System Dynamics in Engineering Education

Martin Simon, Hans U. Fuchs
Technikum Winterthur
P.O. Box 805
CH-8401 Winterthur, Switzerland
fax: +41 - 52 - 46 35 13
phone: +41 - 52 - 46 20 25

Abstract

System dynamics can play an important role in the education of engineers. On the one hand, students in engineering profit from system dynamics. On the other hand, the system dynamics methodology can be enhanced if we take advantage of the training in physics and mathematics received by the students. It is found that new forms of teaching physics (systems physics) support systems thinking in a unique way. Advanced courses in engineering disciplines can then build upon modeling and simulation taught early on in the curriculum.

1 Introduction

Graduate engineers form the major body of the work force with higher education in industrialized countries all over the world. Educating engineering students today means shaping the mental models applied by this work force tomorrow. Therefore, not only managers but also engineers should be trained in the general methodology of system dynamics. That way system dynamics contributes to the creation of the future learning organizations.

At Technikum Winterthur (TWI) we have used systems thinking and system dynamics in courses within the departments of physics, mechanical engineering, electrical engineering and chemical engineering. We have employed system dynamics at introductory through intermediate levels, and we have taught graduate courses specifically designed for training SD-modelers in different professional fields.

This paper first describes the rationale behind our decision to use system dynamics in the training of engineers. It goes on to discuss the unique role the teaching of physics can play in this educational process by outlining the feedback relationship between system dynamics and a generalized form of classical physics (systems physics). Finally, our experience with a concrete example of a course using the system dynamics methodology is described.

2 Coping with change in engineering education

Fueled by changes in society and in the relation between society and nature, engineering education is undergoing profound transformations. This section will briefly list forms of change and discuss a model of how system dynamics can be instrumental in accompanying us through times of change.

Transformations in engineering education

The driving forces behind change in engineering in general and in engineering education in particular are very much the same as those found in other areas of human endeavor. Put simply, we are facing problems of increasing complexity at an accelerating pace. Not only do we find ourselves in a highly dynamical situation, the particular tasks encountered by the profession increasingly demand knowledge of the behavior of dynamical systems at the technical and mathematical level. Just consider the field of renewable energy engineering for which steady-state models of classical energy systems simply do not suffice any longer; the variability of the natural environment combined with the necessity for storage elements make regenerative energy systems highly dynamical.

Some of the change we would like to describe here has to do with the particular situation our school (TWI) finds itself in. In order for you to understand the possibilities of leverage for the system dynamics methodology, you should be aware of the special circumstances at TWI. Our school is an undergraduate engineering school which is undergoing rapid transformation from a Swiss Polytechnic to a European Engineering College as they emerged in Britain and Germany some 20 years ago. As far as science and engineering go this transformation has meant a strengthening of the role of applied research and development which in turn has led to a marked build-up of the application of modeling and simulation at TWI.

Last but not least we will fuse with the School of Business and Administration of the Canton of Zurich (HWV Zurich) to a College of Engineering and Business/Administration. More than anything else, this change might bring with it opportunities for applying system dynamics for fostering a true shared understanding between the two sides which up to now have been independent of each other. Again, energy engineering proves the point. In the future, energy engineering will not achieve its potential without simultaneously considering energy management and the role of the interaction of energy and society.

How to cope: a model for identifying areas of leverage

Whereas the initial buildup of the students' knowledge about system dynamics has to be provided by their teachers, we found that courses putting more emphasis on system dynamics methodology have a strong self-enhancing component. It is clearly not the self-enhancing process which is amazing but the thoroughness of this process, it's speed, and the momentum it creates. We hypothesize this to be a result of (1) an increasing relevance of the SD approach to dealing with dynamical problems professional engineers encounter in their fields, and (2) the SD approach in itself creating positive feedback in taking engineering problems head on that look insurmountable without SD methodology. A simple model reveals the main areas, where a SD approach could add value to the educational process.

Figure 1 presents a rough mapping of the educational process students at TWI undergo. The main chain on top represents the process for one out of three or more groups of about 25 students within one of the departments of the school (Mechanical, Electrical, Chemical, and Civil Engineering, and Architecture). For simplicity's sake, the model assumes that the students all pass the exams. The first conveyor in the chain depicts students of a single group during their first and second years; during this time the students receive all their training in the same initial grouping. The second conveyor represents the same group of students during their third year.

During the first two years, each group of students essentially has a different set of teachers. However, all of the courses in mathematics, physics, and in computing are given by a pool of teachers shared among the departments. This defines the first area of leverage for a SD approach. The unique role teachers of physics and mathematics can play in first and second year education is the result of the following three facts: (1) teachers of physics and mathematics have the possibility of creating the basis for a more unified view of dynamical processes by employing SD methodology early in the process; (2) as these teachers can reach across the borders of the departments, they are able to efficiently spread a systems thinking approach, thus invigorating the students' capabilities of coping with interdisciplinary project work and applied research and development later on; (3) once physics has been understood as a historically grown and experimentally validated way of modeling nature expressing relationships in the form of laws, physics can be used for an immense reservoir of rich and meaningful models. Of course, these could easily be translated into simulation models, as the laws also provide for the mathematical relationships. But then, this merely would mean to replace the brain as the simulation engine by a computer. Instead, physics teachers should tap into the fundamental resource of physics as a highly effective facilitator in the process of learning how to model. How this can be done by teaching physics will be explained in more detail in the next section.

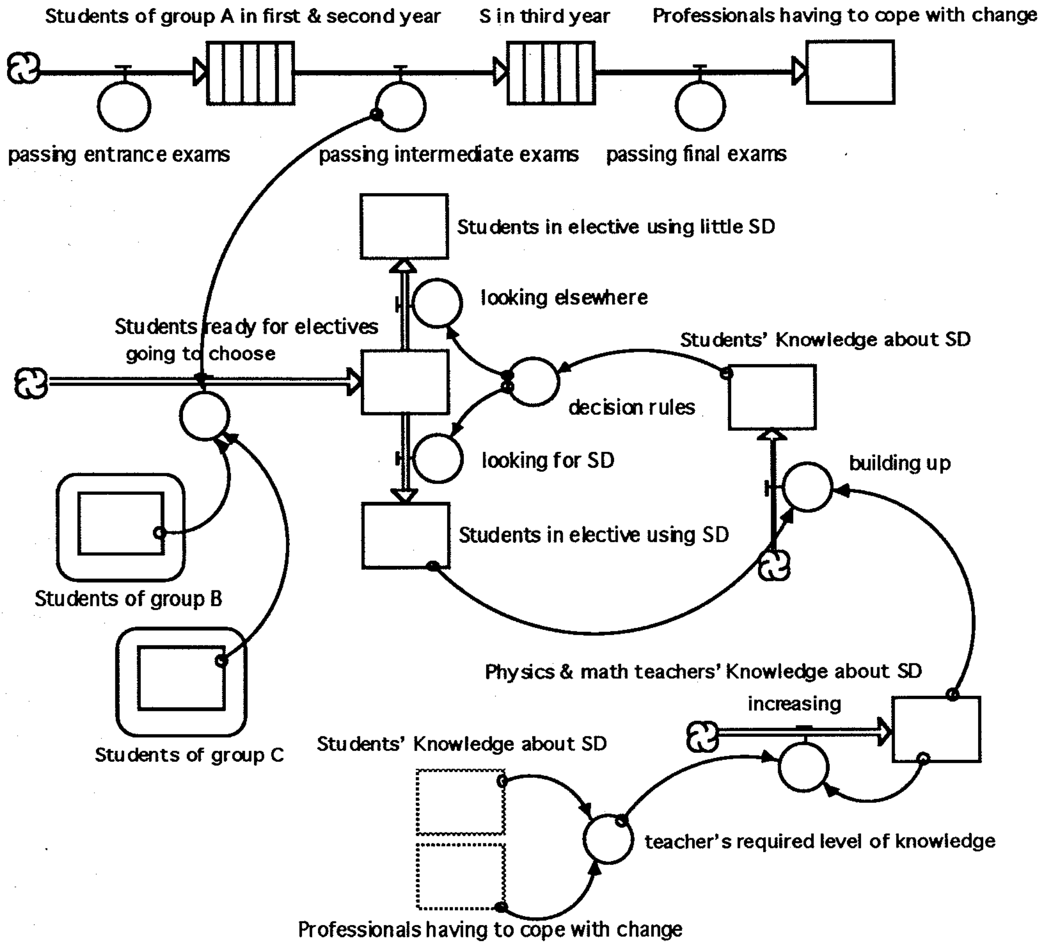

Figure 1: A rough mapping of the educational process a student at TWI undergoes. The map helps to reveal areas of leverage for teaching SD concepts.

After two years, having passed their intermediate exams, the students of all groups have a choice between several elective courses, along with courses in the core subjects within their respective departments. This can be modeled by a common stock of students ready for electives.

Figure 1 shows the inflow to this stock driven by the outflows of students of group A through C (groups B and C depicted by compressed symbols). Here we have identified a second area of leverage for SD concepts. The familiarity of students with what they have been taught during the first two years naturally influences their choice. However, the more confidence the students build in the applicability of system dynamics concepts and the more convincing its cross-disciplinary potential appears to them, the more easily they cope with new challenges provided by complex tasks in the field of engineering. Thus, by using SD concepts early on, a teacher will be able to pick up topics in an elective course that go beyond tradition. We have done this for example in a course on solar energy engineering. The results are described in section 4.

There are still more implications in the model presented in Figure 1. By looking at the map one easily detects at least two positive feedback loops in the center of the diagram. (1) The practical relevance of the students' knowledge about SD acquired in their first elective course influences their decisions wether or not they should take another one-semester course stressing SD-concepts. (2) Students familiar with systems thinking ask different questions. This gives their teachers a clear incentive to improve their own systems thinking skills. Also, there is feedback from older students to the decisions of newcomers, which is not expressly included in the map.

Still another loop shows highly important feedback from professionals having to cope with systems of ever increasing complexity in their field of engineering. After having passed their final examinations, the students finish their studies with thesis work. Most of the theses are prepared by project work lasting for one or two semesters during their final year. By communicating their experience back to their former teachers, professionals are able to stimulate SD-related topics for thesis work.

3 Teaching systems thinking by teaching physics

The first major steps toward systems thinking and system dynamics can be taken in undergraduate physics courses which are part of the engineering curriculum. In this section we would like to explain why this is so and how the goal can be achieved.

The relationship between physics and systems thinking

It certainly should not come as a surprise that physics and system dynamics have some form of relationship. Physics provides for the premiere example of mathematical theory building and of mathematical modeling. We should not underestimate the influence of physics upon our belief that nature is amenable to modeling which leads to predictions of the outcome of physical processes. In this manner physics provides one of the cornerstones of control theory (see Figure 2).

However, in at least two important ways their relationship is strictly limited. First, feedback thought is rather underdeveloped in physics which explains why this crucial ingredient of control theory was borrowed from biology (Fig.2). Secondly, the relationship is completely one-sided: physics has not been influenced by the engineering disciplines of systems theory, cybernetics, and control theory, at least not in its foundations and in its teaching.

System dynamics has evolved on the basis of control theory out of a desire to apply systems thinking to other than just engineering control systems (Fig.2). Generalizations of this nature often mark important transitions from one paradigm to another. A paradigm shift of some sort has also taken place in the foundations of classical physics during the last three or four decades in the form of a generalized version of continuum physics (Truesdell and Toupin 1960; Truesdell and Noll 1965; Truesdell 1984; Müller 1985). This generalization of the foundations has recently been transferred to the introductory level which has led to the teaching of what might be called systems physics (Maurer 1990; Fuchs 1996; Burkhardt 1987). It is interesting to see that the relationship between the generalized versions of control theory (system dynamics) and of physics (systems physics) is of a much deeper nature than the one enjoyed previously by physics and control theory (Fig.2).

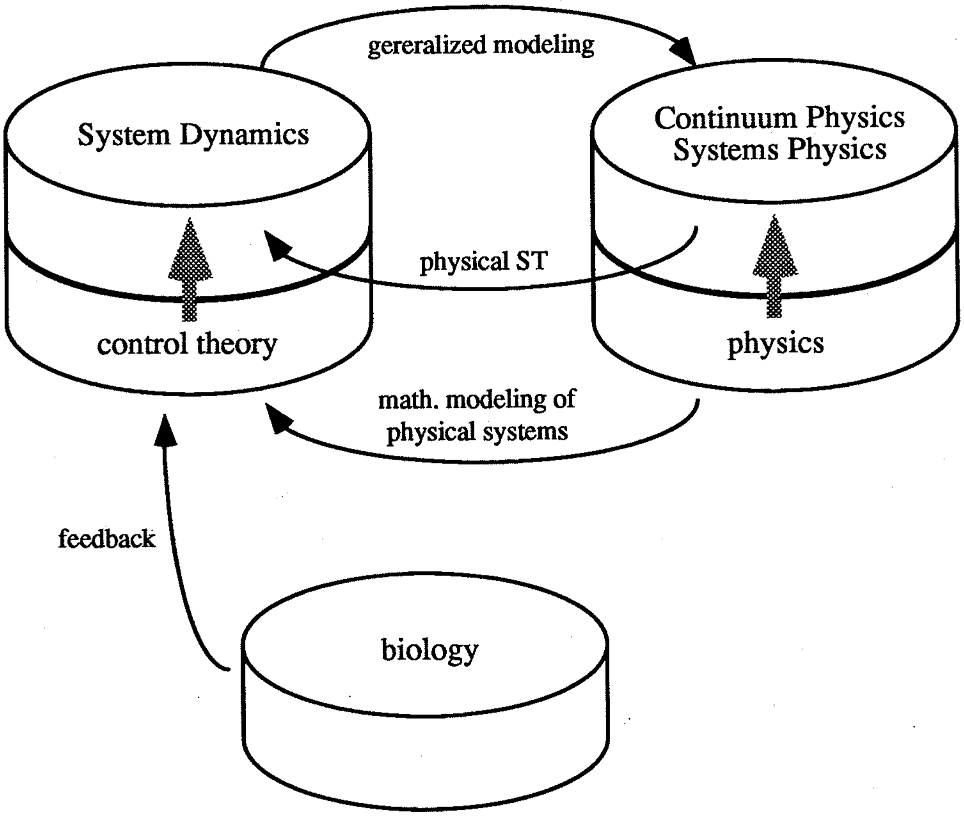

Figure 2: Relationship between physics and control theory on the one hand, and between their generalizations, namely System Dynamics and Systems Physics.

Physical systems thinking

Put simply, both continuum physics and systems physics use at their core the image of the flow, the production, and the storage of physical quantities such as electrical charge, momentum, and entropy. While this image has not yet been used extensively in the presentation and the teaching of physics, it is well known to anybody familiar with the notion of stocks and flows as they are employed in system dynamics modeling. Now, what systems physics has to bring to systems thinking is an example of processes where the image of flow, production, and storage, and the necessary constitutive relations for the flows can be cast into a precise, well known form. Therefore, in our view, physical systems thinking can furnish a secure platform for the learning of systems thinking and system dynamics.

System dynamics and systems physics
The reverse of the relationship just outlined is very important as well: the system dynamics way of modeling can be employed as a vehicle for teaching the modeling process in systems physics (Fig.2). We can even make this modeling process the core of what we expect (engineering) students to learn from their physics courses, which would mean that system dynamics becomes the paradigm of new ways of teaching physics. Experience at TWI (Maurer 1990; Fuchs 1996) shows the this goal can be achieved.

Taking a close feedback relationship for granted, system dynamics and systems physics not only profit from each other but provide for a synthesis at a higher level as well. If you consider the ability of engineering students to deal with interdisciplinary problems and to apply the modeling process as increasingly important, then the new relationship between system dynamics and systems physics may serve as a tool for bridging the widening gap between theory and application. Looking at physics as the theoretical side of (much of) engineering, students adept at modeling dynamical processes will not shy away from what otherwise might be considered to be too difficult, namely the application of theoretical foundations to their practical profession.

4 System dynamics-based solar energy engineering as a model

We have built up a two-semester course on solar energy engineering at TWI. It is one of the list of elective courses students of mechanical engineering have to choose from. As described in section 2, students have gone through their first two years before this point. From the very beginning in 1989, we have built the concept of our course on aiming at the interesting dynamic features solar thermal systems exhibit. Therefore we have used SD methodology and systems physics to introduce students to this complex field of mechanical engineering.

After an introduction to the foundations of solar energy engineering and a spectrum of its analytical methods and design tools, we encourage and strongly emphasize a shift of attention towards modeling of solar energy systems as a means of thoroughly understanding their behavior. Students mainly use STELLA when modeling complete solar energy systems or parts thereof. Although STELLA is of very limited use for the simulation of rigorously modeled solar systems, it is a valuable tool for doing the first steps in the modeling of more complex examples of engineering applications. At the end of the first semester students have to choose from a variety of topics to do project work in the following semester. We have offered topics for project and thesis work in the field of modeling such as a comparison of different modeling approaches for seasonal heat storage for solar energy applications.

The first course on solar energy engineering started in 1991 with 12 participants. In subsequent years 18 students, then 27 students and eventually 35 students signed up for that course. The example of thesis work done by two students as a team and finished in 1994 clearly shows the value SD concepts can add to the field. One of the students had to construct a solar domestic hot water system for experimental work. The other student's task was to develop in parallel a simulation model which would mimic as closely as possible the solar hot water system constructed by the first student. The model was developed with MATLAB/SIMULINK. Although they had one semester of project work to prepare for their thesis work (which lasted for only 6 weeks), the complexity of the problem went well beyond what traditionally could be expected under time and resource limited conditions prevailing during thesis work (Bontognali 1994; Meyer 1994).

Simd Lin
Simulation
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5 Summary

The following lists a number of observations we have made during the years of building up system dynamics related topics within the curricula of some of the departments at our school.

- As long as K12-education in System Dynamics is not standard, the SD-training of the students requires active reversal of their normal mental models from static to dynamic ones.
- The System Dynamics approach enhances both the traditionally taught skills of the students and their willingness to keep learning beyond graduation.
- Besides delivering a multitude of interesting applications, physics provides for a particular way of systems thinking which can be of great advantage in the teaching of system dynamics.
- Teaching and thesis work have given us extensive experience with integrating system dynamics in an engineering curriculum. The available computer tools for building models allow for developing more precise mental models of dynamic processes such as in physics, chemistry or energy engineering. By learning about SD early on, students are able to reach beyond usual limitations. SD has proven to be an excellent learning tool for exploring complex engineering problems and preparing sustainable solutions. Without getting bogged down in non-conceptional details, students acquire practical experience for a thorough discussion of mathematical implications later on.
- Through the emphasis on structured thinking and the commitment to sustainability Systems Thinking apparently fosters the necessary consciousness for high quality work on the job.
- The Systems Thinking framework provides students as well as professionals with a concise language for discussing complex problems on the basis of shared understanding despite different backgrounds.

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