Making System Dynamics Cool?
Using Hot Testing & Teaching Cases

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Abstract

This paper deals with the use of 'hot' real-world cases for both testing and teaching purposes such as in the Introductory System Dynamics course at Delft University of Technology in the Netherlands. The paper starts with a brief overview of the System Dynamics curriculum. Then the problem-oriented teaching and testing approach is explained, followed by a presentation and discussion of several examples of 'hot' cases. The main goal of presenting the use of 'hot' testing/teaching cases is to spur other System Dynamics lecturers on to doing the same, and to start up a small network for exchanging the 'hottest' cases.

Keywords: System Dynamics, Education, Actuality

1 Introduction

The rationale behind this paper is three-fold. We believe first of all that (higher) education determines to a large extent the quality of (the next generation) professional System Dynamics modellers, and hence, the field of System Dynamics. Second, we believe that sharing (innovative and/or proven) educational practices, and exchanging (teaching and testing) cases may lead to further improvement of System Dynamics education. And third, we wish to form a small network of university lecturers of System Dynamics courses around the world who (wish to) use similar 'hot' teaching/testing cases, in order to share relevant real-world testing/teaching models and cases. The goals of this paper are to share some actual teaching/testing cases, and to start up a case-exchange network.

Although several papers discuss aspects of teaching System Dynamics at the university level (e.g. (Hovmand and O'Sullivan 2008)), there are no contributions dealing with the use of 'hot' teaching/testing cases for Introductory System Dynamics courses.

In section 2 we provide a brief overview of the System Dynamics stream within the larger curriculum of the Faculty of Technology, Policy and Management at Delft University of Technology. Section 4 deals with the gap that existed in the past between the small/simple exercises of the introductory System Dynamics course and the big/difficult case of the System Dynamics Project that lead to the development of the actual problem-oriented cases. This 'hot' cases approach is discussed in section 4 and illustrated with several recent examples in section 5. Finally, some conclusions, lessons learned, and proposals are distilled in section 6.

2 System Dynamics at the Faculty of Technology, Policy and Management of Delft University of Technology

The Faculty of Technology, Policy and Management at Delft University of Technology offers a three-year Bachelor of Science programme in Dutch, the '*SEPAM*' [SEPAM] BSc programme, and

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three two-year Master of Science programmes in English, among which the '*Systems Engineering, Policy Analysis and Management*' [SEPAM] MSc and '*Engineering and Policy Analysis*' [EPA] MSc programmes. All students of the SEPAM BSc and EPA MSc programmes, are first required to take an Introductory System Dynamics course.

After successfully passing the Introductory System Dynamics course, students are allowed to participate in the System Dynamics Project. Based on a case description of about 15 pages, students have to work in pairs to make a System Dynamics model, to validate the model, to use the model to analyse the problem situation, to report on the results and recommendations (to a fictitious client), and critically reflect on modelling. After having passed both mandatory courses, students can choose to take the Advanced System Dynamics course, and/or choose to apply System Dynamics in their individual BSc and/or MSc theses.

This year, there are about 245 students in two Introductory System Dynamics courses, 130 students in two System Dynamics Project courses, 20 students in an Advanced System Dynamics course, and several students doing an individual System Dynamics BSc or MSc thesis. The number of 245 students in the Introductory System Dynamics course is expected to be a current maximum and to reduce next year to an annual average of 150-200 students. The number of students in the System Dynamics Project and Advanced System Dynamics courses are expected to increase to annual averages of 150 and +30 students respectively. The number of BSc and MSc students applying System Dynamics in their thesis projects is also expected to increase.

The totality of these System Dynamics-related courses corresponds –at least for SEPAM students taking all System Dynamics courses and doing System Dynamics thesis projects– more or less to a full-time 1-year master programme in System Dynamics. However, at Delft University of Technology, these System Dynamics courses are embedded within the broader SEPAM and EPA programmes in which students are required to take –amongst many other courses– several problem-structuring and modelling courses. Upon completion of their studies, students leave the university with a tool box filled with a multitude of problem structuring, modelling, simulation, problem analysis, and process design methods.

3 Closing The Gap Between Introductory Exercises and Project Case

Until two years ago, small/didactic and technical/mathematical exercises were used during non-mandatory computer labs of the Introductory System Dynamics courses to familiarise students with the System Dynamics modelling language and softwares. Computer-aided modelling and simulation were not tested during the exam. However, the case of the System Dynamics project was –and still is– rather large and difficult. It has broad, fuzzy boundaries, contains relevant and irrelevant information, uncertainties and contradictions, information and indications needed to specify the System Dynamics simulation model.

For many students, the transition from small/didactic exercises to the big project case went anything but smoothly. The gap between the exercises dealt with during the non-mandatory computer labs of the Introductory System Dynamics course and the large case study of the System Dynamics Project was simply too big for most students to be bridged smoothly. Because students Modelling skills of some of the students passing the Introductory System Dynamics course were insufficient to successfully participate in the System Dynamics project. Their lack of applied modelling skills made the project too difficult: consequently, they had to start acquiring basic System Dynamics modelling skills during the project instead of learning how to deal with broader boundaries and fuzzier descriptions. Although the latter were exceptions, many students had difficulties bridging the gap.

In order to ramp up their practical System Dynamics modelling skills, several changes have been made over the last two years (see (Pruyt et al. 2009)). One of these changes was the introduction of computer-based testing of their practical modelling skills as part of their exams – which seems to be a good incentive for students to invest in acquiring the necessary applied System

Dynamics modelling skills during the Introductory System Dynamics course. Another change was the introduction of more difficult cases, at first purely didactic ones, and later also 'hot' real-world cases, which are almost automatically more difficult. The rationale behind the use of 'hot' cases is discussed in section 4 and examples are provided in section 5. For more innovations/changes in the Introductory System Dynamics course to ramp up the System Dynamics modelling skills of the students to the level necessary to participate in the System Dynamics project, see (Pruyt et al. 2009).

4 Teaching & Testing by means of 'Hot' Real-World Topics

Today, most exercises and cases used in weeks 4, 5, 6, 7 of the introductory System Dynamics course –as well as all test and exam models– deal with actual, relevant, real-world issues of increasing complexity (see section 4).
'Hot' real-world testing/teaching cases –instead of just bigger and more difficult cases– allow to:

- illustrate the relevance of System Dynamics modelling for dealing with important dynamically complex issues with which most students are already familiar but do not know how to study them,
- teach students what System Dynamics models could really be used for,
- show students what high-level System Dynamics models of real-world issues may look like,
- spur students on to look at current issues from a systems modelling perspective and getting students to connect news stories to potential System Dynamics models, and how these models could be useful [Students are informed that exam and test questions are as much as possible related to actual issues.]
- and, in the end, to enthuse students for using System Dynamics modelling to deal with important real-world issues whenever it is appropriate.

Anecdotic evidence suggests indeed that students find it inspiring and motivating to work on relevant issues, even if they are more difficult. Many (motivated) students persevere for hours at modelling these cases until they finally succeed, which is not the so for purely didactic cases.

And quite often after an exam, students comment that the case was 'extremely interesting, but rather difficult'. Some students immediately expressed their desire to extend/adapt these models for their thesis projects. Five of these students are currently developing more detailed/specific models of testing/teaching cases presented in section 5).

In spite of the difficulty of the cases, passing rates are higher than before, which may be partially attributed to the use of these 'hot' cases. Only very few students fail their exam/test because they think they are so familiar with the issue at hand that they can easily make a model of their own in the limited time available. Modelling according to one's own interpretation/inspiration is to be avoided during the exam of this introductory '*99% sweat and skills and 1% inspiration*' course. The large majority of students –in spite of being familiar with a 'hot issue' at hand– conscientiously follow the case description.

Anecdotic evidence also indicates that students start to listen/read/watch the news differently: since starting this initiative, students have been sending spontaneous e-mails with links to news stories that are interesting from a System Dynamics point of view.

However, developing such current, real-world cases –especially the exam cases– is a difficult and time-consuming balancing exercise: good cases need to be

- relatively simple and short,
- actual, relevant, and interesting,
- sufficiently realistic in terms of boundaries, structures and behaviours,

- sufficiently interesting in terms of structure, dynamics and the link between them,
- useful for proposing and testing policies,
- and perfectly tested and worded.

Hence, developing good cases is extremely demanding for lecturers –especially in large-scale System Dynamics courses for which many different tests/exam cases need to be prepared[1]. It may therefore be desirable for university lecturers of Introductory System Dynamics courses around the world to join forces, start up a small network, and start exchanging the most relevant real-world testing/teaching cases (and underlying models and answers to the questions).

5 Examples of Recent 'Hot' Testing/Teaching Cases

Six 'hot' cases developed between August 2008 and January 2009 are discussed below in order to illustrate the type of issues and System Dynamics models used for these cases. Five cases are traditional mixed qualitative-quantitative cases, and one case is purely qualitative.

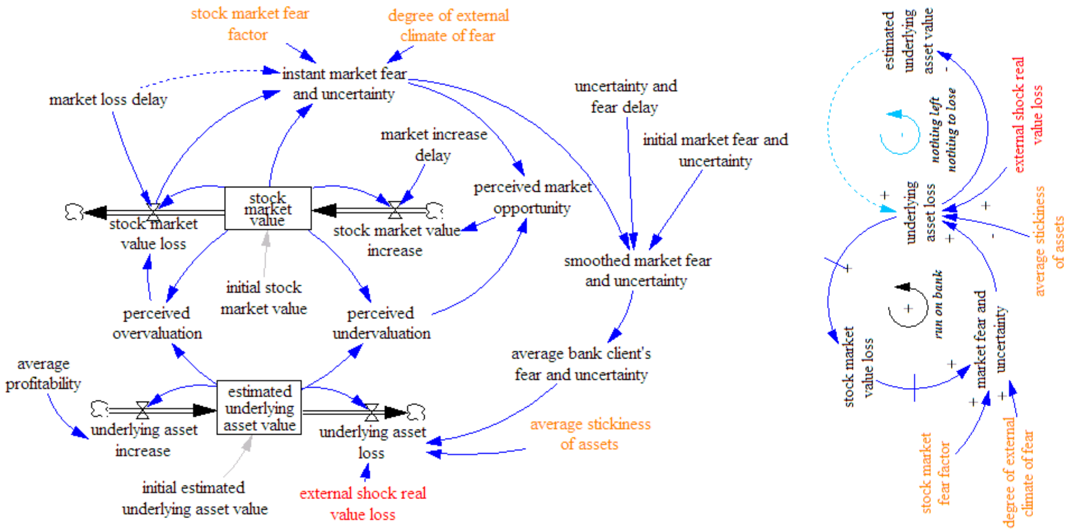
Most of these cases have been created for testing purposes but have been used for teaching purposes afterwards. At these 2 to 3 hour tests/exams, students need to solve 20 MC questions and one major modelling question. The modelling question consists of one to two pages of detailed case description and about ten guiding questions. Case descriptions for the Introductory System Dynamics course are usually very detailed, specifying almost all variables (in italics) and relationships (in plain language). Case descriptions are followed by about ten questions, guiding students step by step through all modelling phases, asking students to generate and interpret outputs, and to derive and formulate policy recommendations.

Descriptions of the cases below can be found in the appendices and (from p14 on) and in the appendices of related papers ((Pruyt 2009a), (Pruyt 2009b), and (Pruyt 2009c)). The corresponding System Dynamics models and answers will be sent upon request to colleagues willing to exchange 'hot' cases. All models are available in Vensim and in Powersim formats, all cases are available in Dutch and English.

[1]Over the last year, the lead author alone had to develop ten different testing/teaching cases for different exam sessions of the Introductory System Dynamics course at Delft University of Technology.

5.1 Saving a Bank? The Case of the Fortis Bank

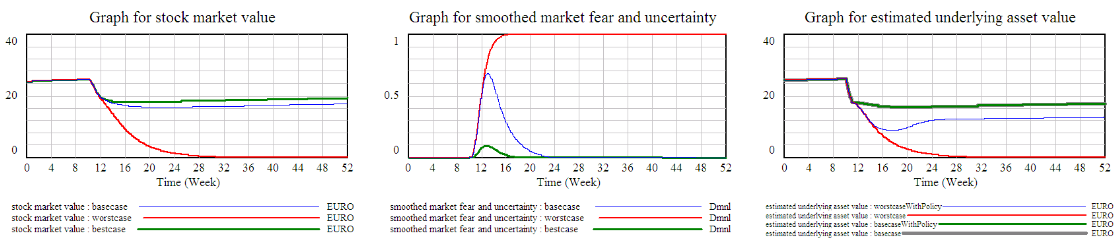
The System Dynamics model of the 'Fortis Bank' case was developed on 28 September 2008, at the same day the ministers of finance of the Benelux countries met in a great hurry to rescue the Fortis bank. A System Dynamics model was built in order to gain a better understanding of potential dynamics of bank crises and to test policies for saving banks (see Figure 1 for the model structure and (Pruyt 2009c) for a more detailed discussion).



(a) Stock Flow Diagram of the 'Fortis Bank' model (b) Causal Loop Diagram

Figure 1: Structure of the 'Fortis Bank' model: Stock Flow Diagram of the simulation model (left) and Causal Loop Diagram of a 'Run on the Bank' (right)

The model was subsequently turned into an exam case for EPA MSc students (exam of 23 October 2008) and a teaching case for SEPAM BSc students. It was –and still is– an excellent case: the topic is –and most certainly was– very actual and important, the model is small and simple (see Figure 1), useful for generating different families of dynamic behaviour (see Figures 2a and 2b – all potentially interesting behaviours can be generated with it) and for exploring possible policies to save the bank from collapsing (see Figure 2c for a 50% guarantee of the initial underlying (asset) value). Although some students performed exceptionally well on this case, many students found the case rather difficult because of the high levels of aggregation and abstraction.



(a) Stock Market Value in the base case, worst case, and best case (b) Market Fear and Uncertainty in the base case, worst case, best case (c) Worst and base case with/out a guarantee of 50% of the asset value

Figure 2: Behaviour of the 'Fortis Bank' model for different scenarios and a policy (a 50% guarantee of the initial underlying (asset) value)

5.2 The 'Soft Drugs Summit'

On 21 November 2008, a 'Soft Drugs Summit' ('*wiet top*') was held in the Netherlands to discuss the future of the Dutch policy of tolerance related to soft drugs, also known as 'het gedoogbeleid', which is in fact a very peculiar pragmatic way of dealing with a small but serious gap in the Dutch law. Nowadays, most Dutch citizens and policy makers agree that this policy of tolerance needs to be revised. Dutch society is nevertheless strongly divided about the direction of the revision. Currently the Dutch soft drug debate is –broadly speaking– dominated by two groups with opposing views about the direction soft drugs policy reforms. On 22 November 2008, the day after the highly mediatised summit, qualitative System Dynamics models were created for each of the opposing views (see (Pruyt 2009b) for a detailed discussion and analysis of both points of view).

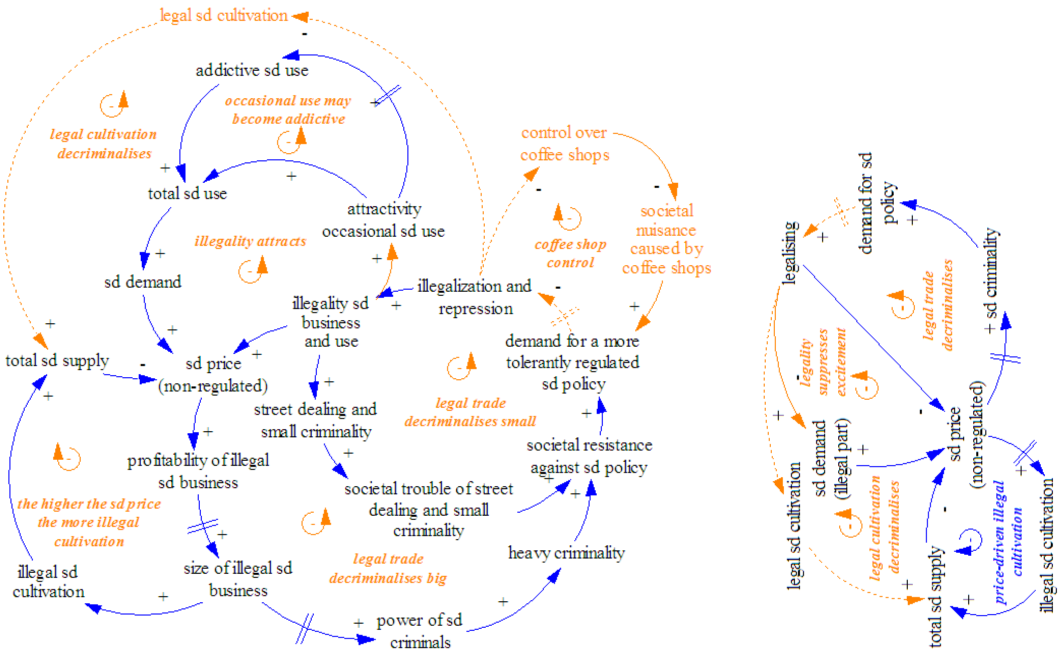


Figure 3: Detailed (left) and aggregated (right) causal loop diagrams from the point of view of the proponents of a more tolerantly regulated soft drugs policy

Only the models corresponding to the point view of the proponents of a more tolerantly regulated soft drugs policy were turned into a testing case for the first intermediate test of the SEPAM BSc students which took place 5 days later, on 27 November 2008.

The case was (and still is) very actual and relevant for Dutch students and policy makers. The case study describes the assumptions of proponents of a more tolerantly regulated soft drugs policy. Students are asked to make a causal loop diagram from this description (see Figure 3a), to aggregate loops in order to develop an aggregated causal loop diagram (see Figure 3b), and to (mentally) simulate the model and describe its possible behaviour.

Then, students are asked to make changes to the extended and aggregated diagrams in order to model the policies proposed by their opponents, the proponents of more restrictively regulated soft drugs policy, and to mentally simulate the expected impact of an ever more restrictive soft drugs policy from the point of view of the proponents of an ever more tolerantly regulated soft drugs policy. In order to do so, the dotted policy loop needs to be eliminated, and the polarity of 1 crucial link needs to be changed, changing the polarity of most loops – compare Figures 4 with Figures 3.

A small number of students constructed causal loop diagrams that corresponded to their own

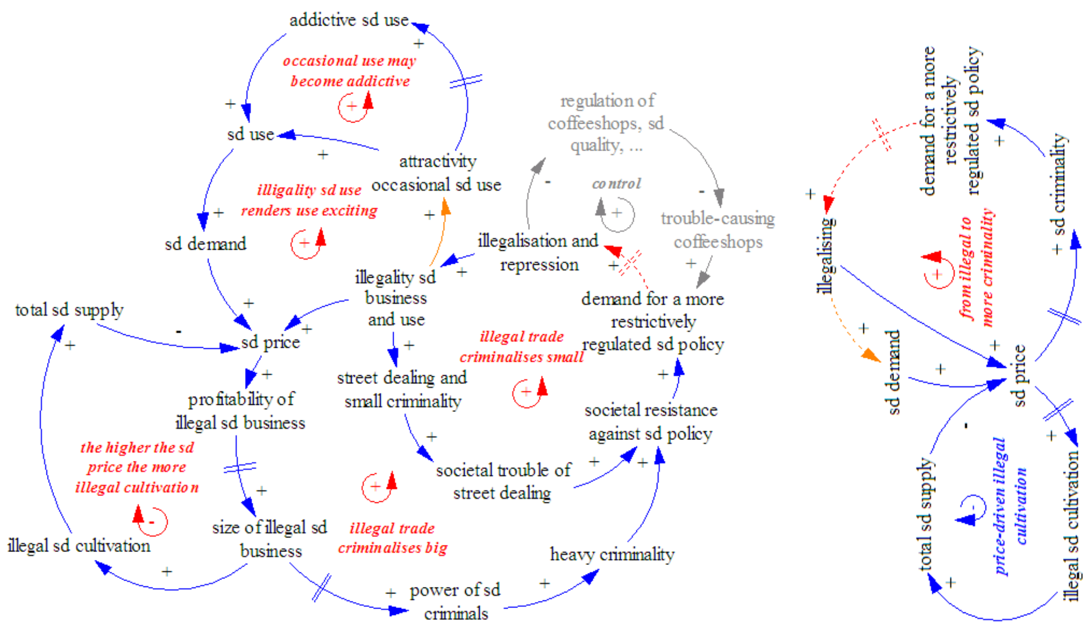


Figure 4: Detailed (left) and aggregated (right) causal loop diagrams from the point of view of the proponents of a more tolerantly regulated soft drugs policy on the implementation of an ever more restrictive soft drugs policy

mental models instead of the case description provided. Since this was 'just' a test, and not an exam, it provided a good opportunity to discuss modelling mental models of stakeholders versus modelling one's own mental models.

5.3 Smart Grids? Large-Scale Electrification of the European Car Fleet

Enexis, a Dutch Distribution Network Operator, considers developing a 'Smart Mobile Grid' in which Electric Vehicles [EVs] are used among else to improve their grid usage, to store electricity, and to decouple load and large-scale intermittent renewable energy generation. Several articles about this 'Smart Mobile Grid' were published in Dutch magazines and several brain-storm sessions with policy analysts were organised. After participation in several of these sessions, a high-level System Dynamics model was developed related to the coupled dynamics of a large-scale transition to EVs, the use of electrical batteries (those in the EVs as well as those plugged into the grid after having serving in the EVs) to decouple intermittent electricity supply and variable load, the impact of EVs on the grid, the accelerated depletion of lithium resources, and the potential feedback of those effects on the large-scale transition towards EVs.

The model was simplified, reduced in scope and size, and turned into a testing/teaching case (used for a second intermediate test for SEPAM BSc students on 21 December 2008). The focus of the model is the large-scale electrification of the European passenger car fleet and its impact on world lithium resources and availability.

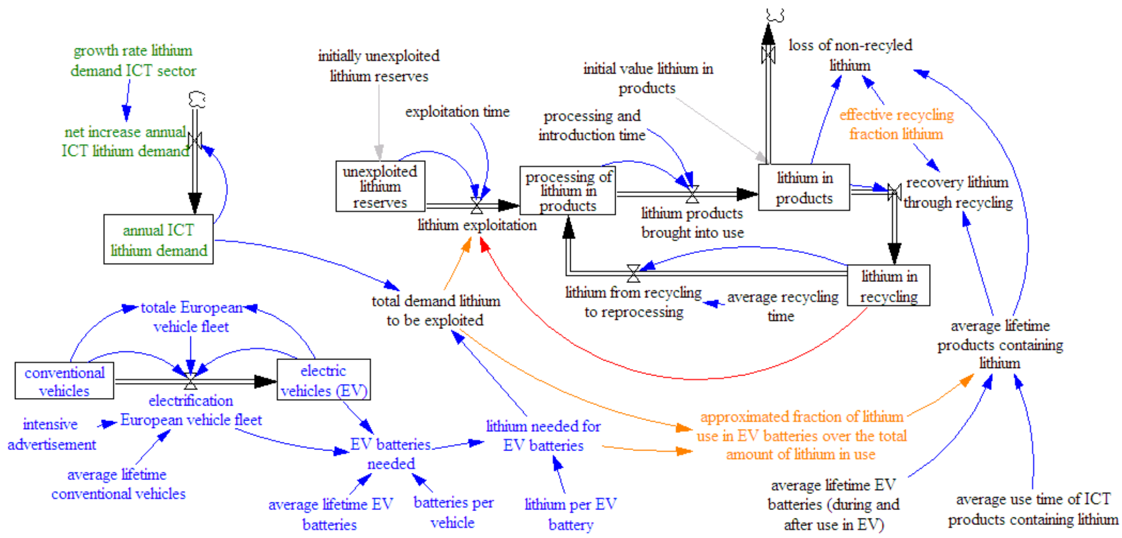
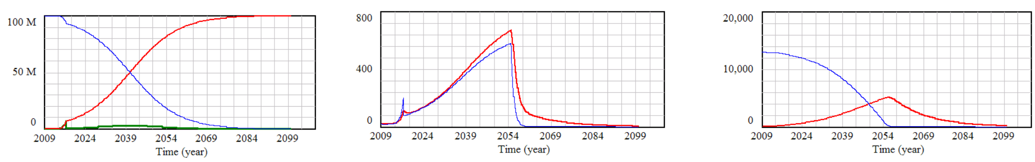


Figure 5: Stock-Flow structure of the Electric Vehicle-Lithium model

The case consists in developing three submodels (see Figure 5, first the blue, then the green, and finally the black submodels), constructing a causal loop diagram of the lithium chain, validating the model, simulating and mapping its behaviour (see Figure 6), performing uncertainty/sensitivity/scenario analyses, closing the model by adding links from the lithium submodel towards the electrical vehicle submodel, and drawing conclusions.



(a) electric vehicles (red); electrification (green); conventional vehicles (blue)

(b) lithium exploitation (blue); processing of lithium in products (red)

(c) unexploited lithium reserves (blue); lithium in products (red)

Figure 6: Behaviour of the Electric Vehicle-Lithium model

5.4 Cholera Epidemic in Zimbabwe

By the end of December 2008, alarming reports and articles concerning the cholera outbreak in Zimbabwe started to receive international media coverage. By that time 30000 cases of cholera infections and 1600 cholera deaths had been reported. In the first week of January 2009, a hypothetical System Dynamics simulation model related to this cholera epidemic was created (see (Pruyt 2009a)) which was turned into an exam case (for one of the four versions of the SEPAM BSc exam of 14 January 2009). Although the model has not been validated by Cholera experts yet [and contains 2 bold assumptions that require further elaboration], the dynamics of the model is sufficiently interesting for teaching/testing purposes to be presented here. This case is a classic System Dynamics case in the sense that students are asked to:

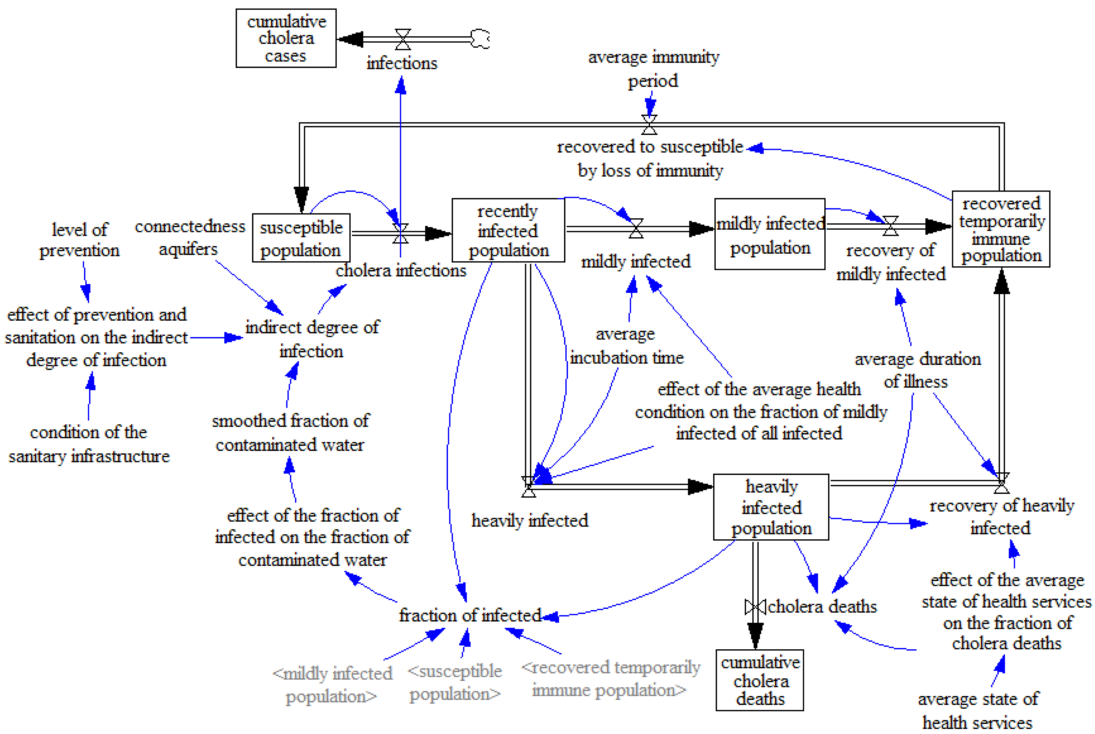


Figure 7: Stock-Flow Diagram of the Simulation Model of the Cholera Case

1. *Make a System Dynamics simulation model corresponding to the case description.* The Stock-Flow Diagram of the resulting model is depicted in Figure 7. The model is simple: it contain a few lookup/graph, max, and smoothing functions.

2. *Make an aggregated feedback loop diagram of the simulation model.* A possible aggregated feedback loop diagram is depicted in Figure 8. The behaviour may already be deduced from it.

3. *Simulate the short term behaviour* and make specific graphs (figures 9a,b,c).

4. *Validate the model.* Here students are required to apply several validation tests and to (roughly) compare the 30000 reported cases of cholera and the 1600 reported cholera deaths reported with the model outputs (as in figures 9b,c).

5. *Simulate the long term behaviour* (10 years) and make graphs of the behaviour of the susceptible population, cumulative numbers of cholera cases and deaths (see Figure 9e,f,g).

The short term, medium term, and long term dynamics –with/out policy interventions– are analysed in (Pruyt 2009a).

6. *Perform sensitivity/uncertainty analyses.*

7. *Propose and test policies, and formulate a policy recommendation.*

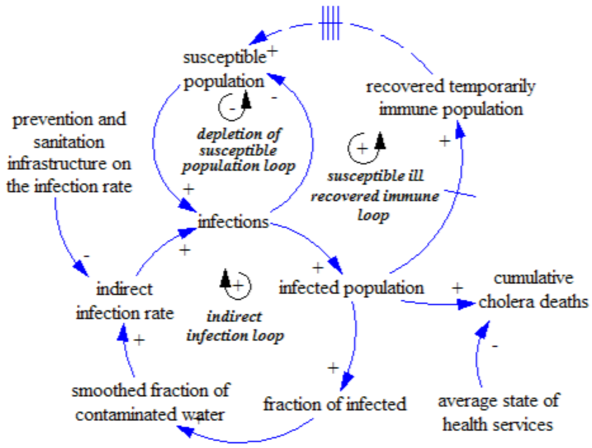
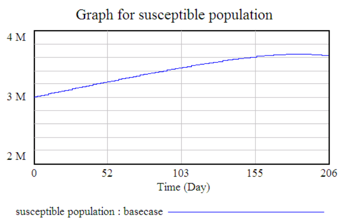
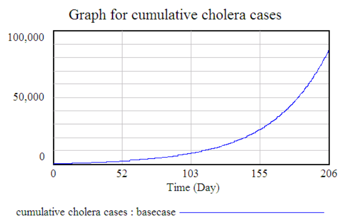


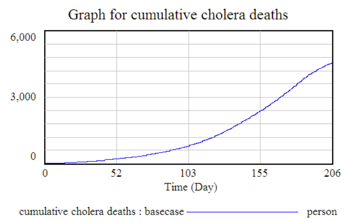
Figure 8: Aggregated causal loop diagram of the Cholera Model



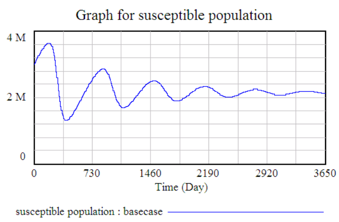
(a) susceptible population (ST)



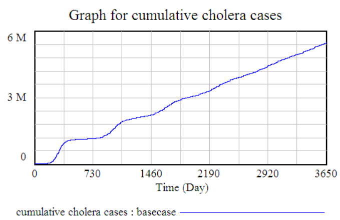
(b) cumulative cholera cases (ST)



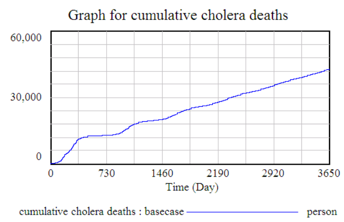
(c) cumulative cholera deaths (ST)



(d) susceptible population (LT)



(e) cumulative cholera cases (LT)



(f) cumulative cholera deaths (LT)

Figure 9: Behaviour of the Cholera Model in the short [(a)(b)(c)] and long term [(d)(e)(f)]

5.5 Ice Hype in the Netherlands

On 11 January 2009, near the end of the most recent Dutch ice skating craze, a System Dynamics model was developed related to cold waves, natural ice skating madness, and ice skates sales booms. In the Netherlands, natural ice is rarely thick enough for tour skating (last time was 11 years ago). But when it is, most Dutch citizens go crazy, especially when the 11-city race may be organised. It is hard to imagine/understand by anyone but the Dutch. A testing case was developed from the model (BSc exam of 14 January 2009). At that time, the case was 'hot' (and painful for many students who left their skates up in the attic in order to study for the exam).

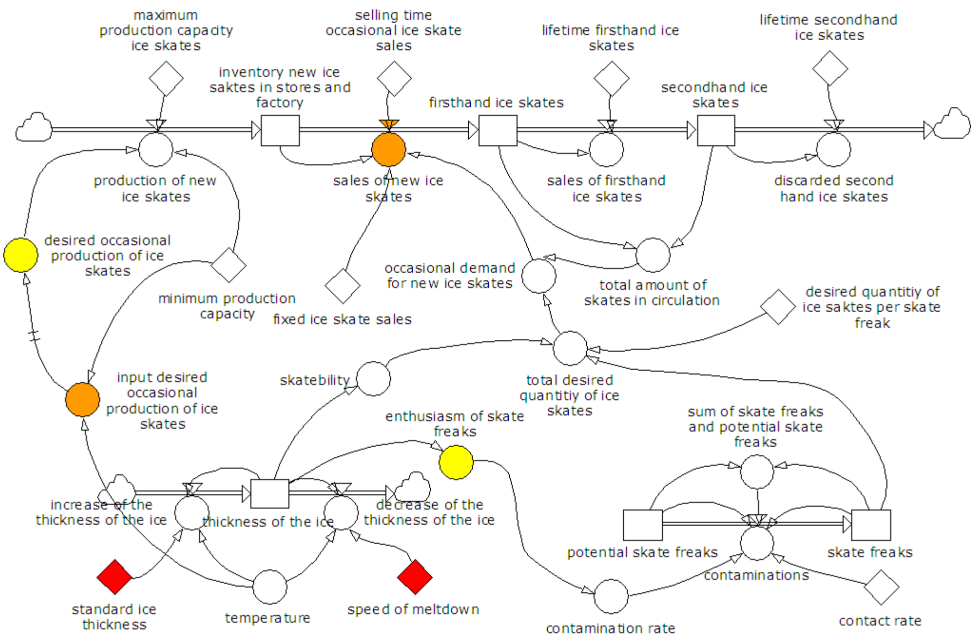
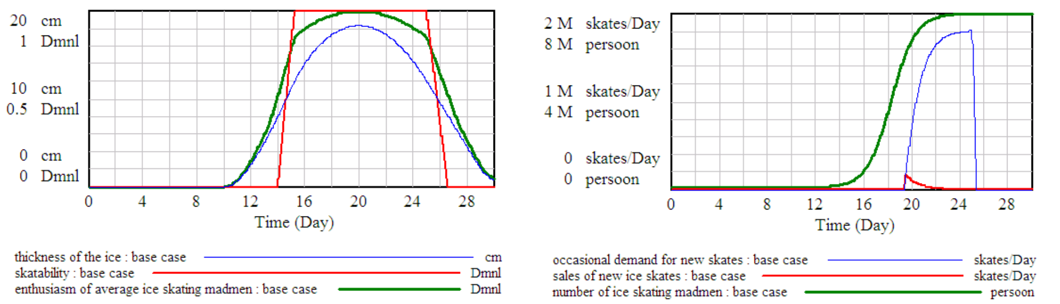


Figure 10: Stock-Flow Diagram of the Natural Ice Skating Model

In this case, students have to make –first of all– an aging chain related to ice skates (and a corresponding causal loop diagram), a small diffusion submodel regarding the spread of the ice madness, and a small (but rather difficult) 'ice thickness' submodel. Then, all submodels need to be connected (see Figure 10) and the system behaviour simulated (see Figure 11). Finally, advise needs to be formulated to a fictitious client, the major ice skates producer.



(a) Thickness of the ice (blue), skatability (red), and enthusiasm of average skate freak (green)

(b) Number of skate freaks (green), occasional demand for new ice skates (blue), and sales of new ice skates (red)

Figure 11: Behaviour of the Natural Ice Skating Model

5.6 Redevelopment of Social Housing Districts in the Netherlands

This case is presented here because it gave the initial impetus towards using 'hot cases'.

The redevelopment of postwar social housing districts is a 'hot' issue in the Netherlands. A simplified version of the 'Social Housing District' model presented in (Pruyt 2008a) was developed and turned into a teaching/testing case (used for the BSc retake exam of 18 August 2008).

Students are required to make the model (see Figure 12), to simulate its dynamics (see Figure 13), to explain the link between structure and behaviour, to perform uncertainty analyses, to test two proposed policies, to propose another –more effective– policy, and to make a simplified causal loop diagram that could be used to explain the link between structure and resulting behaviour (see Figure 14).

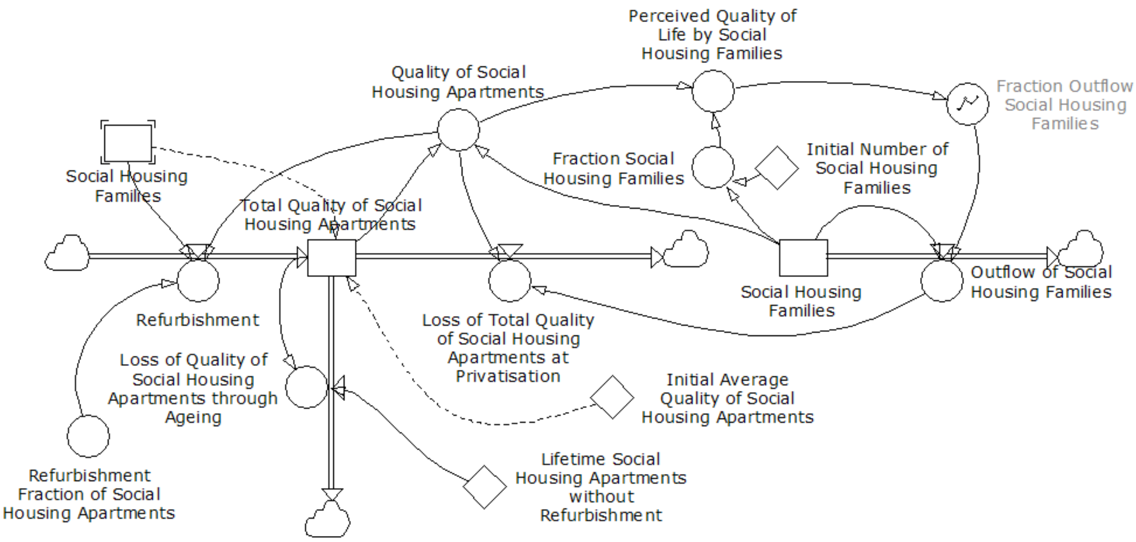


Figure 12: Stock-Flow Diagram of the simplified Social Housing District model

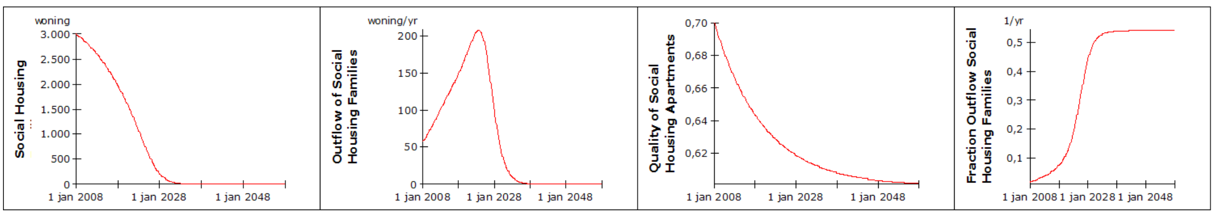


Figure 13: Behaviour of the simplified Social Housing District model

Currently, two former students are developing –in cooperation with housing corporations and consulting/research organisations– models based on this model for two important postwar housing districts.

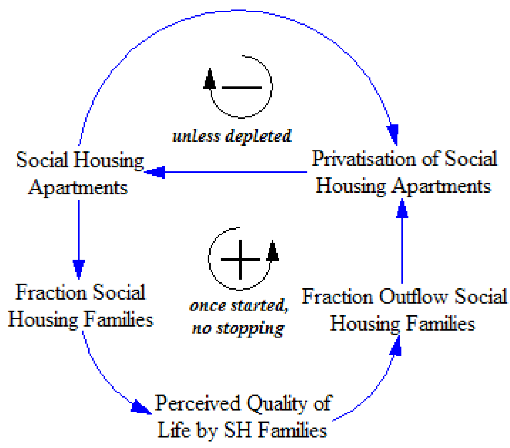


Figure 14: Causal loop diagram of the simplified Social Housing District model

6 Conclusions, Lessons Learned, Proposal

Over the last year, almost all new testing/teaching cases developed for the Introductory System Dynamics course at Delft University of Technology have been based on 'hot' issues.

Using 'hot' cases is a good way to enthuse students and to arouse their interest in applying System Dynamics in case of real-world issues. Applying System Dynamics to 'hot' issues illustrates the relevance of System Dynamics for dealing with real-world complex issues, which takes System Dynamics testing/teaching models one step further than being didactically responsible exercises.

Although actual real-world testing/teaching cases are often more motivating, mostly they are also more difficult than exercises developed in the first (and only) place to test/teach, because they need to be sufficiently close to reality to be relevant.

Hence, using 'hot' cases is a good way to plug the gap between small/didactic System Dynamics models often used in Introductory System Dynamics courses and large/difficult Project Cases.

However, developing relatively simple, actual, relevant, real-world testing/teaching cases is very time consuming and difficult, especially when they need to be developed very rapidly in order to be as actual as possible.

These 'hot' cases have reinforced the reputation of the Introductory System Dynamics course at Delft University of Technology of being difficult, but also clarified its relevance and goals. Consequently, students seem to work harder and in a more focussed way, and with a side-long glance at the actuality and real-world issues. After only 7 weeks, students are able to construct and use models of real-world issues of a reasonable complexity, be it based on a precise description and almost full specification.

The use of 'hot' cases may well be the main cause of a significant improvement of the System Dynamics modelling skills and in an increased passing rate: although it is difficult to prove, it seems that the use of these testing/teaching cases has accomplished more than the other measures discussed in (Pruyt et al. 2009).

In order to maximise the advantages and minimise the disadvantages of using 'hot' cases, it is proposed to:

- start up a small (informal) network of university-level lecturers interested in sharing 'hot' testing/teaching cases,
- start exchanging cases bilaterally or by means of a central 'case depository',
- agree upon a set of criteria (e.g. hot) and a specific standard/format (e.g. italics for variables),

- respect authorship and correctly reference/cite (e.g. 'developed by' or 'based on a case developed by') even for testing cases.

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A Teaching/Testing Cases

A.1 Saving a Bank? The Case of the Fortis Bank

See (Pruyt 2009c, appendix A).

A.2 Cholera Epidemic in Zimbabwe

See (Pruyt 2009a, appendix A).

A.3 The 'Soft Drugs Summit'

See (Pruyt 2009b, appendix A).

A.4 Smart Grids? Large-Scale Electrification of the European Car Fleet

Given[2] the climate change issue, expected long term energy security problems, and the current crisis in the automotive industry, electric vehicles (EVs) are more and more often said to be '*the* solution'[3]. For example:

- Obama wants 1 million EVs on the American roads by 2015.
- The Dutch electricity grid company Enexis, the former Essent Networks, pushes the concept of smart grids in which many EVs and old EV batteries (taken out of EVs after about 3 years and used for another 7 years in the grid) to balance/buffer intermittent electricity generation and variable electricity demand.

Unless a revolutionary technology breaks through, these ideas depend to a large extent upon the availability of the most important and constrained element of the most promising batteries, that is to say, lithium.

The Dutch network company hires you to investigate the long-term consequences (e.g. until 2100) of the availability of lithium. Follow the indications below in order to develop a (simplistic) experimental System Dynamics model to investigate the influence of a large-scale transition from ICEs to EVs on the lithium resources and availability (and vice versa). Model all time delays, unless indicated differently, as simple first-order delays.

1. Currently, the ICT sector is a large customer for lithium. Supposing that there are/will be no other customers for lithium than the ICT and EV sectors, the *total demand for lithium to be exploited* equals the sum of the *lithium needed for EV batteries* and the *annual ICT lithium demand*. Suppose initially that the *annual ICT lithium demand* equals 20 kton lithium per year and the *lithium needed for EV batteries* 0 kton lithium per year.

   This *total demand for lithium to be exploited* drives the *lithium exploitation*. Specialists estimate the current *unexploited lithium reserves* that could be exploited in the future to amount to 13000 kton lithium. It goes without saying that the maximum *lithium exploitation* is smaller or equal to the *unexploited lithium reserves*. Suppose, for reasons of simplicity, that there are no further production constraints and that *lithium exploitation* follows –in the absence of recycling– the *total demand for lithium to be exploited*. [In case you need an *exploitation time*, use a first order time delay of a month.]

   Lithium exploitation is followed by *processing of lithium in products* which takes time and could be modelled with a stock variable. This stock is emptied by means of a *lithium products brought into use* flow with an average *processing and introduction time* of 1 year. Initially, the *processing of lithium in products* equals 22 kton lithium. After lithium products are brought into use, the lithium is tied up as *lithium in products* during an *average lifetime of products containing lithium*. Initially the amount of *lithium in products* equals about 100 kton lithium. The *average lifetime of ICT products containing lithium* is 5 years. And, as already mentioned, the total *average lifetime of EV batteries* (first 3 years in the EVs and afterwards 7 years in the electricity grid) may amount to 10 years.

   Suppose that after the *average lifetime of products containing lithium*, these products are either thrown away –leading to a *loss of non-recycled lithium*– or recycled –leading to a *recovery of lithium through recycling*. The respective sizes of these flows depend on the *effective lithium recycling fraction*, initially equal to 20%. The recycled lithium is blocked as *lithium in recycling* during an *average recycling time* of a quarter before it flows as *lithium from recycling to reprocessing* to the *processing of lithium in products* stock.

   (a) Make a submodel corresponding to the description above.

[2]Date in this case are nothing but guestimates in order to test students' model building skills.

[3]Strangely enough, EVs are also one of the oldest solutions: electric motors existed before internal combustion engines (ICE) became the dominant technology.

(b) Make a *Causal Loop Diagram* corresponding to the description/model.

(c) How many *feedback loops* should the diagram contain?

2. Suppose that the *total European car fleet* currently consists of some 100 million ICE cars and only 1000 EVs. Model the *electrification of the European vehicle fleet* as follows:

$$intensive\ advertisement * \frac{conventional\ vehicles}{average\ lifetime\ conventional\ vehicles} * \frac{electric\ vehicles}{total\ European\ vehiclefleet}$$

Assume an *average lifetime of conventional vehicles* of 9 years. The batteries can only be used inside EVs –due to loss of capacity– during an average of 3 years. The total number of *EV batteries needed* therefore corresponds more or less to the *electrification of the European vehicle fleet* plus the existing *electric vehicles* divided by the *average lifetime of EV batteries.* Suppose that the *intensive advertisement* corresponds –between 2009 and 2016– to 10 times the normal amount of advertisement. To calculate the amount of *lithium needed for EV batteries*, assume that 20 kg or $2 * 10^{-5}$ kton *lithium* are needed per EV battery, and that 1 battery is needed per vehicle.

Assume that the *annual ICT lithium demand* initially equals 20 kton lithium/year, and grows with a (severely underestimated) *growth rate of lithium demand of the ICT sector* of 1% per year.

(a) Make a submodel of this description (without connecting it to the other submodel).

(b) Make a diagram of the transition of the vehicle fleet.

(c) Connect both submodels. Given the level of aggregation you may use an *approximated fraction of lithium used in EV batteries over the total amount of lithium in use* instead of a precise fraction.

(d) Simulate the model and make graphs of the *unexploited lithium reserves*, the *processing of lithium in products* and the *lithium in products.*

(e) The model is highly aggregated and should in a later stage be refined. It is nonetheless useful in this stage to do some validation tests. List four validation tests (except sensitivity analysis and risk analysis) that would be useful in this stage, execute them, and briefly describe the results.

(f) The model contains some very uncertain variables/assumptions. List 2 of them. Do they have a large impact on the behaviour of the model? Explore and explain.

(g) Perform a manual sensitivity analysis using a best case and a worst case scenario. Use following intervals into account: *initially unexploited lithium reserves*: 4000–20000 kton lithium; *effective recycling fraction van lithium*: 10–100%; *growth rate lithium demand ICT sector*: 0–25% per year. What could be concluded? Why?

3. Closing the Loop:

(a) Until now, the consequences of possible lithium shortages on the electrification of the vehicle fleet have not been taken into account in the model. Include structures such that the electrification of the European vehicle fleet also depends on the availability of lithium. Divide the available lithium –if lithium supply is a bottleneck– between the ICT-sector and the EV-sector in proportion to their respective demands. Does that have an influence on the large-scale transition to EVs?

(b) Briefly formulate your conclusions and recommendations.

A.5 Ice Hype in The Netherlands

The first two weeks of the year 2009, The Netherlands fell once more under the spell of natural ice skating. In the Netherlands, natural ice is rarely thick enough for tour skating (the last episode dated 11 years back). But when it is, up to half of the Dutch population goes crazy, especially when (it seems that) the 11-city race can organised. It is hard to imagine/understand by anyone but the Dutch. This exercise deals with cold waves, natural ice skating madness, and ice skates sales booms.

Submodel 1: The Life of a Pair of Ice Skates

First, let's make a submodel regarding ice skates[4] in circulation. The *production of new ice skates* increases the *inventory of new ice skates in stores and factories.* This inventory decreases only through *sales of new ice skates.* Assume first that there is no initial *inventory of new ice skates in stores and factories.*

The *production of new ice skates* equals the sum of the *minimal production capacity* –which amounts to 550 pairs of ice skates per day– and the *desired occasional production of ice skates*, and can never exceed the *maximal production capacity* of 5500 pairs per day. (Suppose for the moment that the *desired occasional production of ice skates* amounts to 0 pairs of ice skates.)

If the *inventory new ice skates in stores and factories* allow it, then the *sales of new ice skates* amount to the *fixed ice skate sales* of 137 pairs per day plus the *occasional demand for new ice skates* divided by the average *selling time occasional ice skate sales* of 1 day. Set the *occasional demand for new ice skates* for the moment to 0 pairs per day.

The amount of *firsthand ice skates*, initially 1 million pairs, only increases in case of *sales of new ice skates.* After an average *lifetime of firsthand ice skates* of 10 years, *firsthand ice skates* are sold turning them into *secondhand ice skates.* Initially there are 5 million *secondhand ice skates.* These *secondhand ice skates* are discarded after an average *lifetime of secondhand ice skates* of 20 years. The *total amount of skates in circulation* consists of the sum of the firsthand and secondhand ice skates.

1. Make a SD model and simulate it over a 10 year period (∼ period without natural ice).
2. What are such Stock-Flow structures called?
3. Make an extensive *causal loop diagram* of this submodel.
4. How many feedback loops should this *causal loop diagram* contain?
5. How big is the *inventory of new ice skates in stores and factories* at the end of this 10 year period?

   Use this value as the initial value of the *inventory new ice skates in stores and factories* in following versions of the model: it corresponds to the initial inventory available, built up during 10 years without natural ice.

Submodel 2: Natural Ice Skating Madness . . . Very Contagious

Even if there is no natural ice, there are at any moment at least 100000 *skate freaks* in The Netherlands. The number of *potential skate freaks* amounts to 7.9 million Dutch citizens. When *potential skate freaks* are 'infected' by skate freaks they become *skate freaks* too. The number of infections could be modelled as:

$$\frac{potential\ skate\ freaks * skate\ freaks * infection\ rate * contact\ rate}{sum\ of\ skate\ freaks\ and\ potential\ skate\ freaks * skate\ freaks}$$

Set the *contact rate* equal to 1 per day and the *infection rate* (for the moment) to 50%.

[4] The phrase 'ice skates' stands for 'pairs of ice skates'.

1. Extend the previous submodel with this submodel and save it.
2. Simulate the model over a period of 30 days. Make a graph of the evolution of the number of *skate freaks*.

Submodel 3: Nothing Compared to Natural Ice

Now you still need to construct a (simplistic[5]) ice model. Suppose that the *thickness of the ice* increases only by means of an *increase of the thickness of the ice* at temperatures below 0°C, and decreases by means of a *decrease of the thickness of the ice* at temperatures above 0°C. Increase and decrease of the thickness of the ice need to be modelled separately because they are not symmetrical. Both are always greater than or equal to 0 and the decrease cannot be greater than the *thickness of the ice*. Use the 'ice function' provided by the lecturer.

Initially, there is no ice. Use a Graph/Lookup to model the average *temperature*. Suppose that the average *temperature* is 6°C on day 0, 3°C on day 5, 0°C on day 10, -7°C on day 15, 0°C on day 20, 5°C on day 25, and 5°C on day 30. and that the temperatures between these values can be interpolated linearly.

The '*skateability*' is 0% if the *thickness of the ice* is smaller or equal to 8 cm, and 100% if the *thickness of the ice* is greater than or equal to 12 cm. Between those values, the '*skateability*' increases linearly. The *enthusiasm of skate freaks* is a function of the *thickness of the ice* too: at 0 cm thickness, enthusiasm is 0%, at 6 cm 35%, at 12 cm 85%, at 18 cm 99% and at 24 cm 100% (because then the the 11-city race ('Elfstedentocht') cannot but take place).

1. Make this submodel.
2. Simulate the model over a period of 30 days. Make graphs of the evolution of the *thickness of the ice*, the *skateability*, and the *enthusiasm of the skate freaks*.

Integrating the Submodels...

Finally, the three submodels need to be connected.

Set the *rate of infection* equal to the *enthusiasm of skate freaks*.

The *total desired quantity of ice skates* is equal to the product of the number of *skate freaks* and the *skateability*. Suppose that the *occasional demand for new ice skates* then equals the *total desired quantity of ice skates* minus the *total quantity of skates in circulation*, provided that this occasional demand cannot be negative.

Construct a decision rule to calculate the *desired occasional production of ice skates* which is a third-order smoothing construction with a delay time of 3 days, with an input of ($5 * \textit{minimal production capacity} * MAX(-\textit{temperature}, 0)$), and an initial value of 0.

1. Connect the submodels as described above.
2. Verify and validate the integrated model. Propose 3 validation tests, perform these, and briefly describe your results/conclusions.
3. Simulate the model over a period of 30 days. Make graphs for the *occasional demand for new ice skates* and the *sales of firsthand ice skates*. What could be concluded?

A.6 Redevelopment of Social Housing Districts in The Netherlands

Many[6] of the peripheral quarters or residential districts in the Netherlands were –and still are– constructed in their entirety by (social) housing corporations. Many of these districts gradually deteriorated over time and currently need to be redeveloped. Different redevelopment options are

[5] and unrealistic

[6] This case is a simplified version of the model presented in (Pruyt 2008b).

chosen: some districts are (partly) demolished and rebuild, some districts are entirely renovated, some districts are gradually privatised in order to bring about a healthy mix of (social) tenants and home-owners (owning the home in which they reside) and to generate the necessary revenues to renovate the social housing fraction, et cetera. However, any of these option chosen leads to complex dynamic behaviour over time that needs to be investigated before the choice is actually made: the future development of the districts in terms of the mix of inhabitants, the quality of the housing, etc., crucially depends on the redevelopment option chosen. System Dynamics could be used to investigate this dynamic complexity.

In this case, the gradual privatisation option will be investigated for a hypothetical social housing district. The main goal is to investigate the dynamics of privatisation on the district level. Suppose that initially there are 3000 (single-family) apartments in a district, of which 2990 are still in the social housing market and 10 are already privatised. Suppose that an apartment is privatised right away when a *social housing family* leaves. The *outflow of social housing families* is proportional to the *perceived quality of life by social housing families.* The precise values of this causal relationship are unknown: assume therefore at first that 100% of the remaining *social housing families* leaves at a *perceived quality of life* (QoL) of 0%, that 45% leaves at a perceived QoL of 25%, that 15% leaves at a perceived QoL of 50%, that 5% leaves at a perceived QoL of 75%, and that 0% leaves at a perceived QoL of 100%.

You suspect that the *perceived quality of life by social housing families* depends on the average *quality of social housing apartments* and the social cohesion between the social housing families (take the *fraction of social housing families* as a proxy for the social cohesion between the social housing families). However, the relative importance of these two criteria is unknown. Given the fact that the district is a close-knit district of the 'common people', it could –at first– be assumed that the relative *importance of social cohesion* is twice the relative *importance of the quality of social housing apartments.*

The average *quality of social housing apartments* equals the *total quality of all social housing apartments* divided by the number of *social housing apartments* (which equals the number of social housing families). Initially, the *total quality of all social housing apartments* equals the product of the *initial average quality of the social housing apartments* and the number of *social apartments.* The *initial average quality of the social housing apartments* amounts to 70% of the average quality of corresponding newly built houses. An annual *loss of quality of social housing apartments through ageing* decreases the *total quality of all social housing apartments*: this annual loss equals the *total quality of all social housing apartments* divided by the *lifetime social housing apartments without refurbishing* of 30 year.

The *total quality of all social housing apartments* increases through *refurbishment.* Suppose that 5% of the social housing apartments are refurbished each year, increasing the average of refurbished apartments to 100% (the quality level of corresponding newly built houses).

A flow *loss of total quality of social housing apartments at privatisation* also decreases the *total quality of all social housing apartments* when social housing apartments are privatised.

1. Make a System Dynamics simulation model of this description. Simulate the model over a period of 50 years. What is the general dynamics of the model? Make graphs of the number of *social housing apartments*, the *quality of social housing apartments*, and the privatisation of social apartments.

2. Do the uncertain assumptions have a major influence on the behaviour of the model? Explore and explain.

3. You present the results to the housing corporation and the Mayor and Aldermen. The long-term dynamics of the mix of social housing and private housing makes them sit up a bit. They ask you to investigate whether a different refurbishing policy leads to a better social mix. Explore:

(a) What happens if 10% of all social housing apartments are refurbished annually? Make graphs of the *quality of social housing apartments* and the number of *social housing apartments*. Is this policy effective?

(b) What happens if all social housing apartments are (all together) renovated once every 10 years? Make graphs of the *quality of social housing apartments* and the number of *social housing apartments*. Is this policy effective?

4. What policy would you propose in view of obtaining a healthy mix of social housing apartments and private apartments?

5. Assume that the average *quality of social housing apartments* remains constant, which means that part of the model (related to the quality of social housing apartments) could be deleted. Draw an aggregated *causal loop diagram* of the remaining system that allows to explain the dynamics of the *fraction of social housing families* to laymen.

6. Briefly explain the link between structure and behaviour.