Teaching Systems Thinking to Industrial Engineering Students

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ABSTRACT: *This paper describes the development of a senior and a graduate level course on Systems Engineering and Design for Industrial Engineering students. Students are first taught 'Classical Systems Engineering' topics, and they are then exposed to Sociotechnical System Theory (SST), Cognitive Systems Engineering (CSE) and Soft Systems Methodology (SSM). These methodologies are treated as complementary, useful in resolving a range of problems from hard to soft where all problem situations are presented on a continuum from well structured to unstructured.*

Keywords: Systems Thinking, Industrial Engineering Education, Systems Engineering

INTRODUCTION

The objective behind this paper is to describe the nature of two courses developed for the purpose of teaching *Systems Thinking* or *Systems Approach* to industrial engineering students. Through this paper, it is hoped that the author will receive some feedback from the people involved in this area, and conduct further research on the topic and make improvements in the way the subject matter is taught.

There is a considerable amount of material that can be taught to industrial engineering students in *Systems Thinking*, who are mainly concerned with the design, operation and maintenance of complex human-machine systems. The author of this paper taught System Science and Dynamic Systems to industrial engineering students at Middle Eastern Technical University, Ankara, Turkey, in the early 1980s. The approach then was mainly analytical, based mostly on physical engineering systems, while the extensions of these techniques to socio-economic systems were also considered. Later, in the early 1990s, the author started teaching Systems Engineering at Eastern Mediterranean University, Cyprus. In parallel to the developments in Systems Science and Engineering, the courses were redesigned, combining both analytical and non-analytical techniques, covering both 'hard' and 'soft' systems. As a result, the courses described below have emerged.

Before describing the structures of these new courses, the author will present a brief review of the historical developments in the area, as they are related to the theme of this paper. An initial evaluation of the robustness of the approach on the first course will be also provided at the end of the paper; the second course has not been taught yet.

SOME NOTES ON HISTORICAL DEVELOPMENTS

The reasons for the emergence of *Systems thinking* are usually related to the 'inadequacies' of science dealing with complex systems. Complexity in systems is highly pronounced particularly in *Socio-Economic Systems*; social sciences have to deal with messy and ill-structured problems. Systems Thinking developed in several different disciplines, mainly in organic chemistry, then in biology, and control and communications engineering. *Systems Thinking* or *Holistic Thinking* was developed by Ludwig Von Bertalanffy, a biologist, who suggested generalising these ideas to any kind of system. His work was followed by contributions from other fields, such as engineering, psychology, anthropology and linguistics, leading to the development of *General System Theory (GST)*. Later, in the 1960s and 70s, major advances were seen in the application of Systems Thinking in communications and control engineering where systems ideas were readily applicable. The body of knowledge developed in this area came to be known as *Hard Systems Engineering* in later years, which is concerned with *systematic* approach to engineering design by means of model building and model optimisation. Computers are used extensively in the design process, which includes system or need analysis, developing design options, mathematical and experimental evaluation of potential designs according to some defined 'measure of effectiveness', principal design, prototype construction, testing, training and evaluation. Later, Wymore formulated this process as an interdisciplinary approach for 'the analysis and design of large-scale, complex, man-machine systems' (Checkland 1993). Wymore's definition expanded the horizons of Systems Engineering from communication, transportation and manufacturing systems, to education, health and law enforcement systems.

In parallel to the above developments, another methodology, which came to be known as *System Analysis* was developed at RAND in the 1950s. This methodology was originally used to solve resource allocation problems in military operations and it was closely related to the applications of Operations Research. Later, this technique was applied in business as a popular methodology in the solution of business related problems. Compared to *Systems Engineering*, which represents all the processes involved in a large-scale engineering project, *System Analysis* is mainly concerned with a systematic appraisal of the costs and other implications of meeting a defined requirement in various ways. In the 1980s and 1990s, various different interpretations of Systems Engineering have appeared; the interested reader may find some information related to these approaches in the following articles: (Fuenmayer, 1997), (Gaboury, 1999), (Kappel, 1999), (Mason, 1997), (Niepce, et.al., 1998), (Novelli, et.al. 1993), (Sushil, 1997). The author of this paper is relatively more familiar with the following works: Sage's view of Systems Engineering can be summarised as creating a structure which describes the Systems Engineering process as a life-cycle model that can accommodate engineers across a wide range of specialities (Sage, 1992). Sage emphasises the *process* of Systems Engineering rather than the *product* of it, believing that proper attention to processes inevitably leads to higher quality products. Senhbar views a *Systems Engineer* as a person who is capable of integrating knowledge from different disciplines and technologies, and seeing problems with a holistic view by applying *Systems Approach* (Shenbar 1994 and Shenbar 1997). He emphasises the close *link* between *engineering* and *management*, and stresses that designing, operating and controlling complex systems always requires an engineering as well as a managerial part. Hazelrigg, on the other hand, adopts an information-based approach to *Systems Engineering and Design* (Hazelrigg, 1996). He believes in a rigorous mathematical approach to decision making and views engineering design as *a decision making process.*

Beginning in the 1960s and 70s, relative 'successes' of *Hard Systems Engineering* techniques in the design of physical engineering systems encouraged engineers and researchers to transfer this knowledge into the arena of S*ocio-Economic Systems*, such as formulating public policy. The results appeared to be disappointing, and the idea of making transfers from engineering disciplines to Socio-Economic Systems was discredited. As development continued, new and fresh approaches appeared, three of which are *Sociotechnical Systems Theory (SST), Cognitive Systems Engineering (CSE)* and *Soft Systems Methodology (SSM)*.

STRUCTURES OF THE COURSES DESIGNED

The first course is offered at the senior level, providing a background on the *Fundamentals of Systems Engineering*. The second course is designed as a graduate level course – it can also be offered as an elective course at the senior level, its prerequisite being the first course - introducing students to *unconventional methodologies in Systems Engineering*, in particular to SST, CSE and SSM.

The First Course

The first course is mainly structured on Hazelrigg's view of Systems Engineering: '…engineering design is a decision-making process. Good design requires good decision making, and good decision making requires good design options and good information to enable comparison of the options. We focus on three questions: What information is needed for good design? How do we get that information? How do we use it when we get it?' (Hazelrigg, 1996). Due to the fact that his approach is an information-based one, industrial engineering students find it easier to understand the topics and relate them to the material they learn in the other courses, such as Operations Research, Engineering Economics, Production Planning and Control, and System Simulation. Also, the fact that Hazelrigg's approach is mainly analytical and structured helps undergraduate students absorb the material comfortably; it helps them to appreciate the significance of *Systems Thinking*. They then become ready to learn design approaches that are less structured and learn how to deal with ill-structured problems. The following topics are covered in the first course:

(a) Introduction: The relationship between science, engineering, technology and art is explored. The concept of design is introduced, and the contributions of science, engineering and art in the design of engineering systems are investigated.

(b) Design Options: Here, the creation of option space for physical and non-physical systems are taught, with a total life-cycle approach- which includes considerations of options in all phases of system design, manufacture, deployment, operation, maintenance and repair, and end-of-life disposal.

(c) Engineering Systems Modelling: In this section, the differences between disciplinary design models and Systems Engineering models are shown. Students are expected to see that in conventional and *disciplinary* approaches, the focus of the modelling process is on *subsystem design*; *System Engineering* models go beyond design of physical systems and *include design validation, manufacture, distribution and sales, liability and disposal*. Furthermore, it is demonstrated that imposition of subsystem boundaries and fairly arbitrary constraints can be avoided in systems modelling, allowing design options to emerge and help designers to develop a better understanding of the consequences of each individual design option.

(d) Analysis of System Reliability: The theme here is that we can not perform a successful design without taking its operation into account. Monte Carlo simulation techniques are used in an innovative manner to study problems of system reliability.

(e) System Dynamics and State Transition Matrix Models: Here, students are taught the use of differential and difference equations in developing models of dynamic systems. This analytical approach helps students better understand the modelling procedure and how to improve their understanding of systems' behaviour (Mcmillan, et.al., 1973).

(f) Modelling the Research and Development Process: The purpose here is to show how such processes can be modelled and how the results obtained can be evaluated.

(g) System Life-Cycle and Optimisation: In this section, development of firms' and consumers' objectives are studied, and their relationship with the life-cycle of a product in terms of design options are examined. Also, means of improving available product options are studied- as far as the design, manufacture, distribution and sale, maintenance and repair, and disposal are concerned.

(h) Management of Engineering Systems Design and Operation: This section covers managerial aspects of system design, operation and product maintenance; it is emphasised that decisions that are taken by systems engineers and the designs they perform represent allocation of resources (material, human and capital), hence they are vital to the survival of the company.

Depending on the depth of coverage, the following material may be needed as the background material: Probability Theory, Optimisation, Engineering Economics, Utility Theory, Forecasting, Cost and Benefit Analysis, Decision Analysis, Information Theory, Game Theory, Differential and Difference Equations, Matrix Theory.

The Second Course

The main objective of the course is to introduce some unconventional methodologies in Systems Engineering. A summary of these topics are given below:

(a) Introduction to the Management of Advanced Manufacturing Technology: Main theme here is to underline the importance of *strategic* issues related to the selection and adoption of Advanced Manufacturing Technologies (AMT) (Gerwin et. al., 1992). It is argued that the adoption of AMTs has significant technical, organisational, social and political implications. In particular, the role of technology in the overall picture is re-stated as that *technology is more than machines; it is human beings, hardware and software.* Furthermore, it is argued that flexibility provided by AMTs require *innovation* and *flexibility* in organisations, design of individual tasks, formation of work-groups and higher-level organisational settings.

(b) Introduction to Sociotechnical Systems Theory (SST): This section starts with a comparative study of Technological Determinism versus SST. It is argued that hierarchical organisations are outdated and that *new* and *innovative* organisations need to be created in order for the companies to survive in this turbulent, highly dynamic and fast-changing environment. The main thesis of SST is re-iterated that organisations should be designed so that people are in complementary roles to machines rather than being extensions of machines, and that design should be based on joint optimisation of the social and technical systems. Also, students are shown that there is a choice in organisational design, contrary to what technological determinism suggests. Finally, the SST *Design Principles and Processes* are reviewed, and it is shown that they yield a *Comprehensive and Integrated Organisation Design.*

(c) Cognitive Systems Engineering (CSE): First, students are exposed to the position of CSE within Systems Thinking by discussing the following major points: (a) CSE is an interdisciplinary field which is based on the premises 'the study of work and design of information systems have to be concerned with work performance in its associated sociotechnical context, and thus from a *multidisciplinary* point of view' (Rasmussen et. al., 1994). Its components are cognitive tasks (thinking, problem solving and decision-making), engineering, and systems. Hence, it is related to engineering, psychology, information sciences, management sciences, and computer sciences. (b) CSE provides a fresh look at the design of complex human-machine systems. It requires some changes in the way systems modelled and designed, demanding a shift from Operations Research (OR) and System Science-based techniques to field study-based techniques. (c) Optimisation of system design should not be performed *from* a misconceived hypothesis about the users, but it should be based on the actual work content. (d) CSE provides complementary tools for system design rather than tools that will replace the existing tools. Decentralisation, self-organising control and adaptive control are the essential control strategies to be adopted. (e) Design is performed in a framework representing all the aspects of work systems including the functions of technical equipment, the resources and preferences of the actors, together with the functional structure of the work organisation, all in compatible terms. Dimensions of the conceptual framework include Work Domain Analysis, Activity Analysis, Information Processing Strategies, Functional Work Organisation, Social Organisation, and Actor's Cognitive Resources. The above approach has strong parallels with *Situated Design* (Greenbaum et.al., 1991) , which suggests that information technology plays a central role in the design and operation of modern work systems and that computer systems must be designed with the full participation of users -the role of psychology and human-computer interaction in design is given a high priority.

(d) Soft Systems Methodology (SSM): Finally, SSM is introduced which shows students a way of handling ill-structured managerial problems. This methodology is based on the premises that 'approaching ill-structured problems through quantitative techniques, systematic knowledge, structured rationality and organised creativity can not deal with the primary uncertainty involved in the definition of overall goals or objectives' (Checkland, et. al. 1990). The analyst is not asked to formulate the problem in systems terms, but rather in terms of 'structures' and 'processes' and the relation between the two -this approaches is believed to prevent the analyst distorting the problem into a preconceived or standard form. *SSM's Epistemology* and some selected case studies are studied to teach students how the methodology is applied to real world problems. First, students learn how to reflect their observations of the real world on *Systems Thinking*, and how to assemble some 'relevant' human activity systems and develop 'appropriate conceptual models'. They then see how these models are examined, and the ones that are found '*desirable*' and '*feasible'* are kept and '*modified'* if needed. Students are expected to develop a feeling that the methodology enhances the '*learning'* experience of analysts and produces a '*learning system',* leaving room for personal styles and strategies.

AN ASSESSMENT OF INITIAL RESULTS AND SUGGESTIONS FOR FURTHER RESEARCH

Generally, students were enthusiastic about the courses, welcoming the inter-disciplinary nature of the approach. Initially, they found the first course oriented more towards physical engineering systems rather than to systems industrial engineering students are closely familiar with. After revision of the some of the material and some fine-tuning, the first course received a warmer reception the second time around it was taught. As it was mentioned earlier, the second course has not been taught yet, hence no evaluation related to it is available. However, introduction of some of the material contained in this course at the end of the first course indicated that it will be challenging to teach the unconventional methodologies, in particular Cognitive Systems Engineering. It is too early to state whether the adopted approach is reasonably robust, although the initial reaction from the students and faculty members are very encouraging. Some more evaluation and assessment have to be done in the coming years, through the use of tools such as student evaluations, evaluations by the department and the dean's office, questionaries given to graduates and to some experts in academia and industry.

CONCLUSIONS

The two courses described above provide students with the basis for working in the design, operation and maintenance of complex human-machine systems. The topics are arranged so that students first learn relatively more structured and analytical approaches, and then move towards methodologies that are non-analytical and less structured. They also learn that there is no particular methodology that provides the 'best' solution to a given problem, and that all these methodologies are complementary. Hence, they understand that the real world problems may lie anywhere in a large range, varying from highly structured to highly unstructured forms, and that there are and there will be a number of methodologies available to resolve them.

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