Systems in Engineering Education: Account of an Experience

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1 Introduction

Systems Engineering (SE in the following) has not received much attention as a subject matter in engineering curricula. There are several dozens of universities around the world offering programs (most of them at the graduate level) on systems science and engineering [17]. However, SE is, per se, rarely found among the courses offered by engineering schools. This observation does not strictly mean that systems concepts be left apart. For example, it is usual to find specialized courses for systems of some particular classes (e.g., courses on software systems engineering for computing curricula) or for particular phases of the system life cycle (e.g., courses on systems analysis). Even so, these kinds of courses tend to over-emphasize the importance of specific methodologies and, in consequence, to deviate the attention from the realm of systemness.

My institution, the School of Telecommunications Engineering at Technical University of Madrid, has been offering two one-semester courses (around 60 hours each) on Systems Theory and Engineering for the last fourteen years. The contents of both courses have obviously changed over the years, evolving from Cybernetics and Systems Theory towards the study of complexity in information technologies (the first course, described in [16]) and towards systems engineering (the second one). This paper describes an innovative experience carried out during the last year in the course on SE. Both of them are offered by the department of Telematic Systems Engineering[1] as optional matters in the fifth and sixth year respectively[2].

[1]The word *telematics* (*telemática* in Spanish, *télématique* in French) is used, mainly in Europe, referring to the use of the computer as a communication machine.

[2]Engineering programs in Spain are five or six years long depending on the University (six

2 Objectives of the experience

Specific objectives of our experience have been:

- **Teamwork**
  Teamwork should be emphasized. Engineering education has been usually oriented towards the learning of knowledge and skills at the individual level, and almost never towards the development of abilities needed for productive work in groups. This kind of education, yielding to extreme levels of individualism and interaction difficulties, is no more adequate.

- **Communication skills**
  The course should contribute to the improvement of communication skills. Deficiencies in this aspect have been frequently reported by individuals, professional organizations and employers. Ability to make effective presentations or to write comprehensible technical reports are better developed through guided practice in the courses on technical matters than through specialized seminars.

- **Evaluation**
  One important aspect of the activities carried out by engineers is evaluation. For evaluation we mean the professional, critical and constructive appraisal of the work done by subordinates, fellows or even superiors. It has been reported [10] that more than 60% of the people earning an engineering degree become managers at any level in fifteen years. Even more, some of them have subordinate technical personnel from the very beginning. Our students, being used to be evaluated, need some real experience on the other side, as evaluators. The course should provide this kind of experience.

- **Systems Approach**
  Last, but not least, systems concepts and approach should pervade all the activities in the course. Our main objective is the development of a systemic attitude from the part of the students towards the complex problems/systems that they will face during their professional life. This attitude involves a holistic point of view, complementary to the reductionist approach characteristic of the scientific method the students are used to apply in most of the remaining matters of the curriculum.

  On the other hand, systems approach is necessary to compensate for the increasing level of specialization observable in every technological field.

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years in our case at present). The degree of engineer, granted after the completion of a thesis, entitles directly to join a PhD programme.

The society demands from engineers an effort to break down the specialization barrier and communicate effectively with users, clients and other professionals with which they have to collaborate.

Besides the learning of conceptual and applied tools adequate to deal with complex problems in technical environments, we should try to point up that, in the real world, problems show its complexity in a net of technical, social, economic and environmental interrelations. Therefore tools used to understand and solve this kind of problems should be introduced. Moreover, systems engineers can not be people familiar with just a few methodologies. On the contrary,

- Engineers should know several systems engineering methodologies.
- Equally important, engineers should be aware of the limitations and scope of these methods.
- The most important, engineers have to be prepared to appreciate, assess and learn other methodologies and tools. First, it is not possible nor desirable to teach many of them in a single course and, second, our students will be certainly forced to learn others to appear during their professional careers.

The relevance of complexity understanding and management, in particular in information technologies, is now widely recognized. For example, the Association for Computing Machinery devoted its first Conference on Critical Issues to this topic [9].

3 Contents

3.1 Systems and Systems Engineering

Contents of the course are selected according to its prior objective: the development of systems attitudes. Every theme will be articulated around the concept of system, considered as a totality with proper goals, composed by diverse and interconnected elements, and integrated in an environment.

Several definitions of the term SE are discussed in the course, including those proposed by Hall [11, 12], Wymore [19], Chambers [5], M'Pherson [15] and others. The term is explained in a broad sense, as a multi-faced set of methodologies for systems analysis, design and management.

1. **Systems analysis**
   The purpose of systems analysis is to determine the objectives and limits

of the system under study and to characterize its structure and behavior. Depending on the goal of the study, two kinds of problems can be distinguished: a) analysis of an existing system in order to understand, improve or forecast its behavior, and b) analysis as a first phase in the complete life cycle of a new system/product.

Activities involved in systems analysis can be grouped in several tasks: conceptualization, functional analysis, analysis of constraints (non-functional analysis), and validation. These tasks generate a model of the system and can be eventually accompanied by the construction of a physical model (a prototype).

2. **Systems design**
   Systems design evolves the guidelines proposed during analysis in terms of that configuration that will more likely satisfy the established goals from both sides functional and non-functional. The design of a complex system involves usually high level design, implementation, integration and validation.

3. **Systems management**
   The management side of SE tries to integrate, plan and control all the technical, human, organizational, social and commercial aspects of the whole process (analysis, design, operation, maintenance and retirement) within the budget, schedule, quality and any other accepted condition.

3.2 Current contents

The syllabus presented in this section is not intended as a fixed set of topics. Apparently different matters can fit according to the qualifications and experience of the teachers and the interest of the students. In any case, candidate subjects should be carefully evaluated for adequacy, according to objective 4 (systems approach), as stated in section 2.

Current contents of the course can be grouped as follows:

1. **Systems approach**
   This theme, used as an introduction to the course, tries to establish some basic and recurrent concepts for the whole program (system, complexity, hard and soft systems, etc.) Furthermore, sources and history of the systems movement are traced. The Sciences of Complexity (as theoretical and applied developments based on the systems approach are frequently referred to) are explored, looking for their common roots and features.

   Two classes of problems are discussed:

- Hard problems: those that can be formulated as the search for efficient means to reach some concrete objectives starting from a concrete initial state. This is the kind of problems that our students use to see in most of the remaining courses in the curriculum.
- Soft problems: those that can not be expressed in that way without over-simplification. Usually they are dynamic problems dealing with human activity systems, such that their perception and objectives are mainly subjective.

Authors of texts used as reference material for this theme include Klir [14], Checkland [6], Bertalanffy [4] and Hall [12].

2. **System Dynamics**
We consider that System Dynamics, the methodology introduced by J.W. Forrester in the sixties [7, 8], incorporates an excellent educational potential. System Dynamics uses engineering methods to face technical, social or economic problems by building simulation models. This feature makes System Dynamics very attractive for engineering education.

   System Dynamics has obviously its own scope and limitations. Stress is put, not on the methodology in itself, but in the use of graphical and formal tools in socio-technical systems understanding and modeling. System Dynamics applications discussed in the course include models for maintenance planning and for studying the dynamics of software project management. References used for this theme are [1, 2].

3. **Software systems analysis**
Software engineering is presented as a particular systems engineering. Its eventual selection for inclusion in the syllabus is due to the interest of software systems for our graduates, and as a temporary necessity until the establishment of a new curriculum that will include two specific courses on software engineering[3]. After presentation of different software life cycle models, we focus on analysis, as one of the life cycle phases demanding with greater intensity a systems approach. Emphasis is placed on software requirements definition and structured and object-oriented analysis. Several papers are worked out, but the text used as reference is [18].

4. **Soft systems methodologies**
Methodologies for soft (non-structured) systems furnish the students with conceptual tools to face complex problems where human and social components are crucial and formal methods can not be applied. Two specific

[3] Academic curricula have been extremely rigid in our country until now. New regulations will allow for greater flexibility in the near future.

methodologies are reviewed: Checkland's soft systems methodology [6] and Beer's viable system model [3].

4 Educational method

General criteria previously expressed impose the pre-eminence of attitudinal over informational considerations. The prior goal is the development of an intellectual attitude as opposed to the simple transmission of knowledge. This willingness frames the course in a qualitative educational paradigm.

Quality SE education should be based on the work of students acting as systems engineers. Although some theoretical background is necessary, its utility is better revealed when the tools supplied by the discipline are used to solve real problems. Moreover, the learning of SE achieves its real dimension when such work is carried out in groups.

Our course consists of several types of activities:

- Regular lectures, given by teachers, covering 50% of the lecture-hours scheduled for the course. These lectures have motivational and introductory purposes. Themes are not presented with a great level of detail, but applications are outlined whenever possible.

- Work in groups of 4/5 students on a concrete theoretical or applied subject. Following the desire expressed by the students, groups are freely formed according to common interests or from friendship reasons. We think however that random distribution could produce as good or better results. Groups can prepare proposals to work on any SE-related topic. In this case, the proposal has to be approved by a teacher. Otherwise, topics are distributed among the remaining groups (giving satisfaction to their preferences as far as possible and looking for the widest coverage of topics) from a catalogue prepared by the teachers. Groups, under the supervision of a teacher, have to elaborate a written final report. This report has to contain an introductory section reviewing the covered methodology or field.

- Group presentations cover 25% of the lecture-hours of the course, the remaining 25% being assigned to tutoring activities. Time allowed for each presentations is around 40 minutes, including some minutes for questions.

- Evaluation activities. Each group evaluates every presentation for clarity, structuring, adequacy of expression and objectives, utilization of didactic resources, interaction with the audience and global impression. Technical quality is assessed from written reports. Each group evaluates three of them selected at random. Different sections (abstract, introduction, body, conclusions and bibliography) are assessed separately.

Final grades are calculated from weighting the following items:

- Written examination (30%) on the contents of regular lessons and introductory sections from some selected group's reports.
- Group's reports and presentations (60%). Marks are calculated as an average of the marks given by the groups themselves.
- Teachers evaluate the activity carried out by groups as evaluators (10%). Good judgment, constructive criticism and discernment ability are subjectively assessed by the teachers.

5 Evaluation of the experience

The experience has been thoroughly evaluated through questionnaires answered anonymously by 154 students taking part in the experience. Results have been highly encouraging. As an example, we show the responses to the question *"How do you consider this course in the curriculum?"*

Necessary	34%
Very convenient	24%
Convenient	38%
Unnecessary	4%

When they are asked about the interest of the course in comparison with specialized courses in their respective majors, they answer:

More interesting	31%
Same level of interest	50%
Less interesting	19%

6 Conclusions

The experience related in this paper has been designed from our firm conviction that Systems Engineering contributes a great value to engineering education:

- Systems Engineering offers an ideal approach to deal with the problems of increasing complexity that engineers are facing and will be facing during their professional life.

- Systems ideas are more profound, open and durable than the contents of most of the matters in engineering curricula. So, Systems Engineering furnishes the students with a long term background knowledge where detailed technological knowledge, that becomes rapidly obsolete, finds its real sense.

- Systems concepts provide a solid basis for working in interdisciplinary teams.

- Systems approach contribute to make the students more sensitive to the problems (technical or not) of the society.

In our course on Systems Engineering, methodological aspects are considered as important as contents are. In particular, we stress the following points:

- Teamwork. Students working in groups of 4/5 study in depth a concrete systems methodology or application.

- Communication skills: groups present their work to classmates. Presentations cover 25% of the lecture-hours of the course.

- Evaluation experience. Each group evaluates every presentation and the written reports of some groups selected at random.

The experience, once evaluated by the students and by ourselves, has to be qualified as successful. For the next year we plan to maintain the same schema, with slight variations in contents and evaluation criteria.

It has been argued by G. Klir [13] that future information society will see an increase of the knowledge available and, in consequence, the growth of complexity and turbulence. Systems engineering will be necessary to travel light through the intricate paths of such future.

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