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Simulation in Software Engineering Education: A System Dynamics Proposal*

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The shortage of engineering professionals in working life together with the development of new teaching technologies had led to the necessity of real practices in engineering education field. This paper shows a project management simulation in which System Dynamics is proposed to apply for analyzing the effects of adding manpower to a software project management on total productivity, total costs and project duration. Students study how the introduction of new staff has different types of influence depending on the relationship established among the factors involved in the system. Results reveal that this method has a great impact in the competent training of engineers who need real management capacities and real experience in planning and project monitoring. Moreover, students increase their participation and interest in the concepts and encourage their comprehension into the performance of the system.

Keywords: system dynamics; human resource management; software engineering education; business; simulation; teaching based on learning.

1. Introduction

Engineering is a discipline that is characterized by facing more variety of fast changing demand than other areas. Therefore, engineering education has to develop learning objectives related to processes of solving-problems and innovation. However, engineering education has to consider other additional characteristics that will influence the future engineers too where [1] emphasize:

- Globalization. This process involves changes in the labor market and working conditions. So, it is important the development of transferable and social abilities that allow future engineers to be competent in this new business context.
- The importance of applying information and communication technologies in the teaching methodologies that will be used by future engineers in the labor market.
- The necessity of developing attractive study programs and challenging learning environments that attract engineering students.

One of the main objectives of the higher education institutions is to provide professionals with a suitable education for their future working life. Therefore, engineering education has to consider the development of competences to manage changes and develop openness to new circumstances and perspectives [2]. So, the fast development of new knowledge in the science involves the demands on engineers that have to be able to find and evaluate new information and to transform it into new knowledge to apply it on new situations.

In order to promote the development of new knowledge in different subjects, active learning method is a key concept in the present context of engineering education. It is due to the difficult of training engineers for a life-long career within a comparatively short period [3]. By means of this methodology, engineering students develop a "learning by doing", in which they are responsible for their learning process. It is especially relevant the training to search and evaluate information in different contexts with the objective of engineering students can obtain the required skills to use them in unknown situations that could be developed in their future labor context.

Different activities can be used in this active learning methodology. They will entail important benefits for engineering students due to the special characteristics of engineers' work in the labor market. Between them, [4] emphasize:

- Training engineering students in applying knowledge in practical situations.
- Training communication abilities.
- Developing a preparation for a career of life-long-learning. Engineering students should learn to how to learn and therefore organize their own personal development.

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- Raising awareness of environmental and ethical issues in the present business context.

The awareness of developing new teaching methodologies in engineering education is shown with the creation of the international network Active Learning in Engineering Education (ALE) in 2001. Its objective is to develop new teaching methods that allow teachers to promote the active learning in this type of students. Different universities have participated in different workshops of ALE in order to provide brain storms and interactive sessions that allow university community to encourage this type of methodologies in the classrooms.

The expected results of the application of that methodology are the development of essential capabilities in higher education, such as critical thinking, scientific report writing or evaluation of outcomes [5]. However, different types of problems can be developed with an active learning methodology. So, it is necessary that teachers adopt a different role in their classes because their new functions are more related to guide and advisory activities and make a continuous monitoring of students' work in order to optimize their learning [6]. Traditional classes are not so important but the application of their concepts to hypothetical and real situations. Therefore, master classes are not enough for students in software project management because they need practical education in order to develop the required skills for developing software. In this context, simulation is halfway between master class and practical education and it is one of the most valuable methodologies in engineering education [7].

As a software development project is a usual task of engineers in their work, the objective of this paper is to propose a teaching project management in the context of engineering students of a business subject. This is a key concept due to a poor management can increase the software's costs faster than other factors [8]. In particular, we propose the effects of adding manpower to a software project on total productivity, costs and project duration based on Brook's Law. We used interactive means and System Dynamics in students' training as recent investigations advise their use [9] and [10]. Results reveals this method have a great impact in the competent training of engineers who need real management capacities and real experience in planning and project monitoring. Moreover, students increase their participation and interest in the concepts and encourage their comprehension into the performance of the system.

In order to obtain that objective, the paper is structured as follows. Firstly, we analyze the use of system dynamics in software engineering education. Next in the paper we explain our proposal of the application of System Dynamics to a teaching project management of a subject of business in engineering students. Finally, we draw the discussion of our experience and the main conclusions of the paper.

2. System dynamics in software engineering education

Learning is a lifelong process but real practices related to the future working life are rarely taught explicitly in university engineering. Moreover, the expected shortage of engineering professionals drives a desire to accelerate the development of senior engineers [11]. In addition to formal training courses, studio-based learning is a way to teach within the active learning methodology (ALE) embedded nowadays in the engineering education [12].

Recent literature related to software and systems engineering focus on simulations in different aspects, such as important process and critical risks, from requirements specification to product delivery [13], training software engineers in global requirements elicitation [14] or capacity planning [15].

As a starting point, [16] present an architecture framework to facilitate the development of systems engineering process simulators where purpose is clearly identified and best practices and lessons are learned in different aspects of particular organizations such as projects, processes or risks. The use of simulators for educational purposes successfully helps students learn software process concepts in multiple universities, even though they have different abilities and backgrounds [17, 18] identify three main benefits of using software projects simulators: competitive, since each student or group of students acts as a project manager in order to get the better practice; physical, using face-to-face interaction among students and fun and engaging. However, simulators are more educationally effective used in conjunction with other teaching methods and need proper instruction and a set of guiding questions to answer [6].

Focusing on System Dynamics, the objective of this methodology is to facilitate the understanding of the relation between the variables of a system and its behavior pattern over time. *System thinking* is the basis of all system dynamics simulations. It will allow users to know the inter-relationships that shape the behavior of the system and, therefore, the effects of alternative policies and decision rules on it [19].

System Dynamics simulations are based on the principle of *cause and effect, feedback* and *delay* [20]. It assumes that actions and decisions have consequences which can be easily understood in isolated relationships but really complex when are combined into long chains of cause and effect [9]. Besides, it is necessary to consider that all cause and effect relationships do not occur instantaneously but there are delays with the consequent greater complexity in system's behavior.

In this context, *casual-loop diagrams* of the system can be developed. Its function is to illustrate cause and effect relationships of the analyzed system. In these diagrams, the arrows indicate the relationships of the variables and the sign of the arrows shows if the variables connected by the arrow move in the same or in the opposite direction. So, a minus (plus) sign on an arrow means that the variables connected by the arrow move in the opposite (same) direction.

In System Dynamics, every system has to be represented in terms of *flows* that accumulate in various *levels*, with *auxiliary* variables and *constant*. A level is an accumulation over time of flows or changes that come into and go out. The flows increasing and decreasing levels are called *rates* variables. Besides, the flows can be dynamic function of other auxiliary variables (that are combinations of information inputs) and levels.

Simulations models under this methodology make causal relationships more explicit and add more variability and strength to the relationships between the various socio-technical factors associated to projects. The system dynamic approach traces the relations and dependencies among variables with potential to change over the time in a system. Any change in one variable influences the whole system, creating a feedback loop. The complicated interaction of these loops will determine the future behavior of the system [7].

Empirical studies developed System Dynamics in management education gain a better understanding of the dynamic behavior involved in the software projects [21]. Moreover, it shows the importance of managing the systems as a whole and devoting attention to feedback loops and time delays in the systems [15]. Other advantage is that potential decisions can be first applied to the computer model to check their impact before applying those decisions on actual systems, saving a lot of time. New aspects that had not been anticipated could become visible since, due to the complex nature of a systems behavior, results of a system dynamics simulation are often not obvious. Therefore, System Dynamics modeling tool is very useful in this case as a predictive mechanism [22].

Nevertheless, it is important to note that the course must be aligned with the specific curricula of students due to the conflict between curriculum of the university and the target audience [23].

3. Proposal of system dynamics techniques applied to software project management

As it was discussed in the previous paragraphs, it is important that graduates can be prepared under conditions close to real life [24–26]. In this context, a suitable way to get this aim is that engineers are able to develop software in practical classes because it will be an important skill in their future incorporation in the labor market.

This paper focuses on proposing a teaching project management in the context of engineering students of a business subject based on the use of System Dynamics.

Nowadays, different visual software packets have been developed, such as VenSim, iThink or Powersim Studio. They simplify the models' encoding tasks using graphic elements that substitute the pseudo-FORTRAN sentences of the first tools—Dynamo, SimScript, etc. [7].

In our proposal of practical classes, VenSim has been chosen in modeling and simulation. In this software packet, the basis of the simulation is the casual loop diagrams whose development is the starting point of the modeling. Besides, it has sophisticated statistical and graphics features that allow users to create menus as well as input and text screens [9].

Figure 1 shows the procedure to model by means of System Dynamics which will have to be used by engineering students.

Our practical methodology is proposed in the field of business subjects related to software project management in engineering degrees. As engineers are often required to manage a team to accomplish a project, it is important to develop student's software project management with leadership skills. Therefore, it is necessary the introduction of teaching changes where teachers have to establish leadership roles, define responsibilities and priorities [28]. It is based on simulation techniques, specifically in System Dynamics, by means of the use of Vensim software.

The problem that students will have to analyze is based on Brooks' Law [29]. Figure 2 shows this systems dynamics model that is established by Vensim. So, students will have to study the effects of adding manpower to a software project management on total productivity, total costs and project duration.

In this context, teachers have to raise the problem. Really, the adding new personnel to a project will entail different effects on these variables because it will involve an increase of training overhead, an

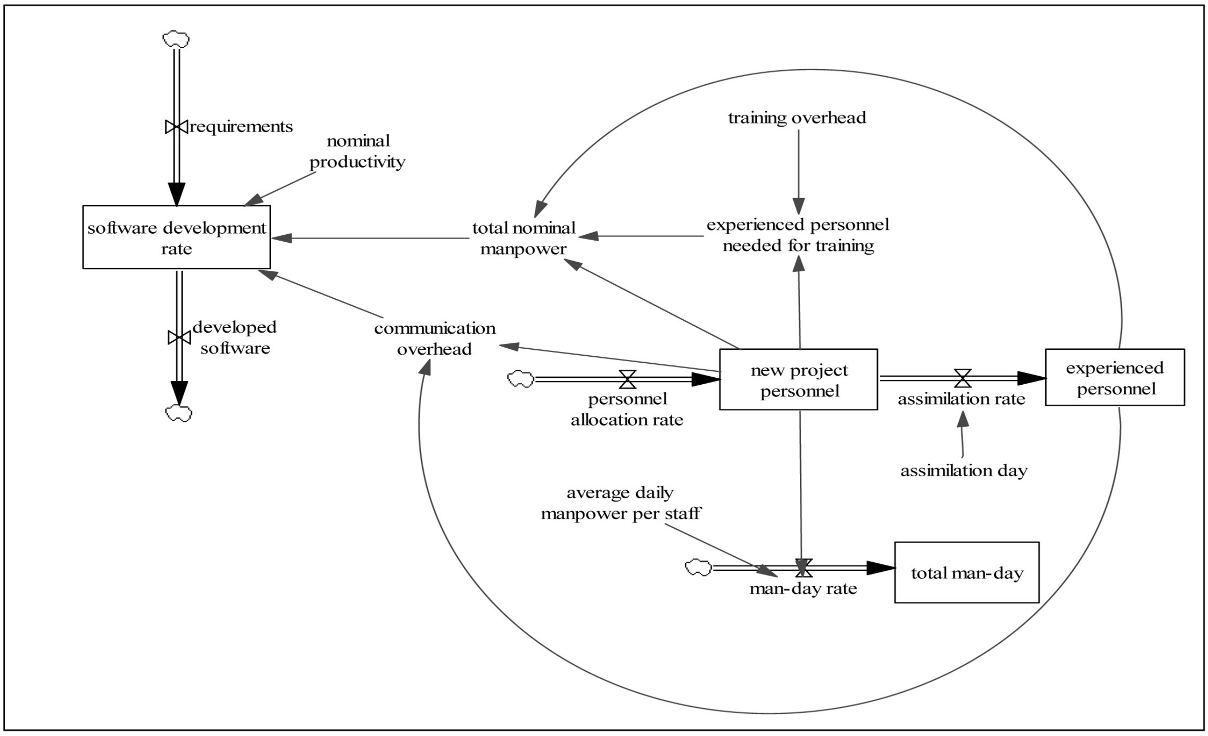
Phases	***Characteristics***
Problem analysis	Clear definition of the problem that will be analyzed. It involves answering the following questions: - What is intended to be modeled? - What is the scope of the model? - What behaviors have to be analyzed in the model?
Establishment of key elements	Identification of tangible and intangible objects and variables that are responsible of the observed behavior in the system.
Development of the cause-effect diagram	Establishment of the cause-effect interrelationships between the variables identified in the previous phase. The diagram links all cause-effect feedback loops and allows users to analyze the system as a whole.
Building the quantitative SD model	Turning the casual diagram into a set of equations. Therefore: - Choice of the model variables. - Definition of rate equations. - Establishment of the initial values of the chosen variables.
Model calibration and simulation	Development of dynamic sensitivity analysis to test the relevance of the chosen variables in reproducing a certain behavior model. Calibration of the simulation model against historical data. Prediction of possible results from different policies, actions or decisions through the observed behavior of the system.

Source: Own elaboration from [27]

Fig. 1. Procedure of SD modeling.

increase of communication overhead and an increase of the total manpower available for project development.

In Figure 2, we can observe that the introduction of new staff in the company will have different types of influence in terms of productivity. This variable is dependent on other many variables, such as nominal productivity, the communication overhead or the total nominal manpower. Besides, it is necessary to consider the effects of the variable assimilation



Source: [29]

Fig. 2. System dynamics model of Brooks' Law.

delay that makes reference to the days that new staff has to be trained in order to become an experienced staff.

Therefore, it is not clear the net effect that adding new manpower to a late project could involve. In order to answer these questions, it is necessary to develop an analysis by simulation because the traditional qualitative analysis is not enough.

Once the problem is established, students groups—previously defined with a leader in every group—will have to define the variables of the model in order to be able to explain the problem. Then, they will have to develop the cause-effect interrelationships of these variables.

An important issue is the necessity for those leaders of every group to explain their work to the rest of groups. After that, all groups will have to collaborate with the aim of creating a unique model that allows them to analyze in the best possible way the proposed problem.

The obtained solution will be explained to the teacher in order to establish improvement recommendations. Then, each group will apply them with the objective of converting the casual diagram into a set of equations where level, flows, auxiliary and constant variables have to be defined.

In this context, teachers will explain the model of Brook's Law so that students can make comparisons between their models and Brook's Law model. Finally, every group will run different simulations with different scenarios in order to be able to develop the required skills regarding the control of the fluctuations and variations in productivity. It is an essential capability that the responsible of economic and human resources' management has to have.

4. Discussion

Systems simulators can help students to develop the crucial systems thinking skills necessary for systems engineers and can promote and accelerate experiential learning and key concepts that might otherwise take a significant amount of time working on real projects [30].

In particular, System dynamics offers us a theoretical tool to analyze such a structure and gain an understanding into the performance of the system. Results prove to be useful for existing problems, making policy changes and strategic decisions as well as get an insight into questions such as how we would distribute existing resources into different parts of the system [22].

Moreover, the experience referred to in this work allows linking management knowledge with students' software capabilities. The immersion in a complex project management helps students to develop skills and improves the abilities of these future professionals in the labor market. Moreover, the application of knowledge and innovation is stimulated and beneficial for the general society [7].

In our initiative, System dynamics simulation models incorporate causal loops, allowing complex system relationships to be understood. System dynamics allowed students to view the system's dynamics over time without having to rebuild the entire system for each change, reducing the time to develop an understanding of complex systems. Students gained a better understanding of dynamic behavior on a project and this knowledge was used to assess the impact of their decisions through a dynamic project in order to improve them.

The initiative and responsibility for the project is in charge of the student so that the self-learning effect is very high. They apply the knowledge acquired in new changing situations developing at the same time complex software. All students were aware of developing their technological literacy and capability to use System Dynamics, even though they had diverse learning skills groups in the class.

On the other hand, they could provide more interesting lessons by learning through interaction and splitting the class into teams. Skills pointed out in this proposal such as communication skills and ethical issues involved in the business context are necessary among the students to agree on issues such as schedule, distribution of tasks or leadership in order to get a successful management project The development of all these profiles is essential for the future development of engineers in the labor market.

Finally, students increase their interest in the concepts and processes of management courses linked to the improvement in the capabilities associated to software simulation practices. Therefore, this tool highlights the role of the student while they enjoy the experience.

5. Conclusions

This paper analyzes the potential of simulators within the international network called Active Learning in Engineering Education (ALE) to provide future professionals with a practical education for their working life. In particular, we present a simulation model from the field of management projects based on the Brook's Law using System Dynamics software.

System dynamics is a powerful tool and computer simulation modeling technique for understanding and analyzing the behavior of complex systems over time. We describe how the model is constructed from the individual components of the program and how a System Dynamics approach is used to analyze the program. The basis of this method is to recognize that interacting individual components are crucial in determining the behavior of the overall structure of any system. The results of the simulations can dynamically predict the future behavior of the system over time and redirect decisions if deficiencies are observed in the system instead of rebuild the system again, reducing time in the feedback process.

Specifically, in our experience, students dynamically simulated a management project as a whole assessing the consequences of the introduction of new staff on total productivity, total costs and project duration. They were becoming aware about the important and complex interactions among factors involved in the system.

From the perspective of education and training of engineers, System Dynamics is a pedagogically effective tool to enhance the classroom interaction through competitive attitudes that contributes to the interest and engagement of the students in the knowledge of engineering real practices. They can effectively learn important concepts, take decisions and gain a better understanding of dynamic behavior on a project, even with different backgrounds, enjoying the experience of working at the same time. This method also allows teachers to target specific learning styles using complementary tools that support the teaching and learning process through a student-centered approach.

Further evidences using System Dynamics oriented to real practices in the engineering field should be developed in order to link academia with working life.

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