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Virtual tool for training and evaluation of problem-based engineering subjects

O A González-Estrada [1*], J F Cáceres-Ramírez [2*] and W Pinto-Hernández [2]

[1] GIC, School of Mechanical Engineering, Universidad Industrial de Santander, Ciudad Universitaria, Bucaramanga, Colombia.
[2] GIEMA, School of Mechanical Engineering, Universidad Industrial de Santander, Ciudad Universitaria, Bucaramanga, Colombia.

[*]agonzale@uis.edu.co

Abstract. In Educational Technology, one of the challenges in the use of virtual tools for engineering education is the assessment of problem-based subjects. In this work, a software generator of exercises is developed, to be contained in a virtual platform, which seeks to improve the learning process and the evaluation of the subjects based on problems such as, e.g., Mechanics of Materials. The student can use it for training, with content corresponding to the subject of the course, monitoring their performance and obtaining effective feedback. Additionally, the teacher has the possibility to periodically conduct formative assessments that allow him to recognize the concepts in which the students are failing. This tool can provide an objective instrument to normalize grading across groups directed by different lecturers. The software was written in the programming languages Java, JavaScript and HTML for the presentation of the contents, and can be used from any electronic device. This tool can be used to enhance classroom learning in face to face, blended or online learning.

1. Introduction

Since its inception, the World Wide Web has undergone several transformations thanks to technological advances and the needs that different types of users demand. Web 2.0 is the conception of the network as a platform, it gives people an active role, and encourage participation and usability [1]. These features have promoted the boom of Educational Technology aimed to enhance the teacher-student experience, improve knowledge management [2], and facilitate the learning process [3]. Within Educational Technology, electronic learning (e-learning) consists in the use of new multimedia and Internet technologies to improve the quality of learning by facilitating access to resources and services, as well as to the collaboration and remote exchange. In e-learning, the formative process takes place through a kind of virtual environment in which the teacher-student interaction takes place as well as the activities of the students with the learning materials. The e-learning serves as a means for face-to-face, online or blended teaching.

Educational Technology has many advantages, it can be used to simplify and reduce the cost for labs used to demonstrate concepts [4], massify access to knowledge with initiatives as massive online open courses (MOOC), improve feedback for effective formative assessment [5], or even help vulnerable populations by facilitating access to remote places affected by security issues [6]. Challenges for developing countries include improving Information and Communication Technologies

(ICT) infrastructure, facilitating access and use of the technological resources, and encouraging the adoption of new training methods [7].

We can find numerous efforts that have been reported in the literature to support the teaching-learning process of various subjects. In [8] a program created in Macromedia Flash v8.0 focuses on the understanding of the laboratory tests that accompany the theory of the course Mechanics of Materials. It includes tests of traction, compression, shear, Poisson's effect, torsion, extensometry, bending, columns and photo-elasticity. The student has different types of evaluations that not only allow him to evaluate his learning but also prepare him for the tests that are normally carried out in theory courses.

In [9], a didactic tool is developed with the objective of supporting the teaching-learning process of Linear Algebra in engineering degrees. When entering the problem data in the software, the operation is processed and the procedure is visualized, showing step by step how the problem is solved. Moreover, it contains theoretical material to review the concepts that the student needs to develop the exercises. The proposed system was implemented in the C ++ Builder.

SimulPhysics [10] is a multiplatform software, written in Java, that contains a set of interactive simulations on different topics of physics that supports the assimilation of the concepts developed in the theoretical part of the course. On the platform, we can find simulations on different topics that are seen in the subject of Basic Physics, e.g., mechanics, optics, waves, etc.

Celosías paramétricas [11] is an Android application, targeted to Education and Learning, that automatically generates trusses by combining parameters related to the geometry, material, supports and loads, and shows the influence of each of them on its structural behavior: reaction forces, stresses, and deformations. It allows the optimization of the structural design by determining the values that produce the lowest stresses and deformations for the highest loads, while minimizing the weight.

MDSolids [12] is an educational software package dedicated to the introduction of the Mechanics of Materials course. The software has an intuitive interface that guides the user to understand important facts that are found in different types of problems. It helps to visualize the nature of internal stresses and strains.

Regarding assessment, Hernández Pina [13] investigates the learning process in the university context, and concludes by stating that the way in which the teacher raises the evaluation affects learning approaches (superficial or deep) and the quality of such learning. Quantitative evaluation strategies lead to superficial learning approaches, while formative and qualitative strategies can produce deep learning and high-performance approaches [14]. In [15], a project carried out by the School of Engineering of the EAFIT University implements an interactive software in a virtual platform. With this tool the students can carry out tests, clarifying doubts and preparing them for the final test. It incorporates a rating system and a problem generator algorithm for the course of Statics.

Following the development of the new Information and Communication Technologies (ICTs), we propose a software tool for a virtual educational environment which could be used to improve the assessment of problem-based subjects and provide a standardized marking system that could be used across classes and campuses. The software generates problems on the different topics of the subject Mechanics of Materials, giving the student an interactive tool that allows him to learn by solving problems that help him to strengthen his analytical skills and increase his cognitive abilities. Moreover, the teacher could perform controls and follow performance indicators, which can be used as a reference of the level of study and understanding of their students on the content seen in class, and the competences defined in the curriculum.

The paper is organized as follows: in the next section, we exposed the methodology, including the knowledge base and performance indicators, which are used to define the constraints for the design of the tool. In section 3, we present details related to the implementation of the tool in the Learning Management System. Conclusions are given in the final section.

2. Methods

The methodology is focused on the subject Mechanics of Materials, although it could be easily extended to other problem-based subjects in engineering curricula. The project is based on the

framework of Educational Technology, which refers to the systematic way of conceiving, applying and evaluating the set of teaching and learning processes, considering both technical and human resources and the interactions between them, as a way to obtain a more effective education.
In this regard, we define a strategy to tackle different issues detected during the learning and assessment process in the schools of engineering at Universidad Industrial de Santander. First, when evaluating problem-based subjects, the teacher should pay attention to the process followed by the student to reach the answer. Normally, the problem solution is divided into steps, and a weighting is given to each of the partial steps. However, if the student fails early in the process, the teacher should evaluate the remaining steps considering the wrong values obtained at the beginning, and their impact in the final answer. This is particularly difficult for large groups, which finally yields non-homogeneous, subjective marks. This difference is accentuated if we consider groups led by different teachers. Moreover, regarding teachers, there is a notable difference in the assessment performed by tenured and non-tenured professors, mostly due to the correlation between the grades and the teacher evaluation, which affects contract extensions for non-tenured professors. There are even instances where the content given by the teacher is incomplete and we end up with groups of students with different level of competences reached. This non-standardized marking system gives rise to problems for the mobility of students across campuses, and helps to increase retention rates.

We start by defining the knowledge base that encompasses the area of Mechanics of Materials, putting special attention on the competences required at the end of the course. Next, we work on the performance indicators for the established competences, which help to define the constraints for the design of the tool.

2.1. Subject description and knowledge by competences

The subject Mechanics of Materials [16] studies the mechanics of deformable solids by simplified linear elastic models, relating in the design process the parameters of geometry, forces, and material. The mechanical engineer works with static and moving mechanical structures and systems. The design and calculation of these systems involve considering all the loads that act on each of its elements and the intensity of internal force (stresses) generated by these loads. In mechanical design, the stresses can be related to the mechanical strength of the material to assess the possibility of failure for a given element. In general, a machine element can fail because the stresses exceed the strength of the material, or because excessive deformation is occurring that prevents its normal operation [17]. The calculation of these stresses and deformations involves considering the internal forces and the geometric features of the element.

At the end of the course the student is expected to:

- Recognize the type of stress produced by a force or moment applied to a machine or structural element, according to the way it acts on the element.
- Calculate stresses and deformations that occur at any point of an element subjected to a specific type of load.
- Select the critical point where the highest stress occurs in any element subjected to several types of load simultaneously.
- Define the plane stress state at the critical point of any element subjected to different types of external load.
- Analyze the possible failure of an element subjected to different types of loads using different criteria according to the type of material, and propose changes to the geometry accordingly.

The curriculum is divided into four fundamental thematic blocks. The first block addresses the introduction to the concepts of stress and strain, and the state of axial loading. The second block deals with elements subjected to pure torsion. The third block describes pure bending, typical of beams. The fourth block refers to multiaxial stress, combined load, pressure vessels and design failure criteria.

2.2. Performance indicators

The performance of the student is evaluated with quantifiable indicators, related to the competences, which provide a global assessment of his understanding of the subject. These are:

- Identifies the type of load produced by a force or a moment applied on a machine or structural element and evaluates the corresponding stress and deformation.
- Recognizes the differences between the different types of stresses and deformations that appear in elastic problems.
- Identifies the critical point where the highest stresses occur in any mechanical element subjected to several types of load simultaneously.
- Calculates the principal stresses, maximum shear stress and equivalent normal stress at the critical point of any element subjected to different types of external load, according to a specified failure theory.

2.3. Design of the tool

In this section, the thematic and evaluative content of the course is identified, as well as the parameters that can be varied to generate multiple versions of the same exercises without modifying their knowledge structure. To carry out this process the following steps were followed:

Definition of the learning objective: to be able to define the exercise that is going to be proposed, we must know what we want to achieve with it, i.e., identify the cognitive competences that the student must acquire during the course. Here, we refer back to the competences listed in section 2.1.

Definition of the exercises: a review of the curriculum of the subject Mechanics of Materials must be done, and the main topics of the subject are identified: axial loading, bending, torsion and combined load. After considering the thematic content, the bibliography presented by the teachers is reviewed in order to look for the most representative exercises. For each topic, a set of exercises is proposed in order to cover the main knowledge components of the cognitive competences.

Solution and generalization of the exercise: the selected exercises must be solved to create a base algorithm that follows the steps taken to obtain the answer, in order to generate several versions of the same problem by modifying certain parameters but preserving the knowledge component. We define and bound the parameters that can vary to enforce randomness in the data of the problem. In Table 1 we can see an example of the design of an exercise that was included in the software database.

The problem template in Table 1 considers the following points: (*i*) the topic and objective of the exercise describing the knowledge component, (*ii*) the problem statement where the questions to be answered are proposed, (*iii*) the list of parameters acting as variables of the problem, i.e., the problem data randomly generated by the software that must have a previously defined range to avoid errors in the answers, (*iv*) a general solution for the exercise is developed, which allows to code the exercise easily.

3. Software implementation

There are many advantages of developing the program as web software. It is multiplatform and the student can use it from any electronic device. This approach is convenient as it makes the tool accessible from virtually anywhere, in agreement with mobile learning (*m-learning*) statement of students using mobile devices at their time convenience. The tool allows the teacher to use it to do quizzes and workshops. Any student will be able to propose new exercises, facilitating communication with the teacher and feeding the database to increase the knowledge base.

Due to the requirements of the software, especially the one focusing on facilitating the process for users with poor programming experience, there is a need to use an expression analyzer. An expression analyzer is an algorithm that interprets a mathematical expression with pre-established functions, assigns values to each of the variables that intervene in the expression, and gives a numerical answer, see Figure 1. This condition speed up the task of introducing new exercises to the database, since instead of programming the algorithm, the existing one can be quickly modified to the required needs. Thus, the expression analyzer is used to separate the coding of the exercises from the main routines, without it, the software was conditioned to a person making a particular code for each of the exercises.

Table 1. Problem template of an exercise for axial loading.

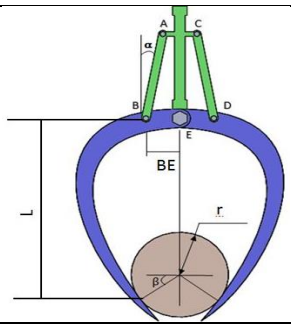
Topic:
Axial loading.

Objective:
Determination of normal stress in the two-forces structural elements.

Problem statement:
There is a machine consisting of two tongs that support a cylindrical element, as shown in the figure.

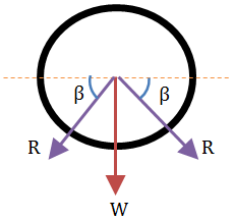
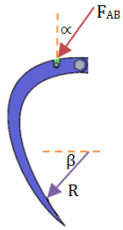
- Determine the normal stress developed in the link AB.
- Determine the shear stress developed on pin A, consider that it is subjected to double shear.

Note: Units are given in international system, SI.



Parameters	Bounds	
	Max.	**Min.**
Cylinder weight [N]	1000	5000
Distance BE [m]	0,3	0,9
Distance L [m]	1	2
Cylinder radius [m]	0,1	0,5
Alpha	10°	80°
Betha	10°	80°
Diameter of the bar AB [m]	0,1	0,35
Diameter of pins [m]	0,01	0,08

Solution

FBD Cylinder	FBD Tong	Stress
 $\sum F_y = 0$ $R = \frac{W}{2\sin\beta}$	 $\sum M_E = 0$ $F_{AB} = \frac{RL\cos\beta - (R\sin\beta)(r\cos\beta)}{BE\cos\alpha}$	$\sigma = \frac{F_{AB}}{A_{AB}}$ $\tau = \frac{V}{A_{pin}} = \frac{F_{AB}}{2A_{pin}}$

After performing a search on the web, we found a previously coded expression analyzer with Lesser General Public License (LGPL) [18]. This analyzer allows simplifying the template definition for the proposed problems. Equations obtained during the solution steps are introduced in the template to parametrize the solution of the problem with random input.

The software was implemented in the proprietary platform COMA (http://calumet.github.io/) [19] used as the Learning Management System (LMS) at the School of Engineering. The software was codified in the programming languages Java and JavaScript, to follow a multiplatform (Linux, Windows, Android, Mac) approach. In addition, the HTML language was used for the presentation of the contents. The database of exercises can be constantly updated since anyone with access to the platform can propose problems. The database contains different types of questions, i.e., multiple choice, calculated, true/false, matching, and essay. As indicated before, the focus is on the

development of calculated questions for problems centered in the process. One key feature that is proposed in this implementation is that values are recalculated with the input values given in previous steps during the process of solving the problem. This segmentation of the process allows assessing the competences of the student independently. For the specific case of problems related to Mechanics of Materials, it evaluates the statics, the geometry, the stress and the strains calculations, all in different steps, regardless of whether the student failed a previous step.

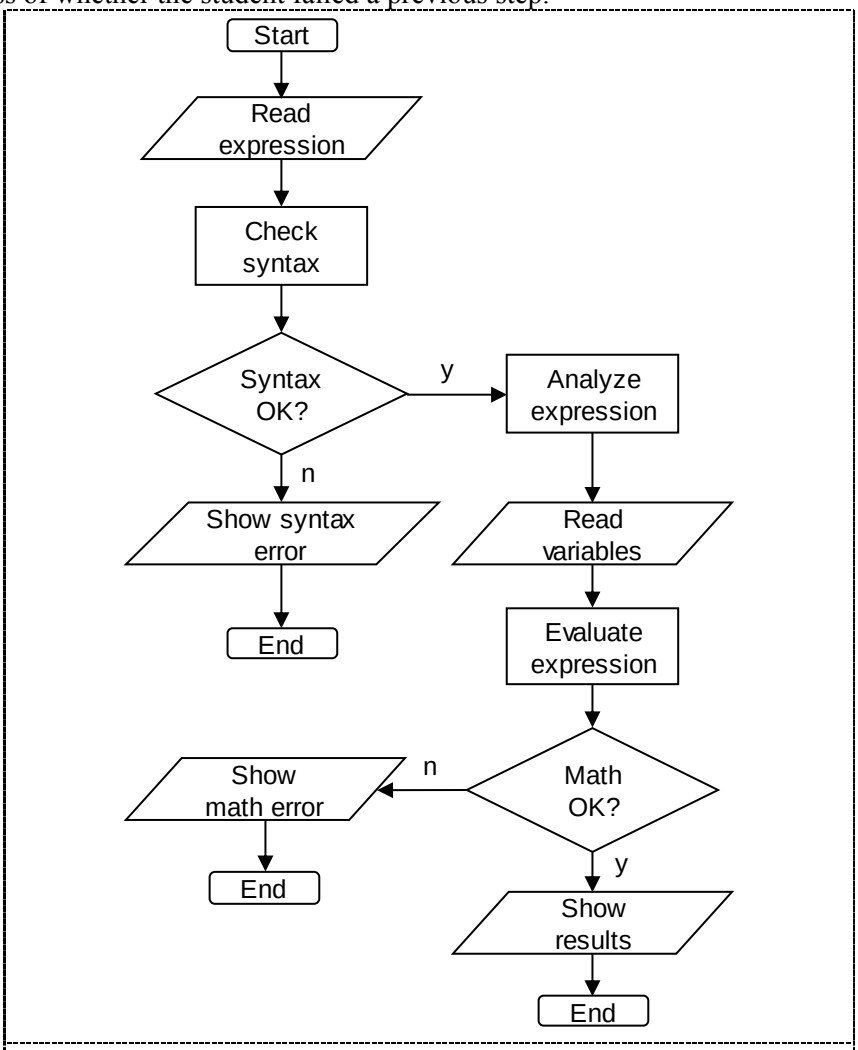


Figure 1. Basic algorithm of the expression analyzer.

The software offers two services: (*i*) *Training*: The teacher creates a workshop by setting the number of problems and the stipulated time to develop them. As the software has the option to review answers, the student can solve the exercise as many times as he wants, monitoring their results, until he is sure the procedure is correct. This improved feedback is required for effective formative assessment [14], and it is extremely difficult with mainstream education, (*ii*) *Evaluation*: The teacher previously creates an exam, setting a number of problems and an adequate time to solve them, and takes the students to a computer room in order for the students to carry out the activity.

Figure 2 shows a flow diagram with the internal process that is carried out when the teacher introduces a query of the type "create questions with expressions" in the system. For a teacher to include a question in the software, he must add the statement and the problem image, followed by the data and the mathematical equations to develop the exercise, then he chooses which expressions will be used as answer. Figure 3 shows snippets for the definitions of variables and expressions in the code.

When the student works on a workshop and presses the review option, the program follows a series of internal steps to show him if the answers are correct. This sequence consists in taking the randomly generated data and calculating the solution to the defined mathematical equations. After that, the software compares the values of the expressions indicated as answers with the values entered by the user, showing in red the boxes with wrong answers and in green the boxes with correct answers.

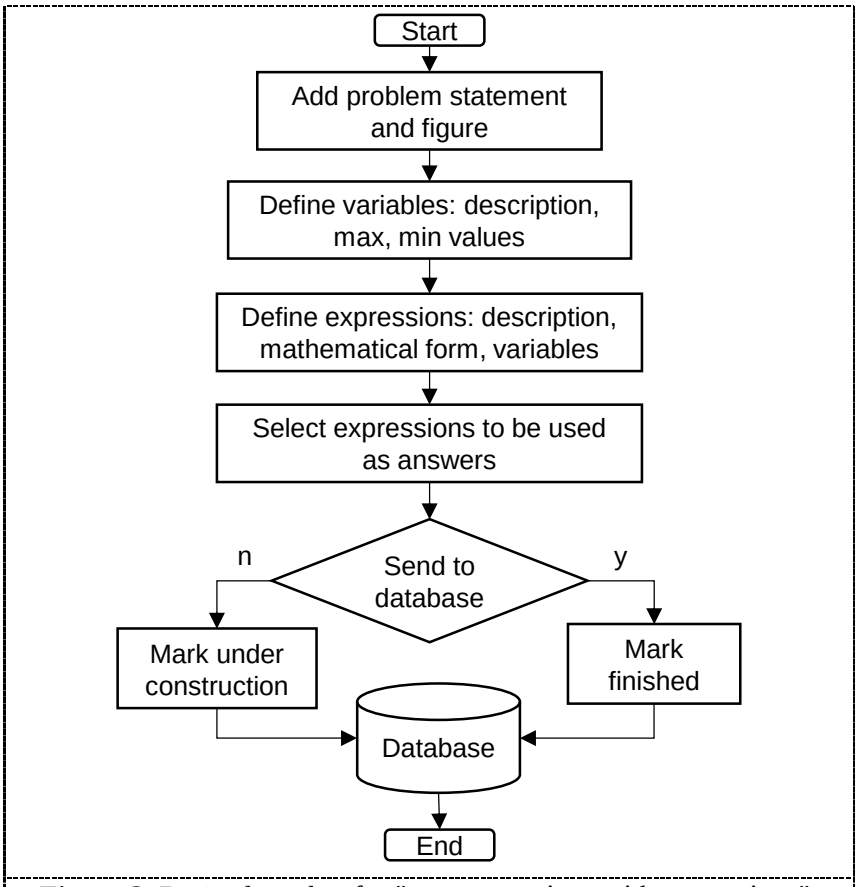


Figure 2. Basic algorithm for "create questions with expressions".

4. Conclusions

We presented the development of a multiplatform software tool to be used for the training and assessment of students of the subject Mechanics of Materials. The tool, implemented in Java, JavaScript and HTML, randomly generates exercises based on a parametric definition of the problems. The solution is calculated and compared with the answer given by the students and can be used to train or mark their performance. The problems are segmented into steps based on the knowledge base and the competences to be evaluated. The software is initially focused on the subject Mechanics of Materials, but it is easily extensible to other problem-based engineering subjects. By reviewing the answers, the student can check their errors and repeat the process in order to obtain effective feedback in the formative assessment process. This tool is based in innovative teaching strategies that seek to favor a teaching based on the active participation of the student. Moreover, it provides a standardized marking system that could be used across campuses and groups, reducing heterogeneities for large numbers of students due to subjective marking and non-uniform content.

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```
[{
   "type": "variable",
   "variable": "b",
   "description": "L   [m]",
   "min": "1.5",
   "max": "2.8",
   "value": ""
  },
…
  {
   "type": "variable",
   "variable": "z",
   "description": "Area bar AB    [m]",
   "min": "0.001",
   "max": "0.002",
   "value": ""
  },
…
```

```
   {
   "type": "expresion",
   "variable": "g",
   "expression": "a/(2*sen(p*e/180))",
   "description": "R",
   "answer": false,
   "value": ""
  },
…
{
   "type": "expression",
   "variable": "l",
   "expression": "k/z",
   "description": "Admissible shear stress AB",
   "answer": true,
   "value": ""
  }]
```

Figure 3. Snippets of the array definition in JSON for the problem in Table 1, for variables and expressions.

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