it for visualization and modelling, to write procedures for problem solving and for the creation of interactive materials. In the second part of the laboratory, the students worked in groups or individually on the creation of an interactive worksheet involving a STEM discipline of their interest. As a final product they could opt for the resolution of a problem with the generalization of the resolution, the study of a problem situation or of a theoretical concept, or the development of an interactive application. Their attitude toward the use of an ACE for the development of skills, previous knowledge on STEM software and their reasons for learning how to use an ACE were measured through an initial and a final questionnaire that students were asked to fill in at the beginning and at the end of the laboratory. The worksheets produced by the students were classified into three main categories (independently of the discipline of interest): problem solving, problem solving applications, applications (function studies or theoretical formulas) and interactive files (such as "program" or "app"); they were analysed and cross-checked with the answers to the questionnaires. The results obtained show that the use of an ACE in the STEM disciplines can develop, in different ways, the key skills mentioned above for the university career and for the world of work.

Keywords: Advanced Computing Environment, Professional Skills, Higher Education, Problem Solving, STEM Education.

1 INTRODUCTION

The Fourth Industrial Revolution, based on digital innovation in industry processes and on technologies that combine hardware, software, and biology, is interacting with other socio-economic and demographic factors and is changing the business model in all industries. New categories of jobs will emerge, partly or wholly displacing others, and the skill sets required in both old and new occupations will change and transform how and where people work [1]. At a time when revolutionary technologies are penetrating more and more into everyday life, the demand for various forms of technology competency such as technology design and programming grows [2]. Proficiency in new technologies is only one part of the skills supposed to keep growing in prominence by 2022; there are also ‘human’ skills such as creativity, originality and initiative, critical thinking, resilience, flexibility and complex problem-solving that will likewise retain or increase their value. It is very important that students, during the university courses, develop all of these skills [1]. In this paper we focus on the cognitive abilities (such as logical reasoning and visualization), content skills (which include ICT
literacy), complex problem solving skills and technical skills (such as programming and computational thinking).

One of the most useful tools to enhance teaching and learning of STEM disciplines with technologies is an Advanced Computing Environment (ACE), a system that allows to perform numerical and symbolic computation, make graphical representations (static and animated) in 2 and 3 dimensions, create mathematical simulations, write procedures in a simple language, programming, and finally elegantly connect all the different representation registers together with verbal language in a single worksheet [3]. An ACE can help develop problem solving competences because it offers various types of representations and it enables the resolution of a problematic situation. Starting from mental thinking, the solving process can be carried out through several modalities, such as words, graphics, algebra, and experimenting through computerized simulations. Being able to properly combine those modalities is a crucial aspect in problem solving, and the fact that they can be used in a single environment promotes high levels of clarity and understanding. An ACE is able to support students in the reasoning processes, in the formulation of exit strategies and in the generalization and re-adaptation of the solution in different contexts [4, 5]. A very important aspect of an ACE for problem solving is the design and programming of interactive components. In the resolution of a problem, they enable to visualize how the results change when the input parameters are changed and therefore they allow to generalize the solving process of a problem. In the problem solving process, generalizing is an important process by which the specifics of a solution are examined and questions such as why it worked are investigated [6, 7]. This process is analogue to the verification and elaboration stages of invention and creativity [8]. The interactive components also allow to create interactive files in which the user interacts with the software by inserting texts or numeric values into boxes, moving the cursor of a slider or clicking a button to get one or more numerical or graphical results. To create a system of interactive components, composed of several interactive components also different from each other, it is necessary to use a special and simple programming language. This process requires great creativity to design the system and a lot of analytical and computational thinking to relate the interactive components regarding the inputs that will be given by the user to the outputs. The objective of our research is to understand if the use of an ACE in the university education of STEM disciplines allows students to develop important skills, such as problem solving, logical reasoning, mathematical reasoning, visualization, computational thinking, that will help them in their university career and their entry into the world of work. In this paper, we discuss the result of a 15-hour laboratory on the use of an ACE, which involved 48 university students. In particular, we discuss the attitude of the students toward the use of an ACE for the development of skills and their reasons for learning how to use an ACE.

2 METHODOLOGY

The laboratory was held in 3 editions, two of them in the first semester (October - December 2018) and one in the second semester (March-April 2019) of the academic year 2018/2019. A total of 48 students participated in the laboratory. They were enrolled in degree courses in various STEM disciplines (Energy Engineering, Chemical Engineering, Physics, Mathematics Engineering, Computer Engineering, Aerospace Engineering, Biomedical Engineering, etc.) and they attended different years of bachelor’s and master’s degrees. The objective of the laboratory was to teach how to use an ACE. The topics of the meetings were: potential of an Advanced Computing Environment and basic functionalities (2h); the geometric display with an Advanced Computing Environment (2h); writing procedures for solving problems (2h); preparation of interactive materials (2h); modelling with an Advanced Computing Environment (2h) and problem solving with an Advanced Computing Environment (5h). Then, during the laboratory, the students learned the functionalities of an ACE and used it for visualization and modelling, to write procedures for problem solving and for the creation of interactive materials. The working methods were the following: in each lesson, part of the time was devoted to the exploration of the Maple ACE led by the teachers; in the remaining time, the students had the opportunity to work independently in the resolution of proposed exercises, so as to become familiar with the system; no homework tasks were assigned. All course materials and activities were made available to students through a Moodle platform integrated with the Maple ACE [9–11]. In the last 5 hours of the course, dedicated to problem solving with an ACE, students were asked to work in groups or individually on the creation of an interactive worksheet involving a STEM discipline of their interest and to submit it as a final evaluation test. As a final product they could opt for the resolution of a problem with the generalization of the resolution, the study of a problem situation or of a theoretical concept, or the development of an interactive application. The teacher was available to students to
help them develop their final product and to understand the necessary commands. At the end of the laboratory, each student completed a satisfaction questionnaire.

To evaluate the attitude of the students toward the use of an ACE for the development of skills and their satisfaction with the laboratory, we analyzed their final products and their answers to the final satisfaction questionnaire.

3 RESULTS

3.1 Analysis of final products

The students worked in groups on the preparation of the final product but each one submitted their own work. To study the work done by the students, we classified submissions into 3 categories:

- resolution of a problem with the generalization of the resolution (16)
- study of a problem situation or of a theoretical concept (25)
- interactive application (7)

To highlight the skills that the students have developed in creating their work, we will show some representative examples for each category.

3.1.1 Resolution of a problem with the generalization of the resolution

The problems developed by the students related to the following topics: statistical test on the production of defective products of an industry, thermal conduction, communication between two satellites in orbit, study of the reaction time of lithium chloride, economic sustainability of a hypothetical stage of ownership, model to describe the variation of the height of the liquid in a tank and energy of a racing vehicle. In this case the students used the ACE to solve the problem and they took into consideration many solving strategies: algebraic and symbolic computations (counts, equations, inequalities, equation or inequalities systems, differential equations and integrals), tables, graphs in two or three dimensions, flow charts, bar charts, unit conversions. At the end of their resolution, they used the ACE to generalize the solving process, to see how the solution to the problem varies with the varying of initial data entered by the user. Many different interactive component systems were used. The example in Fig. 1 refers to the generalization of a problem that aims at verifying the hypothesis that the defectiveness of the objects produced by a company follows the Poisson distribution. The company produces 1000 pieces a day of the same mechanical component and controls the production quality for N=100 days. The defective parts (k) can vary from 0 to 5 and, for each case, the number of days in which k pieces of the daily production are defective is indicated.

![Figure 1. First example of generalization of a problem.](image-url)
In the system of interactive components created, text areas were used to insert the input data: the frequencies observed, the number of tests and the level of significance of the test. A graphical component was used to display the comparison between observed and expected frequencies and a text area was used to display the test results. In this case all the commands that regulate the operation of the system of interactive components are enclosed within the "Run test" button. The button stores the inputs entered by the user, processes the results and inserts them in the appropriate components. To perform all these actions, the "Run test" button has been programmed with the code shown in Fig. 2, present inside the button.

```plaintext
1 use DocumentTools, Statistics in
2 lo := Do(%TextArea0); N := Do(%TextArea1);
3 alpha := Do(%TextArea2); nel := nops(lo); #input data
4 mcamp := 0; for i from 1 to nel do mcamp := mcamp + (i-1)*lo[i]; end do;
5 mcamp := mcamp/N; #Sample average calculation
6 pdiff := mcamp/1000; #Calculation probability of defects of any piece
7 Do(%TextArea3 := evalf(mcamp, 4)); Do(%TextArea4 := evalf(pdiff, 4)); #Output results
8 #Calculation of theoretical frequencies from the Poisson distribution
9 lp := copy(lo);
10 for i from 1 to nel do lp[i] := evalf(N*mcamp*(i-1)*exp(-mcamp)/(i-1)!, 3); end do;
11 hop := ColumnGraph([lo, lp], color=["Red", "Blue"], title="Frequency comparison",
12 legend=["Observed frequencies", "Expected frequencies"]);
13 Do(%Plot0 := hop); #Histograms
14 #Square chi calculation
15 chisq := 0;
16 for i from 1 to nel do chisq := chisq + (lp[i]-lo[i])*(lp[i]-lo[i])/lp[i]; end do;
17 dof := nel - 2; chi2red := chisq/dof; #Degrees of freedom
18 Do(%TextArea5 := evalf(chisq, 4)); Do(%TextArea6 := evalf(chi2red, 4)); #Output results
19 chdist := PDF(ChiSquare(dof), t); #Distribution of the chi square
20 #Calculation probability of obtaining a chi-square value greater than the calculated one,
21 #due to the effect of statistical fluctuations only
22 probtest := int(chidist, t-chisq..Infinity);
23 Do(%TextArea7 := evalf(probtest, 4)); #Output results
24 #Determine the outcome of the test
25 if probtest > alpha then
26 esito := "Accept the null hypothesis";
27 else
28 esito := "Reject the null hypothesis";
29 end if;
30 Do(%TextArea8 := esito); #Output results
31 end use;
```

Figure 2. Code inside the "Run test" button.

The code contains counts (simple operations and integrals) to compute the sample mean and the probability, for loops to compute the theoretical frequencies from the Poisson distribution and the chi square and a condition to determine when to accept or reject the hypothesis and return the correct result to the user.

Other types of interactive components used for the generalization of the problem are the sliders: they are used in the example in Fig. 3 to vary the angle of a second satellite and in the example in Fig. 4 to vary the length and the radius of a beam. In both examples, as the slider cursor changes, the graphs change accordingly: a two-dimensional graph in the case of the representation of two satellites and a three-dimensional graph in the case of the representation of the beam.
In creating this type of products, the students used considerable creativity in conceiving the problem, developed problem solving skills in the resolution of the problem and in its generalization, developed considerable computational thinking skills to design and implement the interactive component system and considerable programming skills in writing the codes to govern them.

3.1.2 Study of a problem situation or of a theoretical concept

As a second type of final product, the students used the ACE to analyse a theoretical or problematic situation through the study of a formula or a model. The topics they dealt with were: the study of an elastic line of a square beam, a linear model for studying a love story mathematically, the computation of pressure coefficients on a flat plate hit by incidence, the interference phenomena of waves, the evaluation of the saturation of the core of a transformer, the finite energy signals, a study of a complete harmonic oscillator, the computation of the Fourier transform, the study of the vibrations of a system, the study of the Doppler effect, the determination of the equation of motion of a damped forced system. In this case, the students used the ACE to study a formula or a model and they considered many solving strategies: algebraic and symbolic computations (counts, differential equations, integrals, systems of differential equations, power series and Fourier transforms) and
graphs in two or three dimensions. The interactive components were used to study a formula or a model designed to vary some parameters, entered by the user.

The example in Fig. 5 concerns the study of finite energy signals, their spectrum and autocorrelation. In the system of interactive components created, the user can insert the ends \([a, b]\) of the support and a real function defined in that interval and he will automatically obtain the graphs of the function, its amplitude spectrum and its autocorrelation. In this case the button that links the inputs entered by the user and the outputs obtained as a result has been programmed.

![Figure 5. Code inside the "Run test" button.](image1)

The example shown in Fig. 6 - very creative and original - shows how a love story can be considered in a mathematical key, through the study of a linear model consisting of two differential equations (one for her and one for him) containing essential information on how each individual reacts to the love and fascination of others. In Fig. 6 a generalization of the study of this linear model is shown that can be applied to any couple relationship. As explained in the file, by entering the data in the text boxes, you can click the button and view and interpret the graph representing the trend of your love story.

AND YOU? DO YOU WANT TO DISCOVER HOW YOU’LL FINISH YOUR LOVE STORY?
To find out how your love story will end up enter:
- A to quantify your feelings (positive if it is love, negative if it is hate, null if it is indifferent)
- B to quantify your feelings conditioned by your partner (positive if it is love, negative if it is hate, null if it is indifferent)
- C to quantify the feelings of your partner (positive if it is love, negative if it is hate, null if it is indifferent)
- D to quantify the feelings of your partner conditioned by your feelings (positive if it is love, negative if it is hate, null if it is indifferent)

![Figure 6. Example of a model to consider a love story in a mathematical key.](image2)
The programming of the interactive components allowed students to generalize a resolution process, even if linked to the study of a theoretical concept and not to the resolution of a problem. In creating this type of product, students developed computational and programming thinking to design the interactive component system.

### 3.1.3 Interactive application

The last type of work produced by the students was an exclusively interactive file designed as a real application, in which the user can insert data and obtain some results. The types of interactive files created were: an application to compute the tax code, an interactive periodic table, an application for the validation of a retinal segmentation algorithm and a program to analyse the variation of filter Bode diagrams active when some parameters change. In this case, only interactive components were used to make the file completely interactive, as an application, and all the solving procedures were inserted directly into the component codes.

Fig. 7 shows an interactive periodic table, in which the user can click on one of the elements (the grey buttons on the left) and will automatically obtain all the information on the element represented in the column on the right. Since the interactive table works when the user clicks on one of the elements, it was necessary to program every single button of the periodic table.

![Interactive periodic table](image)

**Figure 7. Interactive periodic table.**

To automate the process, the student inserted into the Startup Code of the file (a code window that is automatically executed when the file is opened) a procedure that returns all the information of one element.

In the interactive file shown in Fig. 8 an application was created to compute the tax code of a person born in Turin. Different types of interactive components were used to insert the input from the user: text area for first and last name, drop-down menu for date of birth and buttons for gender selection (these last types of components were used to get the data in a specific format). By clicking on the "Click here to generate it!" button, which contains all the necessary commands, the required tax code is automatically generated.

**COMPUTATION OF TAX CODE**

Fill in the following fields to generate your tax code:

Surname: [Text Box]
Name: [Text Box]
Birth place: [Text Box]
Date of birth: [Date Picker]
Gender: [Radio Buttons]

Your tax code, if you were born in Turin, would be: [Text Box]

**Figure 8. Computation of tax code.**
To create this type of file, students have developed remarkable abstraction skills to design the application, computational thinking skills to design and develop the system of interactive components (based on the possible use of the application by the user) and advanced capabilities in the use of the programming language.

3.2 Analysis of the answers to the final questionnaire

At the end of the course, through a final questionnaire which included open questions and Likert-scale questions from 1 to 5 (1 = strongly disagree, 5 = strongly agree), students were asked to evaluate the tools learned in relation to utility for study and for work.

Fig. 9 shows that most students believe that learning how to use an ACE is both useful for the world of work and for their university career. As shown in Fig. 10, they believe it is very useful for solving problems, simulating systems, better understanding some subjects of study, writing procedures and, among all these aspects, the first two in particular.

![Figure 9. Answers to the question “To what extent do you believe that knowing how to use an Advanced Computing Environment can offer you more opportunities in the following areas?”](image1)

![Figure 10. Answers to the question: “To what extent do you think learning to use Maple can be useful for the following aspects?”](image2)

Students appreciated the various functionalities of an Advanced Computing Environment shown during the course (symbolic computation, numerical computation, graphic visualization, procedures, Math Apps, interactive tutors, interactive components) and most of the students believe that they will be useful to them in their future (Fig. 11), especially for numerical computation, graphic visualization and for writing procedures.
The answers of the students in Fig. 12 show a very good level of satisfaction of the laboratory, in fact the majority of the students is satisfied of having followed the laboratory, believes that the course has satisfied their expectations and would recommend to a colleague the frequency of this laboratory.

**Figure 11. Answers to the question: “To what extent can the following features of an Advanced Computing Environment be useful to you in your future?”**

**Figure 12. Answers to the question about the satisfaction of the laboratory.**
4 CONCLUSIONS

From the analysis of the final questionnaires it can be deduced that the students appreciated the laboratory and believe that an ACE is a useful tool to learn for their university career and for the world of work. During the laboratory, the students learned the functionalities of an ACE and used it for visualization and modelling, to write procedures for problem solving and for the creation of interactive materials. In the second part of the laboratory, the students worked on the creation of an interactive worksheet. All the submitted products (resolution of a problem with the generalization of the resolution, study of a problem situation or of a theoretical concept or interactive application) show an excellent use of the ACE achieved by all students at the end of the laboratory. In creating this type of product, the students used considerable creativity in conceiving the problem, developed problem solving skills in the development of the problem and in its generalization, developed considerable computational thinking skills to design and develop the interactive component systems and considerable programming skills in writing the codes to govern the system of interactive components.

The results obtained show that the use of an ACE in the STEM disciplines can develop, in different ways, the key skills for the university career and for the world of work, such as technology design and programming, complex problem-solving, creativity, originality and initiative, critical thinking, computational thinking.

REFERENCES