Dynamical Systems Theory and System Dynamics: Educational Issues

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Abstract

The main theme of this study was to investigate the relationship between Dynamical Systems Theory and System Dynamics, and propose some ideas on educating undergraduate students in this area. It is suggested that "the essentials" of the former should be taught to establish a reasonable theoretical background, while teaching the latter. In this study, the roles and the relationship of Systems Theory and System Dynamics were first investigated within the body of Systems Thinking. This was followed by descriptions of a general framework and two courses designed for the purpose. The aim was to integrate the selected material from linear and nonlinear systems theory into System Dynamics Methodology. The resulting approach was in line with the multi-methodological trend seen in recent systems-oriented studies, and was expected to be quite effective in handling a certain class of systems.

Introduction

Interest in complex system studies has been growing rapidly in recent years; searching for better system paradigms or a combination of methodologies in a multimethodological framework is a part of this phenomenon. It is well known that General System Theory (GST) claims to be "the theory of theories", thus having the potential to resolve the dilemma of selecting and combining methodologies. However, GST does not provide well-defined guidelines in this respect. Although it has been successful in general terms, since its birth in the 1950s, GST has methodological limitations when it comes to dealing with specifics—it deals with general properties of systems, at an abstract level, regardless of physical form or domain of application, supported by its own metaphysics in systems philosophy [1], [2]. Both Systems Theory and System Dynamics are considered to be two of the major strands of GST, with the others being Operations Research (OR), Systems Science, General Systems Thinking, Systems Approach, System Analysis, Systems Engineering and Science of Complexity and Bionics. The Systems Thinking paradigm, primarily developed after the 1980s, includes quite a number of trends, including Critical Systems Thinking. The major concern of Critical Systems Thinking is how to make use of a variety of methodologies, methods and models available in a coherent manner to promote successful intervention in complex organizational and societal problem situations [3-6].

Jackson [3], [4] classifies all important systems methodologies providing critiques of all. His classification, from a social sciences point of view, includes the following groups: a) The Functionalist Systems Approach; b) The Interpretive Systems Approach; c) The Emancipatory Systems Approach; d) The Postmodern Systems Approach; and, e) Critical Systems Thinking. Selecting a particular methodology for a given system is not an easy task since all of these groups include various methodologies or approaches themselves. The two methodologies considered in this study, Systems Theory and System Dynamics (SD), both belong to the functionalist approach. The other major methodologies in this school are OR, Systems Engineering, Cybernetics, Living Systems Theory, Autopoiesis, and Complexity Theory, all including various approaches within themselves. Furthermore, the roots of System Dynamics are known to be in Systems Theory.

In the functionalist approach, systems appear as objective aspects of a reality independent of observers. Systems are studied using the methods of natural sciences to understand their behavior and use this knowledge to improve the efficiency or efficacy of the system—in "soft systems approaches" the primary concern is the multiple perceptions of reality and studying systems in a pluralistic environment. Within the functionalist approach, there is a group of methodologies where "hard facts" are used throughout the study, and this kind of approach is commonly referred as "Hard Systems Thinking". Systems Theory belongs to this category, providing theoretical background to methodologies such as OR, System Analysis and Systems Engineering. SD belongs to the Functionalist Systems Approach, but not to Hard Systems Thinking.

In regards to relating methodologies to problem contexts, Jackson [4] suggests that Hard Systems Thinking is applicable to "simple systems-unitary participant" types of problems. SD, on the other hand, together with Organizational Cybernetics and Complexity Theory, are suitable for "complex systems-unitary participant" situations. Further suggestions from Jackson are as follows: Soft Systems Approaches are applicable to both simple systems-pluralist participants and complex systems-pluralist participants; Emancipatory Systems Thinking is applicable to simple systems-coercive participants; Postmodern Systems Thinking is applicable to complex systems-coercive participants.

The methodology-problem context issue is also addressed by Kurtz and Snowdon [6], who developed a framework called the Cynefin sense-making framework, classifying systems as follows: Known, Knowable, Complex and Chaos. The Known systems are systems that have perceivable and predictable cause-and-effect relationships and can be handled via Sense-Categorize-Respond type methodologies (e.g., process re-engineering). In the Knowable category, cause and effect are separated over time and space, and Sense-Analyze-Respond type methodologies are suitable–Maani and Cavana [7] suggest that SD belongs to this category. Complex systems, on the other hand, are viewed as systems with cause-and-effect relationships that are coherent in retrospect and do not repeat; apparently, the appropriate methodologies for this category are the Probe-Sense-Respond type (e.g., pattern management). In chaotic systems, cause-and-effect relationships are not perceivable and can be handled only by the Act-Sense-Respond approach (e.g., crisis management). Although it is not possible to draw clear lines between different systems and different problem categories, the above suggestions help to develop a picture of where Systems Theory and SD stand, and what kinds of problems can be handled with them.

This study addresses the educational aspects of resolving problematic situations in the "complex systems-pluralist participants" category. This category corresponds to the Knowable area in the Cynefin sense-making framework. Although SD was more of a member of the complex systems-unitary participant category rather than complex systems-pluralist participants originally, the developments in the last decade moved it into the latter category. This paper is organized as follows: In the next section, the authors provide a brief discussion on the relationship between Systems Theory and System Dynamics. This section includes a critical review of Systems Theory and System Dynamics methodology, covering both "Hard Systems School" and "Soft Systems School" perspectives. After this, descriptions of the general teaching framework developed and the two courses designed are given. The concluding remarks and suggestions for future work are given in the last section.

The Relationship Between Systems Theory and System Dynamics

System Dynamics (SD) was developed by J. Forrester to overcome the inadequacies of conventional approaches, including Systems Theory, to enable systems scientist to deal with complex systems more effectively. In Systems Theory, system modeling is performed via mathematical tools, making the representation of "soft" issues quite difficult. Although SD modeling is based on the representation of systems via differential-difference equations, and positive and negative feedback loops similar to Systems Theory, SD methodology offers the capability of simulating non-analytical aspects of complex systems reasonably easily. Nonlinear, verbal and logical processes can be modeled without too much difficulty using software packages like IThink/Stella. Consequently, the system analyst is equipped with additional tools for modeling soft indicators such as human moral, burnout, commitment, loyalty, confidence and capacity for learning, etc. In organizational studies, for instance, modeling soft indicators in addition to conventional performance indicators like KPI (key performance indicator) and CSF (critical success factors) is vitally important. However, SD lacks the powerful tools of System Theory, due to the fact that its theoretical basis is weak. For instance, it is quite difficult or even impossible to conduct pre-simulation analyses and understand the structural properties of a system using SD; the analyst often has to try to foresee the consequences of certain decisions after some lengthy simulation studies, if and when possible.

Systems Theory has additional advantages over SD as far as structural analysis is concerned. In complex systems, the appropriate policy or strategy is developed often intuitively after examining all of the results of system analysis. Certain variables or a combination of variables are of special interest to the system scientist, quite often while others are of secondary interest. For instance, there are quite a large numbers of variables in an economic system, and one is usually interested in a few variables such as GNP, industrial production, inflation rate, etc. Such variables are normally grouped as system outputs. The way that inputs and outputs are connected in a system's structure provide an important perspective for system control. The input structure determines the degree to which the system's behavior can be modified, and the output structure determines the kind of information available for control. In Systems Theory, a system is said to be completely controllable if it is possible to drive the system from any initial state to another state within a finite number of steps. If the system is not completely controllable, then the system scientist either has to modify the control structure or base the design on the controllable portion of the system. Similarly, the dual concept of complete observability allows the system scientist to study the structural properties related to system measurement structure. It refers to the ability of inferring the system state by measuring the outputs. If the system is not completely observable, one then either has to modify the output or measurement structure, or employ an observer (an estimator in stochastic systems) to be able to determine (or estimate) the whole state vector. The system scientist loses all of these valuable structural analysis tools when using SD.

The shortcomings of the SD methodology have been addressed in the last decades, particularly in the 2000s. The developments in Hard Systems School and Soft Systems School have been influencing each other, creating richer versions of available methodologies and even new methodologies. As a result, quite significant developments in the capacity for hadling and managing complexity have been observed in various areas, including health, production and sustainability—particularly in the broad policy and strategy context where the wicked problems are. For instance, the contribution of Systems Thinking to the practice of OR (via Systems Approach, Complexity Theory, Cybernetics, SD, Soft OR and Critical Systems Thinking) is traced by Mingers and White [8]. Their major finding was that many of the core ideas of the systems approaches have been assimilated by other disciplines, where they continue to influence further developments, while other principles seem to have been forgotten, only to be periodically rediscovered or reinvented in different domains. In this context, they see the growth of the complexity theory as possibly the most significant development. Paucar-Caceres [9] explored similar issues within the context of MS/OR (management science/operations research). They look at both sides of the Atlantic and argue that American MS/OR has remained close to the positivist MS discourse, while the UK side has broadened its scope, establishing British MS soft and critical traditions. They think that the UK MS/OR community was succesfull in soft OR, but still needs to establish a bridge between theory and MS/OR practice by promoting multimethodology and multiparadigm approach.

Similar changes can be observed in the SD methodology; it has also been affected by Systems Thinking and the area of its applicability has been widened. Soft System Dynamics emerged along with various soft system thinking tools such as Checkland's Soft Systems Methodology, Soft Cybernetics and Soft OR [3], [4], [10], [11]. Soft SD enables system scientists to model soft issues more effectively and more realistically. However, unlike the works reported on OR-Systems Thinking, studies on the relationship between Systems Theory and SD are quite limited. Most of the published work on the theoretical issues in SD methodology are related to the modeling procedure and model validation.

The primary problem in modeling appears to be related to linking feedback loops and systems behavior via some formal tools. Groessera and Schwaninger [12] argue that most of the existing mental models in SD studies measure only parts of the system structure, and refer the system scientist to dynamical systems theory as the mathematical basis for SD to complement and validate the conceptual structure. The mathematical basis of SD is Systems Theory, as pointed out earlier in this study. This conceptual structure was explored by Kampman [13], where he studied the link between the System-theoretic and SD models. Kampmann attempted to establish this link between feedback loops and System behavior through the use of the "eigenvalue elasticity" concept. The idea is to apply tools from graph theory, formally linking individual feedback loop strengths to system eigenvalues. It helps analysts in understanding complex simulations by showing the usefulness of linear methods to nonlinear systems. On the same issue, Mojtahedzadeh [14] focused on consistency in explaining model behavior and model stucture, illustrating some of the issues related on three case studies; he calls for comparative studies on the subject. Stermann's [15] work is also related to this issue, but it is mainly concerned with structural validity, partial-model testing and over whole-model testing for structural adjustment.

It is widely known that SD models are often not validated thoroughly and they appear to be imprecise. They may also be based on poor data and ignore existing theories in the particular field. In fact, for most people working in Systems Theory, SD does not look scientific enough. Chaos Theory perspective even suggests that if SD models achieve sufficient precision and rigor, and are subject to proper validation procedures, they cannot predict the changes in response due to small changes in initial conditions. Jackson [3], [4] urges considerable caution in employing system dynamic (SD) models. The authors of this paper think this warning is important and still valid.

In general, the number of studies on the theoretical aspects of SD model building and validity is on the rise, but the theoretical issues involved are far from being resolved. In the practical world, the tendency for adopting an eclectic approach to multimethodological lementation can be observed. For instance, Morrison's [16] approach is quite a typical one. He uses two models to study the dynamics of managing process improvement; a formalized model to give the analytical solution, and an SD model to simulate the process. This particular application demonstrates how such models can be used practically, and effectively, in combination to understand the dynamics of a complex system. The authors of this paper are considering adopting a similar approach to expand the work reported by Temponi et al. [17], whose work reportedly combines several mathematical dynamic models of different business functions in order to obtain an aggregate model of an enterprise system to assist management's strategic decision making. This model can be complemented by an SD model in order to include soft indicators in a fairly realistic manner, relaxing the assumptions imposed by mathematical representation. Parallel use of these two models may bring some improvements in the overall operation of business systems. Similar arguments can be made for a recent study conducted by Ivanov and Sokolov [18] in which they address the operative perspective of supply chain dynamics through the use of control and systems theory. However, the links between these abstract models and the realities of supply chain systems remains to be resolved. This work can also be expanded via a multimethodological approach.

At this point, it is appropriate to look at INCOSE's (International Council on Systems Engineering) views on multimethodological approaches and the Systems Theory-Systems Engineering relationship. This study suggests that Systems Engineering lacks two essentials: 1) a fundamental systems engineering theory and principles on which the practice of Systems Engineering is based, and 2) inclusion of appropriate human, or people, engineering [19]. This is how Systems Engineering of 2020 is described in the vision developed here: The systems engineer of 2020 will develop expertise in the user domain and be able to address the social, economic and political impact of solutions. The education and training for systems engineers will focus on developing expertise in specific domains of interest, with an educational foundation in non-engineering disciplines such as sociology, psychology and economics. As a result, the systems engineer will have the requisite competence to work in a highly distributed and multidisciplinary environment with rapid access to a broad range of resources, and an understanding of human behavior and human-system interaction. The multidisciplinary and multimethodological approaches will certainly become more popular in the future. The book, Decision Making in Systems Engineering and Management [20], is a valuable work in the vision provided by INCOSE. It integrates new systems thinking tools into the conventional systems engineering lifecycle model fairly successfully—this book is one of the primary references used by the first author of this paper in systems-oriented courses.

The Proposed Teaching Framework

The two new courses designed at Ýzmir University are *Introduction to Dynamic Systems,* and *Systems Dynamics and Managing Complexity.* These courses will be offered primarily to Industrial Engineering students; students from other engineering departments and Business Administration/ International Trade and Finance will also be admitted. Due to lack of space, only the general aspects of the framework and summary of course descriptions are given here. Further details can be found in articles by Yurtseven and Buchanan [21], [22].

Systems Science basically provides a single vocabulary and a unified set of concepts applicable to practically all areas of science and engineering, bringing different academic disciplines together. In particular, Systems Theory, the core of Systems Science, makes use of mathematics, which provides an economy of language and establishes a conceptual framework for understanding the behavior of dynamic systems. Hence, the use of Systems Theory provides a far better understanding than the intuitive approach. Laware and Davis [23] examined the professional development of engineers from a systems thinking perspective. They view the mental model of systems thinking as a framework that can be utilized by students and professionals in professional development where Systems Theory serves as a tool to better understand economic and organizational change and processes. They suggest that students must develop a systems thinking approach to understanding their careers and to prepare themselves for the changing professional environment. Ropp [24] described the development of a safety management system within an aviation technology laboratory curriculum at Purdue University. Students are educated to view the associated system as a complex system; a system that places new demands and competency requirements on engineering and technology graduates in the aviation industry. The practical aspects of this systems-oriented education help students become competent in hazard identification, risk mitigation and proactive performance-based safety. Theuerkauf [25] stated that system theoretical considerations can help to convey engineering subjects and methods to students. He noted that viewing all technical systems from the point of view of material, energy and information and their modifications was a fairly strict technical approach in the past. He added that systems thinking has been expanded to include socio-technical aspects, hence its integration into secondary school and university curricula requires thinking in terms of systems and system models.

The differential and difference equation representations are the most common tools employed in representing dynamic phenomena or the time-evolutionary change. These equations represent the time linkages between various variables and allow one to study the interplay between the reality and the abstract. The vector notation of matrix algebra allows one to suppress the details, but retrieve them when needed. This is an effective and practical language, allowing the application of the theoretical results of linear algebra to large-scale systems. Markov chains, on the other hand, are employed to model dynamic systems that evolve probabilistically. All complex systems involve a fairly large number of variables, making them multivariable. Such systems can be observed everywhere, such as in population studies, economics, supply chain systems, ecological systems, etc. In representations, the large numbers of interrelated variables are seen as a whole set of relations in a complex system, suppressing the details.

What constitutes the essentials of systems theory obviously depends on one's perspective. In this study, they are identified by looking into the stages of SD methodology, in the general sense. The major steps of the methodology, as viewed by Maani ande Cavana, are as follows: Problem Structuring; Causal Loop Modeling; Dynamic Modeling; Scenario Planning and Modeling; Implementation and Organizational Learning [7]. Problem structuring or representation of dynamic phenomena is probably the most important step in the methodology. The powerful tools of Systems Theory, particularly Linear Systems Theory, can be employed effectively here. Due to the sound theoretical basis involved, the systems scientist or the student will feel comfortable in abstracting complex reality and developing a formal system model. As mentioned earlier, differential/ difference equation representations, matrix algebra and Markov chains can be used effectively to develop mathematical models of multivariable systems.

The preliminary analysis (stability, controllability and observability analysis) will be presented to students as described in Systems Theory. System stability will be introduced in the sense of Lyapunov, in the most general form as applied to nonlinear systems, followed by its results in linear system theory. Studying structural properties will help students to understand systems' behavior without going through complex simulation runs. Since the theory applies to all kinds of systems, students will see that one does not need to study one particular problem with set parameters. Furthermore, exploration of system structural properties will help to get some initial ideas on how realistic the models are. After developing some feeling about a system's behavior, students will be ready to relax some significant constraints imposed on the model and build an SD model of the system under study. Comparative response studies will allow them to improve the SD model and possibly the theoretical model as well.

In the generation of the solutions phase, students will observe the time variation of variables for various purposes, such as for planning, control, etc. They will realize that a specific solution can sometimes be found in analytical form, but more often with simulation. However, they will also see that simulation studies have obvious limitations; the number of experiments conducted by implementing different combinations of changes in the controlled variables, parameters and assumption often exceed practical levels. They will appreciate the fact that, the analytical techniques, when applicable, can provide valuable insight into the behavior of a system. Furthermore, they will realize that the influence of selected system parameters or operational policies on solution can be studied via some auxiliary concepts (stability, controllability and observability) in the exploration of the structural relations phase. Here, they will appreciate the use of different models in parallel.

The analysis conducted thus far will give students the opportunity to develop an intuitive insight into the system's behavior and foresee the possibilities for behavior modification. Normally, the suitable modification or control policies or strategies are determined after completing all of the studies summarized, intuitively in most cases. In the control or modification phase, students will attempt to change the system's response to an expected stimulus either by changing model parameters or introducing new connective mechanisms in the system. For instance, they will experience behavior modification by changing the birth rate in a population, or by changing production policy in a production system. They will also get a chance to work on more complex problems such as developing more effective policies through control after forecasting future trends in a macroeconomic model. At this point, students will be introduced to optimization, optimal control in particular, but only at a conceptual level; there will be no time for a detailed treatment. They will learn how to select the system input functions so as to optimize (maximize or minimize) an objective function (a measure of the quality of the system's behavior), leaving the rest of the work to computer software. They will be constantly reminded that mathematics serves as a language for organized thought; it should not be seen as a tool to generate the best policy or strategy.

Nonlinear System Analysis is also an important aspect of this framework. It will help students to establish a reasonable theoretical background and relate Systems theory to SD, since most SD models are nonlinear. Students will appreciate the value of SD when dealing with highly complex systems. Also, with a fairly strong theoretical background, they will be in a better position to interpret the results obtained from an SD study. They will realize that analysis of nonlinear systems is similar to that of linear systems in some respects, but different in other aspects. They will see that entirely different new types of behavior can be seen in nonlinear systems, as contrasted to linear systems. This phenomenon will be demonstrated on typical nonlinear systems such as the logistic curve and the finite escape time—the former is used to model exponential growth, often modified to reflect crowding, limited resources, etc., while the latter is a model of the growth process, where growth rate increases with size. They will also see that explicit solutions are rarely available in nonlinear systems, but it is possible to approximate or bound them with linear models, hence they will learn linearization. Here, they will learn the role of a summarizing function in characterization of systems behavior in broad terms. These concepts will be demonstrated on examples such as economic systems, studying equilibrium points, stability associated growth rates, predicting behavior resulting from perturbations in stimulus, characterizing limiting behavior, studying finite time escape phenomenon, saturation effects, threshold effects, etc.

The two courses designed to teach the above approach are briefly described now. Introduction to Dynamic Systems course has the following objectives: 1) to introduce the history and fundamentals of systems thinking and dynamic systems; 2) to teach analytical modeling and analysis of dynamic systems via various techniques; 3) to teach the essentials of linear systems theory; and, 4) to show the basics of nonlinear system analysis. The learning outcomes of the course are determined as follows: Through this course, students will learn the history, the main concepts and the major trends in systems thinking. They will appreciate the value of systems theory and its analytical power, and see how this theoretical framework can be extended to more complex systems. It is expected that the theoretical framework provided will help them to develop a deeper insight into the behavior and regulation of highly complex systems. The course includes the following topics: Historical Development of Systems Thinking; Classifications of the Major Strands in Systems Thinking; System Methodologies and Problem Context; Introduction to Dynamic Phenomena; Linear Systems Theory (modeling systems via differential/difference equations, linear algebra, and Markov chains, and concepts of control, controllability, observability, observers, estimators, and optimal control); and, Basics of Nonlinear System Analysis. The learning outcomes and their measurement process are given in Table A.1 in the Appendix; the table is summarized from the course ECTS (European Credit Transfer and Accumulation System) forms.

Concluding Remarks and Suggestions for Future Work

The main message to be delivered to students via these courses is that design and operation of today's systems require a certain amount of knowledge and skills of systems thinking. Students should be made aware of the fact that almost all systems are socio-technical in nature; whether they are dealing with a manufacturing system or a service system. Such systems cannot be handled by conventional thinking and tools; they tend to be messy and may require teams that involve engineers, managers, experts in finance, sociologists, psychologists, computer scientists, political scientists, etc., at various stages of the systems lifecycle. Systems thinking provides a common language, a set of system concepts, and a set of system methodologies to be able to deal with such complexities. Students should be prepared so that they can select and implement more than one methodology to analyze/design a complex system. The multimethodological approach developed in this study, via the combined use of Systems Theory and System Dynamics, is expected to provide students or system scientists with relatively more powerful tools in handling complex systems.

The potential areas for further work are as follows: 1) The framework and the courses will be updated as more information becomes available in SD methodology and its applications. There are an increasing number of research studies on the use of feedback loops and SD model validation. Also, cognitive aspects of modeling appear to be one of the important areas for improvement, and 2) Two more courses will be designed via a similar approach. The first one will be entitled "Fundamentals of Systems Engineering" and the second one will be related to Systems Engineering Management topics. The former will be a compulsory course for industrial engineering students in their fourth year (an elective course for other engineering students), and the second one will be an elective course for all engineering students.

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Appendix – ECTS Forms

Table A.1 ECTS Form to Measure Course Learning Outcomes

No	Program Qualifications / Learning Outcomes	Level of Contribution				
		1	**2**	**3**	**4**	**5**
1	Ability to apply the acquired knowledge in mathematics, science and engineering			b		a
2	Ability to identify, formulate and solve complex engineering problems				a	b
3	Ability to accomplish the integration of systems			a	b	
4	Ability to design, develop, implement and improve complex systems, components, or processes			a	b	
5	Ability to select/develop and use suitable modern engineering techniques and tools			a		b
6	Ability to design/conduct experiments and collect/analyze/interpret data				a	b
7	Ability to function independently and in teams				a	b
8	Ability to make use of oral and written communication skills effectively			a		b
9	Ability to recognize the need for and engage in life-long learning				b	a
10	Ability to understand and exercise professional and ethical responsibility			a	b	
11	Ability to understand the impact of engineering solutions				a	b
12	Ability to have knowledge of contemporary issues				a	b

- (a) Introduction to Dynamic Systems; (b) Systems Dynamics and Managing Complexity.
- Grading catagories:
  1=Lowest, 2= Low, 3=Average, 4=High, 5=Highest