

Essential Skills for System Dynamics Practitioners A Delft University of Technology Perspective

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Abstract

There is little consensus on the skills set required of a system dynamics practitioner. In this paper we use the teaching approach and learning goals of the system dynamics courses at the Delft University of Technology as a starting point to explore the development of system dynamics modeling skills. System dynamics is embedded in the curriculum of students at the Faculty of Technology, Policy and Management (TPM) of the Delft University of Technology. The staged approach by which real world complexity is introduced in the system dynamics curriculum is first explained and the learning goals of the system dynamics education at TPM are described. The role of the quadruple jump approach to system dynamics education in achieving the learning goals of the curriculum is then illustrated using the case of urban dynamics. Finally, we compare the results of the teaching approach, as exemplified in the learning goals, with the skills needed by system dynamics modelers as derived from literature. We conclude that the question of which skills can be taught and which need to be learnt in (professional) practice remains open.

Keywords: system dynamics, skills set, education, urban decay, complexity

1 Introduction

System dynamics is an integral part of the study programmes offered by the Faculty of Technology, Policy and Management (TPM) of the Delft University of Technology. Students who follow all the system dynamics courses on offer (of which two are mandatory and three are optional) have almost the equivalent of a one-year, fulltime master programme in system dynamics (Pruyt et al., 2009). In their full curriculum, however, students learn a range of problem exploration and structuring methods and study a selection of other modeling methods. These include discrete systems modeling, multi-criteria decision analysis and statistical modeling.

This paper addresses the issue of the skills set required of a system dynamics practitioner by exploring the teaching approach and learning goals of the Delft

University of Technology. The different system dynamics courses in the TPM curriculum are described and the learning goals of each are discussed. The way in which real world complexity is introduced in a quadruple jump approach over the whole curriculum is explained and illustrated using the topic of urban dynamics. Finally, the learning goals from the curriculum and the teaching methods are contrasted with the literature on the required skills set of a good system dynamics practitioner. We conclude that there is no clear agreement on what constitutes a complete set of skills for a system dynamics practitioner and agendize the issue for further research.

2 Courses and Learning Goals of the TPM System Dynamics Curriculum

All Systems Engineering, Policy Analysis and Management (SEPAM) bachelor students and the students of the Engineering & Policy Analysis (EPA) masters program at the Faculty of Technology, Policy and Management (TPM) follow two mandatory system dynamics courses. Students first follow an introductory system dynamics course and after successful completion of this course participate in a seven week system dynamics project course (see also: Pruyt et al., 2009, Slinger et al., 2008). After successfully passing both mandatory courses, students can choose to follow an advanced system dynamics course during their masters programme. Students can also choose to apply system dynamics in their bachelor thesis project or in their masters thesis project.

The hop, step, step and jump approach to system dynamics education (Pruyt et al., 2009) is characterized by the use of real life cases from the outset, with the level of real life complexity increasing throughout the process. An overview of the TPM system dynamics courses and the manner in which real life complexity is built up is provided in Figure 1.

SPM2313: Introductory System Dynamics course

SPM2313, the introductory system dynamics course for bachelor students, focuses on introducing the theory of system dynamics modelling. ‘Hot’ cases are used to demonstrate the use of system dynamics in addressing current issues (Pruyt, 2009, Pruyt, 2010). These cases are embedded in a theoretical shell (Figure 1). The learning goals of the introductory system dynamics course are:

- To understand the role of System Dynamics within the process of problem solving
- To be able to apply the System Dynamics method
- To be able to analyse the behaviour of simple linear continuous dynamic models by hand as well as by computer
- To be able to represent and analyze continuous models in Powersim, Vensim and other computer programs covered
- To have basic knowledge of the domain of System Dynamics.

SPM2391: System Dynamics Project Course

SPM2391 is the system dynamics project course, following the introductory course. Students build a system dynamics model, based on a case description of a real societal problem and report on the development and use of their model to a fictitious client. In this way students are challenged to address real life complexity in a controlled setting. The academic skill of reflecting on a modeling study is also

introduced (Slinger et al., 2008). The learning goals of the system dynamics project course are:

- To gain experience in applying the modeling cycle to unstructured problems.
- To gain insight in the application of system dynamics modeling to policy problems.
- To be able to apply the techniques from the introductory system dynamics course.
- To be able to use the results of experiments on a model to come to (policy) recommendations for a problem owner.
- To be able to formulate a project plan for a new system dynamics study
- To be able to reflect on the role of models (at a bachelor level).

SPM3911: Bachelor Thesis Project

In the bachelor thesis project (SPM3911) students can choose to apply the system dynamics modeling method to a complex, multi-actor, societal problem of their own choosing. Whereas the initial analysis addresses the real world problem complexity, the final product and recommendations do not necessarily have to be used by a real life problem owner. The learning goals of the bachelor thesis project are:

- To independently apply the knowledge and skills gained during the SEPAM bachelor program.
- To structure a complex problem, abstract research questions from this and answer these with TPM analytical methods and to interpret the results taking into account the initial problem statement.

SPM9154: Advanced System Dynamics Course

SPM9154, the advanced system dynamics course, aims at deepening the students' theoretical and practice-based understanding of justifying, building, validating, analyzing and communicating systems dynamics models. Students are required to formulate a model of an ill-defined, real world problem. Students then apply for data structuring techniques, advanced verification and validation techniques and develop a strategy to communicate their model in a multi-actor setting. Certain of the techniques that the students study are 'cutting edge'. For example the focus on formal model analysis, including eigenvalue elasticity analysis (Kampmann, 1996) and the development of an interactive learning environment as a model communication tool (Slinger et al., 2009). In addition, students are exposed to a series of lectures from practicing, Dutch system dynamicists, building their understanding of professional practice. The learning goals of the advanced system dynamics course are:

- To understand the possibilities and limitations of the System Dynamics modeling method;
- To understand the relevant scientific literature on selected topics such as the use of data, model structure and behavior, model validation, communicating modeling results and group model building in the field of System Dynamics.
- To be able to make an informed choice as to when to use System Dynamics;
- To apply the theoretical knowledge on building, validating and communicating models in a problem situation;
- To understand current literature and recent advances in the field of System Dynamics.

SPM5910: Master Thesis Project

Finally, if a student elects to use system dynamics in their master thesis project (SPM5910) the doors are opened wide for full real world complexity. Students are expected to formulate a real life, multi-actor problem and to go through the whole modeling cycle independently. Usually the final product and recommendations are communicated and used by the actual problem owner, putting extra requirements on the use of the model and reporting of the results. Students are also expected to be able to reflect on their modeling in an academic mode of thinking. The SEPAM masters thesis project has the following objectives:

- The student independently plans and fulfills a Master Thesis Project according to academic standards of research design, having a critical stance towards the research/design topic and is able to critically reflect upon the results;
- The student passes through all phases of academic research and/or design
- The student is able to report on the thesis project in a final thesis report including a scientific paper;
- The student is able to present the research project orally and to defend its contents;
- The student shows that s/he complies with the attainment levels of the SEPAM programme (i.e. a master of engineering level).

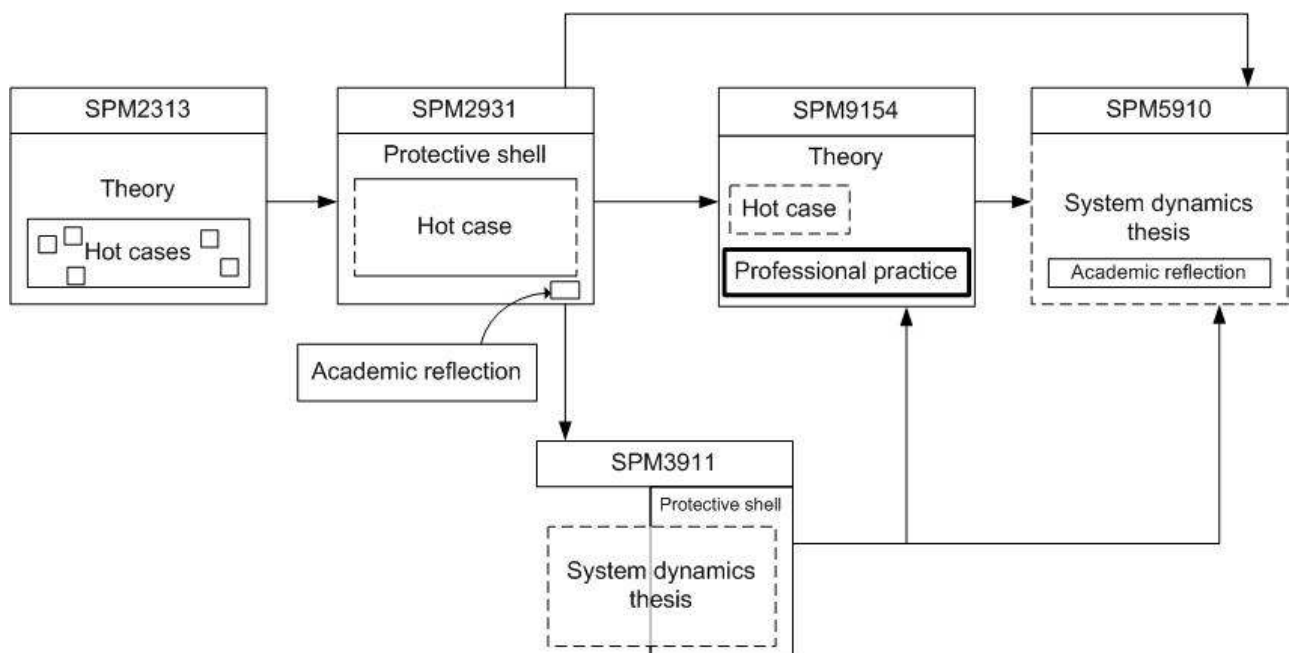


Figure 1 Schematic of the system dynamics courses and the gradual increase of real life complexity in the hop, step, step and jump approach as students stream through the SEPAM curriculum (from left to right)

3 Case Study: Urban Dynamics across the Curriculum

A wide variety of policy relevant topics are addressed in the different system dynamics courses and research projects conducted at TPM. In 2004, the famous urban dynamics work by Forrester (Forrester, 1969, Forrester, 1970) served as inspiration in the development of a case study for the system dynamics project (spm2931). At the time there was much concern in the Netherlands regarding urban decay in areas of

Rotterdam. Over the last three years the topics addressed in the introductory system dynamics course are also based on ‘hot’ cases (i.e. current affairs with high media interest) (Pruyt, 2009, Pruyt, 2010). In fact, the redevelopment of social housing districts in The Netherlands (Pruyt, 2009) provided the impetus towards using ‘hot’ topics in this course. Indeed, the urban dynamics cases generated such enthusiasm in the students that the 2004 case was later revamped to address slum development in a fictitious west African city for the spm2931 course. Additionally, a student chose to focus his bachelor thesis on it and another decided to write his master thesis on the subject (Huisman, 2009).

The interest in modeling urban dynamics at our faculty over the last two years, means that it runs as a golden thread through the curriculum and so can be used to illustrate how the hop, step, step and jump approach is designed to provide students with the skills to practice system dynamics. The only course that has not included any work on urban dynamics is the advanced system dynamics course. This course, therefore, will not be discussed further in this paper.

SPM2313: Introductory System Dynamics Course

The introductory course uses hot cases to make students enthusiastic about system dynamics, help them understand its relevance in today’s complex world and ramp up from small, didactic example models to simple yet practical models (Pruyt, 2009). The redevelopment of postwar social housing districts has been a hot issue in the Netherlands over the last five years and remains so. A simplified version of the ‘Social Housing District’ model was used as a teaching/testing case (in the BSc retake examination of 18 August 2008). Students were required to formulate the model, simulate the dynamics, explain the link from structure to behavior, perform uncertainty analyses, test two policies, propose a more effective policy and make a simplified causal diagram to explain the structure-behavior link.

Figure 2: Stock-Flow diagram of the simplified ‘Social Housing District’ model (Pruyt, 2009)

SPM2931: The System Dynamics Project Course

The system dynamics project course builds directly on the introductory system dynamics course. Students apply the methods taught in the basic course on a substantially more difficult case than those encountered previously. Not only is the model that they are required to build larger and more complex, but the data that is supplied is relatively unstructured, open to interpretation and in some cases incomplete. This setup enables students to work on real world problems from within a protective shell (Figure 1). Students work in groups of two, completing the entire modelling cycle: developing a problem description/statement, deriving modeling questions, conceptualizing, specifying their model in Powersim or Vensim, verifying and validating and then using the system dynamics model to explore behavior and find policy options. They deliver an advisory report with recommendations to the problem owner.

In the system dynamics project course of 2009/2010 an adapted version of the urban dynamics model of Forrester (Forrester, 1969, Forrester, 1970) is used. The setting is contextualized to the problem of slum development in a fictitious city, Kente, in a developing country in west Africa (Sanders et al., 2009).

Students receive a case description of about 25 pages. Included in the description is a specification of the expected weekly deliverables and a proposed time schedule. Students are free to deviate from this planning, but experience has shown that without this guidance students have trouble completing the problem successfully. A reason for this is the high workload and the lack of experience of the students in project work at this early stage in their curriculum. Once students fall behind they find it difficult to catch up. By supplying them with a schedule, students learn the advantage of working to a plan that requires them to model and write a report contemporaneously.

The data for model development are supplied in an initial presentation by the “client” and through a series of fictitious interviews with key people in the city council and municipality. Historical data are presented in the form of statistical data of key performance indicators of the city over the last fifty years. The data is delivered in a deliberately unstructured state. Some of the data are contradictory. Students are expected to use their own judgement, make assumptions if necessary, conduct appropriate data testing and justify their activities and choices in their report.

The main elements of the system are inhabitants, houses and industry. The city becomes more attractive for immigration from different income groups as the number of available jobs and houses goes up. Eventually industry deteriorates and the number of jobs goes down. The city is then almost fully built up, but there are not enough houses and slum development starts.

Students are free to conceptualize the problem for themselves and to use additional material if they choose, although it is not necessary. The data they are given are unstructured, yet adequate for making a model. In this way students are protected from real ‘real world’ complexity, but still have the freedom to tackle the modeling challenge in their own way. At the end of the project, students are expected to develop policy measures for improving the outcomes of the system. In this sense they work at full complexity within the protected shell that the case description forms around them.

Even though the case and data are fictitious, an important aspect of the case description is that it contains a selection of real newspaper articles illustrating the real world relevance of the fictitious case. The Kente case contains a BBC article on the global slums crisis, a New Internationalist article on urban explosion and several photos showing real world urban decay and slum development. Students find that this additional material is an enhancement to the course, because it allows them to understand the relevance of system dynamics to policy problems outside of the classroom.

The project takes place over a seven week period, after which students hand in an advisory report to the city council of Kente and a fully specified and validated system dynamics model based on the data contained in the interviews from the case description. Students also write a short essay showing their understanding of what types of problems are suitable for system dynamics and for what problems other methods are more appropriate.

The grade for the system dynamics model forms 25% of the total grade, while the report forms 65% of the grade. This reflects the fact that the focus of the project course is on embedding the modeling component in an analytical and advisory context. After all, students have learnt to develop a model (albeit a simpler one) in the introductory course, and now have to demonstrate that they can use this simulation tool appropriately and usefully to advise a client. The remaining 10 % is divided as follows: 5 % is awarded for the process they followed in undertaking the project and 5

% for a proposal for a new system dynamics study. Students are also expected to reflect on models and submit an essay for this purpose (see Slinger et al 2008).

SPM3911: Bachelor Thesis project

The bachelor thesis is the final project prior to the completion of the three-year Systems Engineering, Policy Analysis and Management (SEPAM) bachelor program. Students are required to demonstrate that they can independently apply the knowledge and skills they have gained during the programme and acts as a rite of passage to the masters programme. The project specifically focuses on the ability of students to structure a complex, multi-actor problem, derive relevant research questions and select the appropriate quantitative method to address some of the research questions. Students are free to choose the focus of their bachelor thesis provided it is technically challenging and societally relevant. Some students choose to apply system dynamics in their thesis.

In late 2008, a student elected to expand and develop the ‘Social Housing District’ model, further. He undertook a study with an engineering consultancy firm and applied the model in an urban renewal project in the Netherlands.

SPM5910: Master Thesis Project

The masters thesis project represents the culmination of the two year masters programme which follows after the initial three year bachelor programme.

In 2009, a student elected to focus his masters thesis on urban renewal of The Hague South-west and other districts struggling with the problems of urban decay. This area of the city is characterized by houses built in the immediate post-war period. The first residents were professionals, but with time this changed and the small houses were increasingly occupied by immigrants to The Netherlands. The downward spiral of departing professionals and increasingly poor inhabitants has led to the persistent social problems characterizing this area of The Hague. Using a slightly more complex version of the ‘Social Housing District’ model, the student was able to establish that well educated, native Dutch people only stayed between two and four years in this area. He explored policies aimed at altering this behavior pattern and worked with a national scientific advisory board in developing recommendations for retaining the mobile, educated Dutch in these parts of the cities.

4 Towards a Formalized Skills Set for SD Practitioners

In order to assess the quality of the system dynamics education at the Faculty of Technology, Policy and Management we need an idea of what constitutes a good system dynamics practitioner. A survey of the relevant literature did not bring us a clear cut, well established overview of the skills set required of a system dynamics practitioner. Barlas already noted that more work and discussion is needed on this topic (Barlas, 1993), and it seems that this still holds true today. While the master program at WPI could be used in some ways as a reference point, Doyle et al. (2009) do not discuss the learning goals underlying the courses there, so that comparisons can only be made by inference. We also looked at the objectives of system dynamics as envisioned by Forrester (1994), but since this advice is targeted at students who will not primarily be modelers we found the objectives too general for our purposes.

Andersen and Richardson (1980) established the foundations of system dynamics education. They mostly describe modeling skills, stressing dynamic thinking skills and the teaching of elementary feedback structures, before students can

work on more complex models. During the theory course at TPM students learn about the dynamic thinking modes that Andersen and Richardson advise (i.e. reference modes, a suitable time horizon, the proper boundary considerations and policy levers). They are also introduced to several standard model constructs. Students work on these independently as part of the hot cases in the introductory course. In the system dynamics project, students apply the understanding and modeling skills they acquired in the introductory (theory) course to determine the historical and possible future modes of behavior of the system, using an appropriate time horizon. Students also have to determine the boundaries of the system and advise on policy options. It must be noted that students at TPM receive extensive ancillary training in problem structuring, determining boundaries and formulating policy options.

Richmond introduces the notion that modelers have to be able to operate on at least seven thinking tracks simultaneously in order to be effective at modeling (Richmond, 1993). Although these thinking tracks are not directly related to skills sets, we found this framework fruitful for analyzing the courses aimed at skills development rather than evaluating the performance of students in their bachelor and masters projects. Results for three of the courses are presented in Table 1 below. The bachelor thesis project (SPM3911) and master thesis project (SPM5910) are not included in the table, because students need to use all types of thinking in these projects. The thinking mode for which our students are least trained is scientific thinking, which Richmond denotes as rigorously defining measurement scales and testing hypotheses. This is not entirely surprising as TPM is training engineers.

Table 1 The relation between Richmond’s different modes of thinking and the courses SPM2313, SPM2931 and SPM9154.

	SPM2313	SPM2931	SPM9154
Dynamic thinking	‘Hot’ cases make students aware of the time history dynamics of everyday problems	Problem analysis of the dynamics of the case material further develops students dynamic thinking skills. Causal loop diagrams, list extensions etc. are some of the tools used.	Student entering the course are familiar with dynamic thinking and practice it further.
Closed loop thinking	Students learn to recognize feedback loops as the underlying drivers of dynamic behavior in many of the social problems around them.	Students become aware of the closed loop nature of their models while working through the modeling cycle. They transfer these insights to their fictitious clients.	Formal techniques for identifying all feedback loops in a model and determining the simplest representative loop set are taught.
Generic thinking	Students learn to recognize similarities in underlying structure and resulting behavior through the use of appealing ‘hot’ cases.	Students are challenged to distill generic insights from the case and so produce robust and useful advice regarding potential solutions.	Students develop their generic thinking skills further through the practice of model development and extensive model testing.
Structural thinking	Addressed with exercises requiring the translation of causal diagrams into stock-flow diagrams and subsequent simulation of ‘hot’ cases.	When translating their causal diagrams into structural diagrams and then verifying their models, students acquire competence in structural thinking.	Formal model analysis techniques and extensive validation are taught to deepen understanding of how structure drives behavior.

Operational thinking	The contextual reality of the ‘hot’ cases goes some way to addressing this thinking skill.	Grounding of the students structural models in the reality of the case material is supported through personal supervisory sessions. This thinking skill is developed strongly in spm2931.	Practice-based lectures contribute to the development of operational thinking as does the requirement to communicate the model results to the (fictitious) client.
Continuum thinking	Stimulated by the use of appropriate “hot” cases	Careful choice of case material stimulates continuum thinking and challenges the if-then-else paradigm.	Specifically addressed in lectures and practicals on method choice, justification and communication of SD models.
Scientific thinking	Students are taught to generate hypotheses about model behavior and test these.	Hypothesis testing is practiced and used in developing trust in the model. Reflection on models and model use is required.	Underlies the design of the course where theory and practice run in parallel.

The most appropriate overview of a required skills set for practitioners came from an unexpected source. Richardson, in a paper on the problems for the future of system dynamics, while arguing for wise practice, provides a list of skills that a good system dynamicist needs (Richardson, 1996). We found this framework usable in evaluating our curriculum further. Table 2 below displays the framework introduced by Richardson, as well as an overview of the courses in which each aspect is addressed. As is clear from the table, all aspects are addressed adequately apart from practice in group modeling and teaching skills.

Table 2 Modeling skills underlying wise practice according to Richardson (1996) and the courses in which these skills are taught. Brackets indicate that the skills acquisition is dependent upon the modeling being undertaken in a consultancy setting rather than for purely academic purposes.

Modelling skills underlying wise practice	SPM2313	SPM2931	SPM3911	SPM9154	SPM5910
Building blocks of system structure	X	X			
Molecules of generically useful system structure	X			X	
Consulting wisdom		X	(X)	X	(X)
Group modeling principles					
Teaching practice that accelerates growth in modeling capabilities					
Wisdom about problem definition and system conceptualization	X	X	X	X	(X)
Wisdom about building confidence in models for policy analysis	X	X		X	
Solutions to modeling puzzles	X			X	
Wisdom about model-based consulting practice		X	(X)	X	(X)

Practical wisdom about teaching the modeling arts					
Group model building techniques ¹				X	
model use techniques ¹				X	(X)

¹ In Richardson (1996) group model building and model use techniques are combined.

Several skills which we consider essential for a practitioner are missing from the frameworks presented above. These include communication and reporting skills. The development of these skills in association with modeling is given specific attention at TPM. A practitioner needs to be able to communicate about a model (assumptions, results, insights etc), both orally or in written form. Team and project work are other skills that students learn during their project course and the advanced system dynamics course. Students at TPM are also trained in academic reflection. Indeed they are asked to look beyond their modeling practice and evaluate the consequences of using models to inform policy. Furthermore, students who apply system dynamics in their thesis project(s) are encouraged to gain experience outside of university by working with consultants or scientific advisory bodies to further improve their modeling practice skills.

5 Conclusions

The case of urban dynamics has been fruitful in illustrating the system dynamics courses taught at the Faculty of Technology, Policy and Management of the Delft University of Technology. Each of the courses uses different teaching methods in a hop, step, step and jump approach, gradually introducing the students to the real world complexity they will face as system dynamics practitioners. In so doing, students are able to develop a host of skills that enable them to work with system dynamics in a policy setting.

However, the complete skills set required of a system dynamics modeler / practitioner remains an open question. As Barlas already noted in 1993, more work and discussion is needed to come to a good pedagogy of system dynamics (Barlas, 1993). In our view, understanding of an ideal skills set required for a system dynamics practitioner is an important aspect of this. We hope that this paper leads to further discussion and definition of the skills sets possessed by good system dynamics practitioners and how teaching goals can be associated with these skills. This begs the further question of how many of these skills can be taught, and how many must be acquired through (professional) practice itself.

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