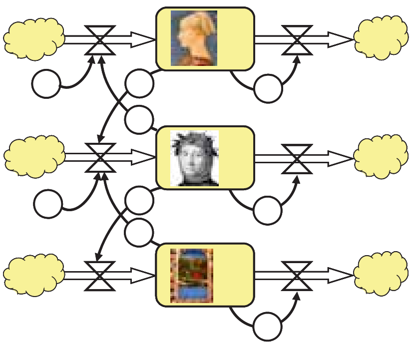
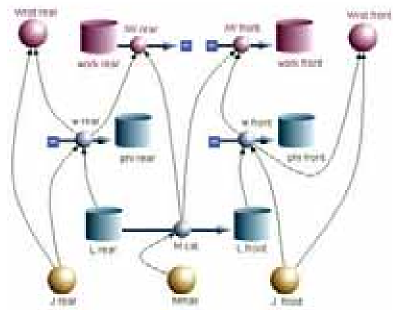
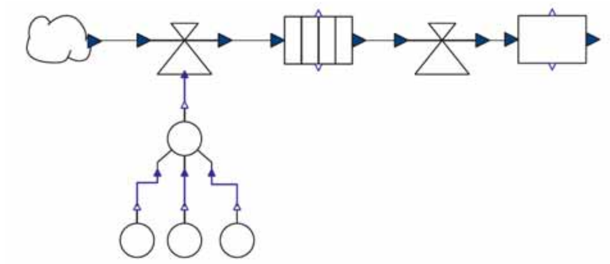
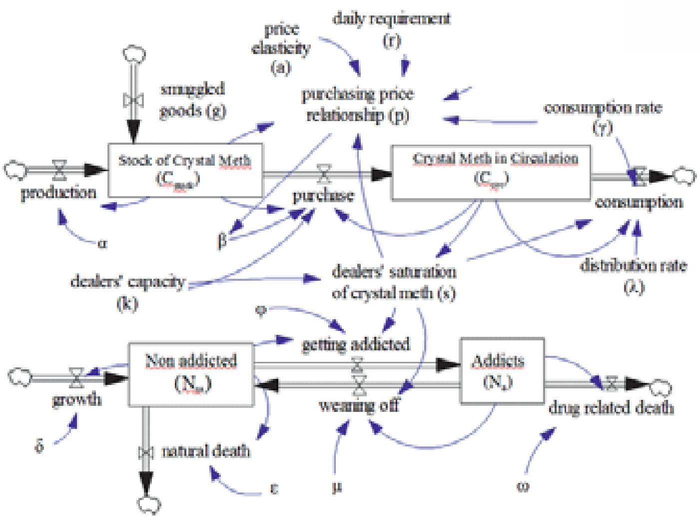
SNE SIMULATION NOTES EUROPE

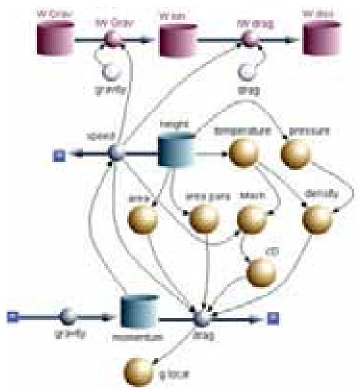
SNE Special Issue
System Dynamics











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Journal on Developments and Trends in Modelling and Simulation

Membership Journal for Simulation Societies and Groups in EUROSIM

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Editorial

Dear Readers – *This third SNE issue of the year 2016, SNE 26(3), the special issue 'System Dynamics', compiled by the guest editors Werner Maurer (Univ. of Applied Sciences Zürich/Winterthur) and Niki Popper (dwh Simulation Services, Vienna), gives an overview on modelling and simulation using System Dynamics and highlights the power of System Dynamics in various applications. The title page shows some sketches of System Dynamics Diagrams selected from the contributions, which indeed underline the broad variety of modelling with System Dynamics: emotions and inspiration (left), drugs and addicts (left), falling cat landing on feet (right), conveyor belt (discrete model; right), and space jump world record (right).*
Furthermore, the first contribution on 'System Physics', a modelling concept combining the concept of System Dynamics with a unified description of classical physics and engineering known from Bond Graph theory, makes evident, that System Dynamics is more than a classical modelling paradigm, also because of the 'unusal' applications using System Dynamics (two further contributions). We hope, readers enjoy this issue, which also intends to continue the discussion about System Dynamics.
This third issue of the year is not a double issue as with the third issues in the years before – from this year on SNE is published with four separate issues, allowing more space and more special issues.

I would like to thank all authors for their contributions, and especially the guest editors for compiling this special issue. And last but not least thanks to the Editorial Office for layout, typesetting, preparations for printing, and web programming for electronic publication of this SNE issue.

Felix Breitenecker, SNE Editor-in-Chief, eic@sne-journal.org; felix.breitenecker@tuwien.ac.at

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→ *www.sne-journal.org*
office@sne-journal.org, eic@sne-journal.org

SNE Editorial Office, Andreas Körner
ARGESIM / Math. Modelling & Simulation Group,
Vienna Univ. of Technology /101,
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Editor-in-Chief: Felix Breitenecker, Vienna Univ. of Technology, Math. Modelling and Simulation Group
Felix.Breitenecker@tuwien.ac.at, *eic@sne-journal.org*

Layout / Administration: A. Körner, A. Mathe, J. Tanzler, C. Wytrzens, et al.; *office@sne-journal.org*

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Editorial SNE Special Issue 'System Dynamics'

System Dynamics – SD – developed by J. Forrester for complex management systems, has become a widespread tool, method and methodology for modelling and simulation, with benefits in various applications. The plan for this SNE special issue originates from MATHMOD 2012 *Vienna Conference on Mathematical Modelling*. There an invited lecture on *System Physics* caused interest and discussion on *System Dynamics*, and as SD could also be met across all sections of the conference, the idea for a special issue came up. At MATHMOD 2015 *System Dynamics* again attracted attention with contributions on new and unusual applications – resulting in the realization of this special issue.

The issue starts with Werner Maurer's contribution *Systems Physics – A Modeling Approach to Fundamental Concepts.* The author presents *Systems Physics* as modelling concept, which combines the modelling concept of SD with a unified description for all branches of classical physics known from Bond Graph theory.

The second and third contribution discuss theoretical aspects of SD. Patrick Einzinger's contribution *Differential Equations and Carathéodory Solutions: How System Dynamics Describes Formal Dynamical Systems*. formalizes the concept of an SD model as a set of rate equations, auxiliary equations, and 'flow coupling', and derives conditions for representing an ODE system – depending on the causalities. Causality is also focus of Peter Junglas' contribution *Causality of System Dynamics Diagrams*. He shows, that causality can depend on the state of the complete system, so that design of SD libraries is affected, e.g. for the different modelling approaches used in Modelica and Simulink.

The following five contributions deal with classical 'usual' and 'unusual' non-classical applications of SD. Barbara Glock et al. presents a classical application in her contribution *Treatment Strategies for the Prevalence of Obesity in Austria Modelled with System Dynamics*. The modular SD model – with cost modules and modules for obesity-related diseases - investigates three interventions with increase in caloric expenditure and / or reduction of caloric intake.

Patrick Einzinger et al. have provided the contribution *Toward Useful System Dynamics Models of Physician Reimbursement and Population Health.* While SD models are widely used in health care systems, this contributions makes use of SD in the relatively new field of reimbursement systems. Several simulated scenarios show that the developed SD models are plausible in behaviour and are in line with theories on the influence of different reimbursement systems.

The contribution *Exploring the Advantages of Multi-Method Modelling in the Use Case of a Large Socio-Technical Infrastructure System: The Airport City* by Barbara Glock and co-authors shows the advantages of SD as efficient method in multimethod – modelling of a big socio-technical systems. Different parts of an airport city are modelled with the best fitting modelling technique: an agent based model for passenger arrival, a discrete event terminal model, an agent-based model of the airside, a SD model with integrated agent-based model modules for the retail area and health care units.

The four contributions with authors Einzinger and Glock present result from investigations within project DEXHELPP *Decision Support for Health Policy and Planning: Methods, Models and Technologies based on Existing Health Care Data*, (www.dexhelpp.at).

The last two contributions deal with 'unusual' applications. In the contribution *A Model of 'Breaking Bad': An Economic Model of Drugs and Population Dynamics Predicts how the TV Series Feeds Back to the Drug Market*, the authors Christiane Rössler, Magdalena Witzmann, and Thomas Schmickl develop and discuss a SD model for population dynamics of Crystal Meth addicts related to the price development of drugs, the society and the market that is affected by the popularity of the TV series 'Breaking Bad'. In simulations, the potential impact of the broadcasting of the TV series on the system is analyzed.

The last contribution *System Dynamics for Modelling Emotions: from Laura - Petrarch to Nowadays Couple* (F. Breitenecker et al) makes use of SD for modelling human emotions in reciprocal attraction – first for famous Laura – Petrarch couple, using data from sonets, and deriving a model for a nowadays couple.

The editors would like to thank all authors, who have contributed to this special issue, and we thank the SNE Editorial Office for the support in compiling this special issue. We hope, that this issue promotes *System Dynamics* as tool, method and methodology also for the future.

Werner Maurer, Univ. Applied Sciences Zürich/Winterthur, School of Engineering; werner.maurer@zhaw.ch
Niki Popper, dwh Simulation Services / DEXHELPP Group, Vienna; niki.popper@dwh.at

Systems Physics – A Modeling Approach to Fundamental Concepts

Werner Maurer

Zurich University of Applied Sciences (ZHAW), School of Engineering, Technikumstrasse 9, 8400 Winterthur, Switzerland; *maur@zhaw.ch*

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Abstract. Systems Physics represents a coherent view of physics. Balance equation, constitutive laws and the well defined role of energy form the framework of this newly developed physics course. According to this scheme, all areas of classical physics are taught in the same way: balance equation, constitutive laws and at last the energy as an interconnecting bookkeeper. This unitary structure facilitates the computer-based modeling with a system dynamics tool. Therefore, students at the ZHAW learn physics by forming dynamic models and not primarily by solving exercises.

In this paper, a few examples from different areas are presented (two PET bottles, space jump world record, landing gear drop test, wind shear, cats land on their feet, water rocket simulator, Stirling engine). Most of these models have been developed in the past decade in a bachelor degree course for Aviation.

Introduction

Systems Physics is a novel approach to physics with which beginners are able to grasp the fundamental concepts underlying processes in nature and technology [1]. It is based on everyday concepts known from fluids which are familiar to everybody. The analogy between physical quantities and fluids offers a very intuitive approach to physics [2]. The powerful pictorial modeling by Berkeley Madonna [3] (a system dynamics tool) offered students to understand basic physical processes.

Systems Physics combines the modeling concept of System Dynamics with a unified description for all branches of classical physics known from Bond Graph theory [4].

Our concept of energy carrier is similar to that of the Bond Graph theory. But there is a crucial difference.

In Bond Graph theory, force and torque are potential quantities (effort quantities) and the kinematic variables velocity and angular velocity are seen as flow quantities. In Systems Physics however, this approach is not possible because force and torque are part of the balance equation and velocity and angular velocity are the “driving force” for the appropriate currents. Therefore force and torque are flow quantities and the two velocities are potential variables.

In our model based approach students start by formulating the balance of a fundamental quantity (bathtub-thinking for volume, mass, electrical charge, momentum, angular momentum, entropy or amount of substance). Then they have to specify the currents and the rates of change (feedback-thinking). On a second layer they can add the balance of energy (bookkeeper-thinking).

In the last ten years we have taught these concepts in a course named *Physics and Systems Science for Aviation*. This course is a core subject in the first year of study and carries 16 of the 60 credit points. In this course, consisting of eight lessons per week, the students learn the basic concepts of contemporary physics. At the same time, they apply their newly acquired skills to concrete systems in a modelling laboratory. The insights gained this way then have to be transferred into reports, presentations or posters. This takes place under the supervision of a language lecturer.

In this paper I show based on seven examples how students learn physics. Based on the balance equation the students have to develop the structure of a given dynamic system. For this they have to know the basic laws and they should be able to apply them to new problems. The first system consists of two PET bottles partially filled with water and air. After opening the valve, the pressure between the bottles is equalized.

To solve this problem, the students have to formulate the volume balance at first.

Then they complete the model by means of constitutive laws for pressure and flow. Optionally, the energy balance can still be formulated. The other six problems should be done analogously: balance of a base quantity, capacitive law, resistance law, further constitutive laws and finally the energy balance.

1 Two PET Bottles

Two PET bottles, which are connected together by a long tube, already form a rather complex system. The capacitive behavior of the air-filled bottle is non-linear and the flow may be laminar or turbulent. One or both bottles can be suspended from a force gauge. Thus, the water volume can be measured in function of time.

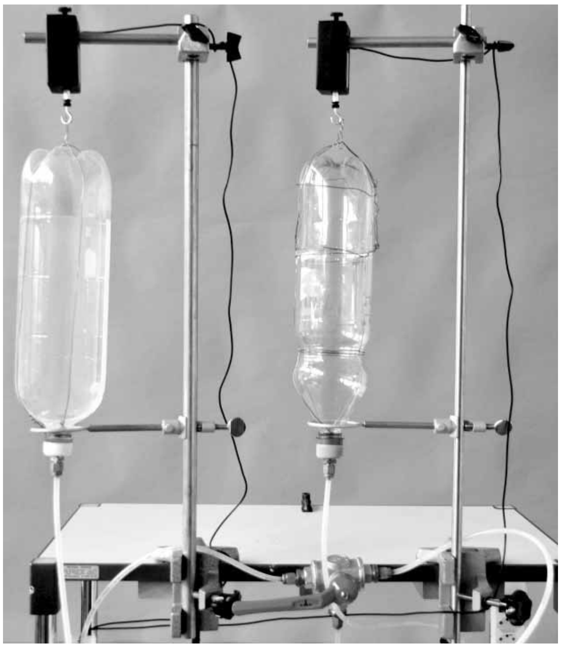

Figure 1: In the first bottle is the air pressurized, the second is under atmospheric pressure.

Model. The SD model consists of a balance layer and an energy layer. Using the Ideal Gas Law and the amount of water in the bottle we can calculate the pressure in each bottle. The pressure difference provides the "driving force" for the volume flow. During the pressure equalisaton, the flow turns from turbulent to laminar. The arrows in the flowchart show the dependencies between the variables.

In contrast to the volume of the water that is conserved, the hydraulic energy is not a conserved quantity.

The dissipated power results from the difference between the two energy currents. The strength of the energy current is calculated as pressure times strength of volume flow (potential times the flow of the primary quantity). The pot in the middle of the energy layer integrates the power over time.

The formula for calculating the energy current from the volume flow and the pressure is very important for the system physics. In each branch of physics we find an analogous formula.

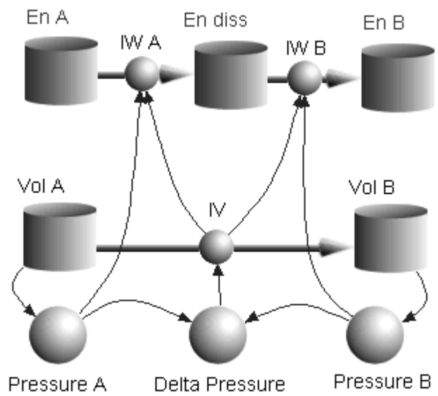

Figure 2: System dynamics model (flowchart) of the two bottles model with volume balance and energy balance layer.

Results. Figure 3 shows the time behavior of the volumes and of the volume flow between the two bottles. The simulation can be adjusted to the measerment (green line) by varying the loss factor. In contrast to the simulation, in reality the turbulent-laminar transition does not happen instantly (buckling in the flow-time function).

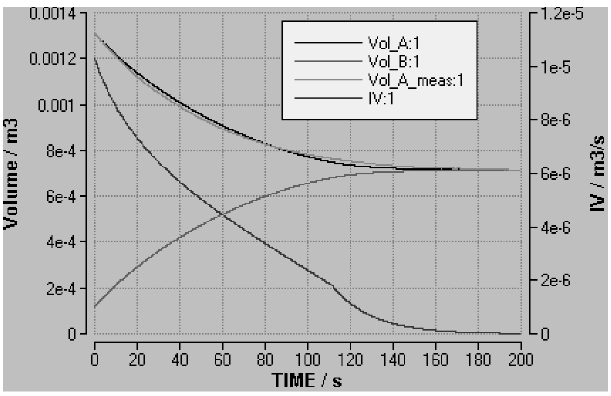

Figure 3: Volume (left axis) and volume flow (right axis) in function of time.

The energy layer is not part of the dynamics system. This is also shown by the causal arrows in Figure 2 which point only from the balance layer to the energy layer. And yet, the energy level contains important additional information related to the system behavior. Compensation processes in which the basic amount is maintained and the associated energy is decreased can also be found in the theory of electricity (charge balance in capacitors) and mechanics (inelastic collision).

Figure 4 shows the energy currents from the first and into the second bottle. The difference between these two currents is known as dissipated power. Figure 4 shows also the dissipated energy which is the inegral of power over time.

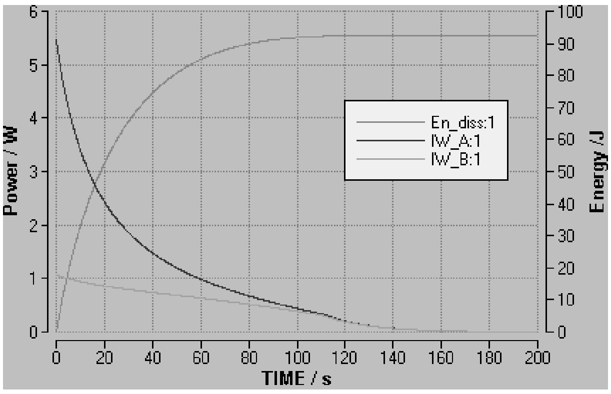

Figure 4: Energy current from the first bottle and into the second bottle (left axis); in the system dissipated energy (right axis).

2 Space Jump World Record

'Red Bull Stratos was a space diving project involving Austrian skydiver Felix Baumgartner. On 14 October 2012, Baumgartner flew approximately 39 kilometres (24 mi) into the stratosphere over New Mexico, United States, in a helium balloon before free falling in a pressure suit and then parachuting to Earth. The total jump, from leaving the capsule to landing on the ground, lasted approximately ten minutes.' [5]

This jump from the stratosphere is ideal to understand the translation mechacanics and to examine the involved laws. In this branch of physics momentum is the primary quantity and the velocity provides the associated potential.

Model. The SD model consists of a momentum balance layer, a kinematic layer and an energy balance layer.

The momentum balance calculates from the inflowing momentum (gravitational force) and the outflowing momentum (air resistance or drag) the momentum content. Then the velocity is calculated from the momentum by division by the (inertial) mass. On the kinematics layer the velocity is integrated to the actual position.

The air resistance depends on the density of the air and on velocity and shape of the jumper. On the other hand the density of the air is a function of pressure and temperature, which depend on the height above sea level. The drag coefficient depends on the Mach number, because the velocity is temporary higher than the speed of sound.

Students learn the structure of the mechanics by building a model step by step. They also develop a feeling for the size of the different variables and the sensitivity of each parameter. This is much more than the parroting of historical theorems and calculating with prefabricated formulas. They also provide much more often questions as in the classic, formula centered teaching.

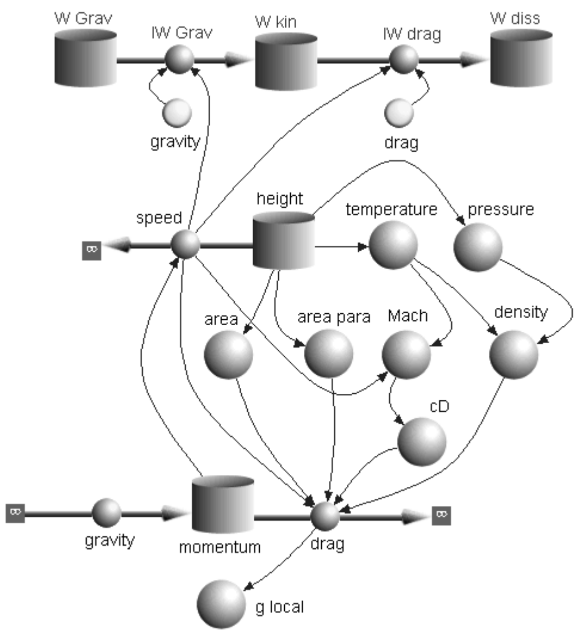

Figure 5: Flowchart of the space jump model with momentum balance, kinematics and energy balance layer.

The energy layer contains three pots for potential, kinetic and dissipated energy. The strength of each of the two energy currents is momentum current time velocity (this formula is also known as power of a force).

As in the hydraulics, the energy layer does not contain any additional information, but promotes an understanding of the orders of magnitude. So you can see out of the simulation that the power of drag rises to more than 500 kW.

Results. Figure 6 shows the velocity-height-diagram with the simulated and the measured data. The measured data are taken from the official website of Red Bull [6]. The two curves could still be better adjusted by adapting the cross section of the jumper in function of altitude. But that is not the aim of such a project. Students should realize how the whole system is set up and how much the individual variables influence the dynamics of such a system.

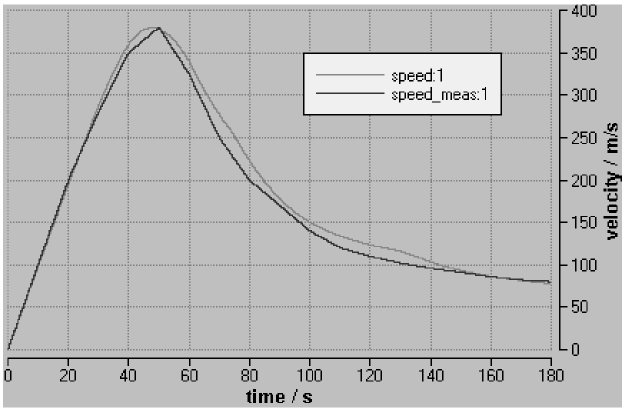

Figure 6: Measured and calculated velocity in function of time.

Skydiving, bungee jumping or base jumping would be other applications of this model. In these examples, the acceleration could be measered by means of a smartphone, and then integrated to speed. So you could compare the measured data with the calculated again.

3 Landing Gear Drop Test

In many textbooks for introductory physics, only the motion of one single body is treated (inclined plane, motion in a uniform gravitational field, harmonic oscillator). This leads to a very limited understanding of the mechanics with respect to Newton's third law and to momentum conservation. The landing gear drop test is a good example of a more complex two-body problem. In the simplest form of this test, a load on a vertically oriented spring-damper system with underlaying wheel falls from a height of three meters on the floor.

Model. As in the example with the jump from the stratosphere the SD model consists of a momentum balance layer, a kinematic layer and an energy balance layer (Figure 7). Momentum flows from the gravitational field into the load (momentum 1) and from there through the spring-damper system into the wheel (momentum 2).

Thereafter, momentum flows from the wheel over the tire into the ground. The great difficulty lies in modeling of the nonlinear spring-damper system and the dynamic behavior of the tire.

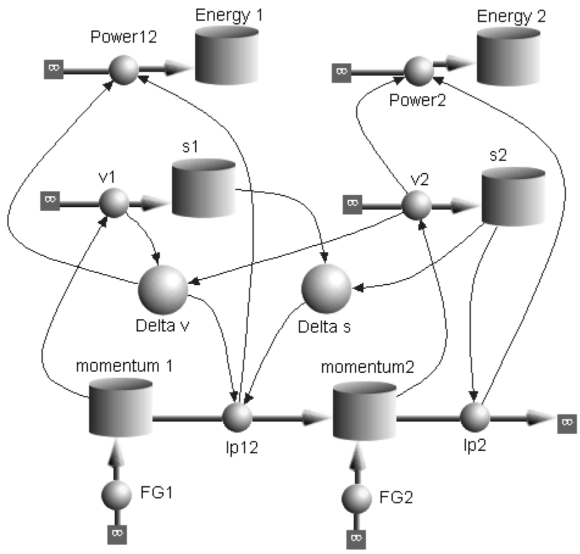

Figure 7: System dynamics model (flowchart) of the landing gear drop test model with momentum balance, kinematics and energy absorption of spring-damper-system and tire.

This model could be validated with the data from an aircraft manufacturer. This data can here not be published because they are confidential.

4 Wind Shear

In the second semester students have to model different phases of the flight of a plane, including wind shear. Wind shear is a difference in wind speed over a relatively short distance in the atmosphere. And wind speed is a very significant factor in landing a plane. First, the students model the flight of a football with drag and Magnus force. Then they have to transform the ball model into a model of a plane. This simple model of an airplane differs from a football by the angle dependence of lift and drag.

Depending on the type of aircraft an engine is also to be modeled. In this simplified model the pilot can influence the thrust and the pitch (angle of the aircraft relative to the horizontal).

Momentum is – unlike mass or electrical charge – a vector quantity. But how can we think about storage and transportation of a vector quantity? To do this, we introduce a global coordinate system which separates momentum in three components.

This fragmentation allows us to treat each component as a single quantity. Then we formulate for each of the three components the balance equation. Therefore, a moving body is able to store a surplus or a deficit of three different components.

The football model is created in the classroom under the guidance of a teacher, and with the help of a video [7]. Then the students are combined into groups with three members. Each group has to model the proper aircraft independently. They must also simulate different self selected scenarios. The results of their studies have to be presented by each group in a speech. The results obtained in this group work are excellent. In addition, students are highly motivated.

Model. To simulate a two-dimensional motion, we need two momentum balances, one for the horizontal and one for the vertical momentum component. The kinematics layer also includes two integrators (reservoir with one flow).

Lift and drag as a function of angle of attack, which is described with the drag polar, characterizes the dynamics of the aircraft. Once the wind begins, both the velociy of the flow and the angle of attack change, but for the first moment the aircraft remains in its state of motion.

This counterintuitive relationship between oncoming flow and aircraft velocity is central to the understanding of the mechanics. In addition to this basic model, students can model further aspects like pitch and thrust control, fuel consumption or load reduction.

Figure 8 shows the flowchart of a student work. This project involved the question, at which wind speed the pilot brings the plane over the hill.

In the last ten years, students have modeled dozens of different problems, from glider winch launch over a parabolic flight path to landing with windsher. It is needless to mention that this project motivated the students of aviation in the highest degree.

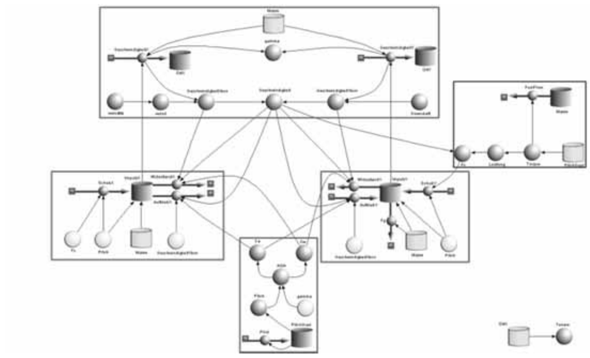

Figure 8: System dynamics model of the two-dimensional motion of a plane with momentum balance (red framed area), kinematics (green framed area), mass balance of the fuel (violet framed area) and pitch control (blue framed area).

The validation of these models is not easy, but the students are very creative. Some use the data of commercial flight simulators. Others rely on the data from an accident report. Because many students have their own pilot's license, a simulated flight is often flown by themselve. To obtain the data they take the acelleration sensor, the GPS-tracker and the video camera from their own smartphone. The most creative examples are modeled by the pilot candidate of the Swiss Army. Parabolic flight with an airliner, looping with a fighter aircraft or take off from an aircraft carrier are only a small selection of what has already been modeled.

5 Fluid Image

In any discussion of angular momentum, the fluid image should be introduced at an early stage, as is the case in any discussion about momentum [8]. In the fluid image of angular momentum, each rotating body is represented as a cylindrical tank standing in an enormous lake. The tank's crosssection corresponds to the mass moment of inertia J, the fill level indicates the momentary angular velocity ω and the lake simulates the earth with its almost immeasurable capacitance. The fluid itself represents the angular momentum.

Figure 9 shows a simple example to illustrate this: two flywheels of different sizes, which initially rotate in opposite directions, are connected by a sliding clutch. In addition, there is a certain noticeable friction in both bearings. What can therefore be learned from the fluid image? First of all, the law of capacitance: angular momentum content equals base area times fill level. In this equation, a negative angular velocity results in a lack of angular momentum content.

The balance equation, which states that the sum of all angular momentum currents is equal to the change rate of the content, appears directly as a volume balance. If the change rate is divided by the mass moment of inertia, the result is angular acceleration. This leads us to an advantage of the fluid image. In this figure, the angular velocity mutates into a length and the angular acceleration into a velocity. In this way, these two abstract quantities are clearly illustrated.

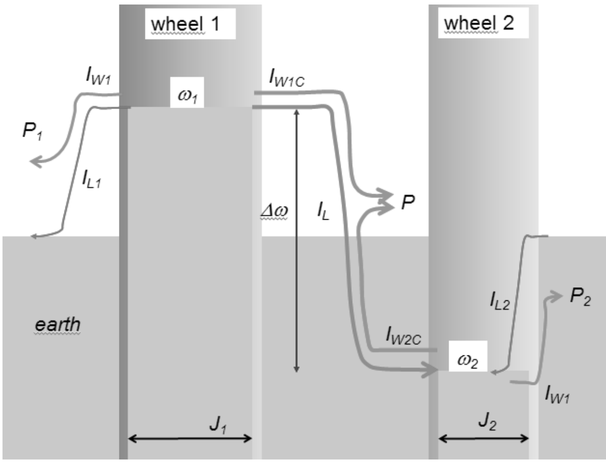

Figure 9: This fluid image of two flywheels which are axially connected by a sliding clutch. Angular momentum flows from the forward rotating wheel into the ground and into the second wheel. The bearing friction supplies the second wheel with additional angular momentum.

The energy becomes intuitively understandable with the fluid image. Every angular momentum current is loaded with an energy flow (I_W). The corresponding angular velocity functions as an energy charge value. If, therefore, an angular momentum current flows at great height i.e. at high energy charge value, it is heavily loaded with energy due to the high angular velocity of the material through which the current flows. As in electrophysics, where energy is often transported against the current, energy flows against the angular momentum as soon as the energy charge value becomes negative. We can easily see this if we look at the second flywheel. Although angular momentum flows from the first flywheel and from the ground into the second flywheel, the second wheel itself releases energy. The process-oriented thinking provides some more clarity: all three angular momentum currents flow from a body with higher angular velocity into a body with lower angular velocity and, at the same time, convert a process power (P) which equals current strength times falling height.

Rotating bodies store angular momentum and energy. Apart from the angular momentum, the momentary value of the rotational energy can also be seen in the fluid image. The rotational energy equals angualar momentum content times the mid height around which angular momentum has been pumped out of the earth and into the body (forward rotation), or out of the body and into the earth (backward rotation).

This relationship, which can be directly inferred from the fluid image, can be expressed by applying the law of capacitance in the familiar formula.

6 Why Do Cats Land on their Feet?

In 1894, the French Academy of Sciences called for ‘a physical explanation for the fact that cats always manage to land on their feet even if they fall from very high up’. The mystery was finally solved by a doctor called Etienne Jules Marey who recorded the fall with sixty images per second. When the film was shown, some physicists still doubted that the rotation was possible without the cat pushing itself off from somewhere. But one of them unravelled the cats’ trick. What is this trick that cats use, which even physicists barely understand?

Cat anatomy is different from human anatomy in that the cat has a highly flexible spine, a surprising deformability, four elastically pliable legs and a long tail. Furthermore, the cat has almost 600 muscles, which enable its body to change shape quickly. The cat uses the same trick as figure skaters controlling their rotational velocity when performing a pirouette. However, the cat’s front and rear parts each perform a pirouette.

The simplest model of a cat consists of two angular momentum storage units whose moments of inertia can change significantly. It is not only by stretching and pulling in its legs that the cat changes the moments of inertia.

As Marey’s film has already shown, cats can greatly adjust their mass axially or distribute it radially both in their front and rear parts.

The actual rotation can be divided into four intervals and illustrated in a fluid image. In the first two intervals, the front part’s moment of inertia is small and the rear part’s moment of inertia is large. The mass of the front part is then shifted outwards, while the mass in the rear part is shifted as close as possible to the body axis.

In the first interval, the cat pumps angular momentum from the rear part to the front part by tensing the appropriate muscles. In the second interval, the cat lets the angular momentum flow back. Afterwards, the cat comes to rest in a completely twisted position and then abruptly changes its mass distribution. In the last two intervals, the cat pumps angular momentum into the rear part and then lets it flow back. As a result, the front part moves back slightly and the rear part performs the all-important rotation.

This rough model can be improved by assuming that the cat pumps angular momentum and changes the moments of inertia simultaneously. Let us therefore describe the angular momentum current as a cosine function and each of the two moments of inertia as a constant with a superimposed cosine function. In order to achieve the desired rotation, the frequency of the moment of inertia must be half as great the frequency of the torque.

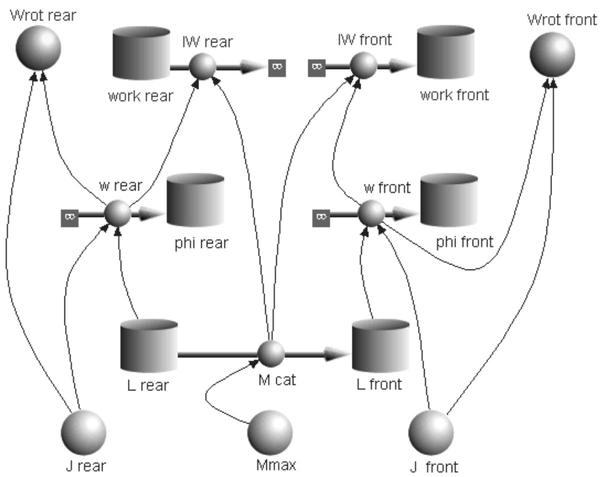

Figure 10: System dynamics model of a turning cat including angular momentum balance, kinematics and energy analysis. Rotational energy and work of the torque are calculated separately.

7 Water Rocket Simulator

A rocket can exchange linear momentum in three modes: conductive over the surface with the air (drag), throughout the whole volume with the gravitational field (gravitational force as a sink for momentum) and convective together with the mass of water. To transfer momentum convectively, each rocket requires energy. The water rocket stores the required energy in the compressed air.

Therefore, compressed air is the energy provider and water is the momentum carrier. Now the question is, in what proportion water and compressed air have to be bottled.

Model. The SD model consists of a momentum balance layer, a mass balance layer and a kinematic layer. The momentum balance pictorially shows that it makes no difference whether momentum is transported through the gravitational field (source-like), over the surface (conductive) or together with mass (convective). All three currents contribute equally to the rate of change of the momentum content.

The energy balance layer is not complet. In this model, only the dissipated energy is calculated from the performance of the air resistance. The calculation of the kinetic or potential energy is not very meaningful, because the mass of rocket changes during launch. An interesting problem is the convective energy transport. However, this problem is examined better in a stationary operating system, such as the jet engine.

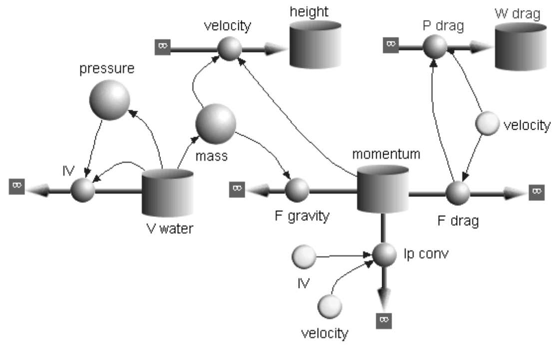

Figure 11: System dynamics model of a water rocket including liner momentum balance, kinematics and energy analysis (dissipated energy).

Results. The altitude of the water rocket is relatively easy to measure. However, this varies from shot to shot, because the trajectory is not always exactly vertical. A key question concerns the amount of water to be filled in. The simulation shows that one-third water and two thirds air leads to greatest altitude. This is also a good rule of thumb for the practitioner.

More important than the simulation of a most accurate trajectory is the knowledge gained for by students in terms of mechanics. Here they realize that forces are momentum currents with respect to a system. This is an important insight in mechanics which is denied by many physicists [9].

8 Thermodynamics

Classical thermodynamics describes systems in equilibrium, i.e. heat transfer is out of the scope of this theory. Furthermore, processes are discussed with energetic terms like heat, work, internal energy, and enthalpy, Helmholtz or Gibbs free energy. This description has a certain similarity with Lagrangian or Hamiltonian mechanics. In Systems Physics we introduce entropy first and then we add the constitutive laws for selected materials like ideal gas. In a final step we complete the theory by adding energy as a bookkeeper quantity [10]. This is the same approach as in all other topics of our course.

A body will move, rotate, be charged or get hot if we add energy to it. Energy is a bookkeeper quantity which says little about real processes. But if we add momentum to a body, we increase its velocity and if we add angular momentum to a rigid body, we increase its angular velocity. The same can be said for a thermodynamic system: if we add entropy to a body, it will raise its temperature or change its state of aggregation.

In everyday speech heat can be exchanged, stored and produced. In thermodynamics heat is defined as a quantity which can only be exchanged (the stored energy is called internal). This contradiction between the scientific and the common usage of the word heat can be resolved by using entropy for heat. Entropy can be exchanged, stored and produced. We try to give the students a picture of entropy as the basic quantity of thermodynamics which should be named heat and which acts as an energy carrier. Thus we draw the same picture as in hydraulics with volume and pressure or in mechanics with momentum and velocity or angular momentum and angular velocity.

The heat flowing through a reference surface can be seen as a flow of entropy or energy. Both quantities are connected by the temperature of the surface: the energy current through a reference surface is equivalent to the product to the absolute temperature of this surface and the entropy current through the same surface. In heat conduction, the energy current is always accompanied by a current of entropy. Or vice versa, each entropy current carries an energy current.

Entropy is like volume or momentum a fluidlike quantity which acts as an energy carrier. Temperature is the associate potential like pressure or velocity. With this picture in mind we can explain various thermally driven machines.

Let's look at a heat pump which pumps entropy from the cold environment to the warm water of the heating. The heat pump has to add power to the entropy current because the entropy coming from outside is less charged with energy then the entropy going into the house.

Heat engines and heat pumps can be compared with a hydroelectric power plant. Entropy corresponds to the mass and temperature to the gravitational potential with the reference point at sea level. In a hydroelectric power plant water discharges only a part of its gravitational energy depending on the height of both reservoirs. This can be applied to a heat engine. This idea was first stated by Sadi Carnot [11].

In a nuclear power plant, entropy which is coming from the reactor transfers part of its energy to the electric current. The rest of the energy is carried by the entropy to the environment. Because the cooling system is hotter than 300 Kelvin a large part of the energy coming from the reactor cannot be transferred to the electric current. With the waterfall picture designed by Carnot we can easily understand why most of energy coming from the reactor is transferred to the cooling system instead to the electric power net.

In a nuclear power plant, entropy is produced in the reactor. The rate of entropy production can be calculated using the entropy balance and the associated formula for the carried energy. As a result we get for the entropy production rate a simple formula: entropy production rate equals dissipated power divided by absolute temperature.

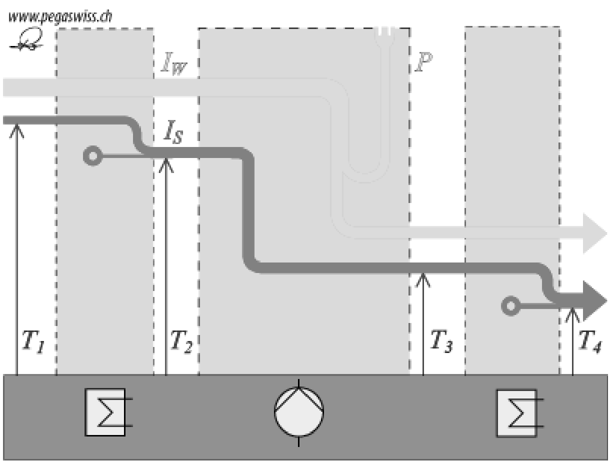

Figure 12: Schematic representation of an endoreversible heat engine.

The often heard argument that energy is converted into heat by dissipation can now be described more precisely using this relation: in a dissipative process entropy is produced and energy is reloaded from another fluidlike quantity to entropy.

Now we are able to explain heat conduction as a dissipative process. In heat conduction, entropy is flowing from a heat reservoir with high temperature through the conduction element to a colder reservoir. In doing this, energy is dissipated, which means that more entropy is produced. It can be shown that the energy flux remains constant: energy is increasingly distributed to a growing current of entropy. This phenomenon might be the reason for the odd definition of heat: in the middle of the 19th century physicists were looking for a thermal quantity which is conserved – and they found the bookkeeper and not the real actor.

As an example of a system with ideal and dissipative processes, we consider an endoreversible heat engine (Figure 12). This engine consists of an ideal heat engine with two heat exchangers. In both heat exchangers entropy flows downhill. The thereby released energy is used for entropy production. So the two heat exchangers reduce the usable gap i.e. the available temperature difference.

9 Heat Storage

In all branches of physics there are a lot of storage systems like reservoirs (mass), plastic bottles (volume), capacitors (charge), moving (linear momentum) or rotating (angular momentum) bodies. In thermodynamics the simplest accumulator is more complex. A homogeneous thermodynamic system can at least change entropy and volume. Therefore the system has two potential, temperature and pressure. To discuss and model such a system we have developed the Carnotor, a simple machine with two ports, a thermal and a hydraulic one (Figure 13). Carnotor is a portmanteau composed of Carnot and Motor (German word for engine).

The Carnotor consists of a double-acting cylinder filled with the substance to be examined on one side of the piston and an ideal fluid on the other side. To each port we can add a pump, a closing-off of or a big storage tank. With this equipment students can think about all four basic processes of thermodynamics (isochoric, isobar, isentropic, isotherm).

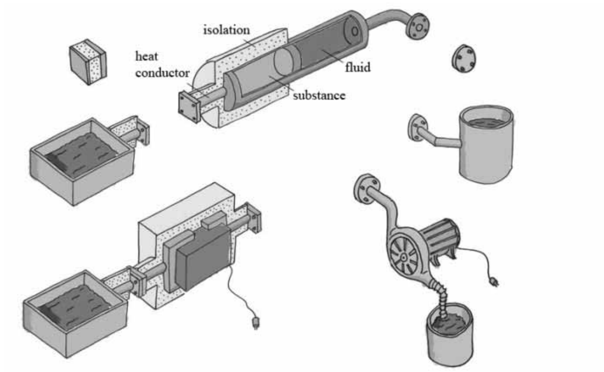

Figure 13: The Carnotor has two ports, one for heat and one for an ideal fluid. Both ports can be combined with a closing-off, a storage tank or a pump.

The simplest thermodynamic system stores at least two quantities. Therefore it comprises two associated potentials. Such a system is more complex than a moving body or a capacitor.

Nonetheless, with the help of the Carnotor students can model real thermodynamic systems.

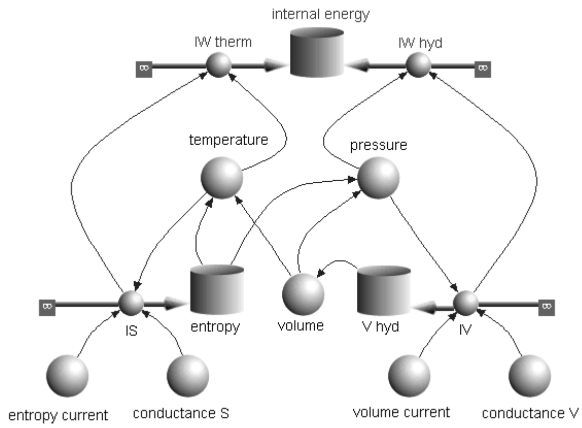

Figure 14: System dynamics model of the Carnotor whith the balances of entropy and volume, the two associated potentials and the energy balance.

In order to calculate pressure and temperature two constitutive laws are needed. As an auxiliary condition for these laws energy has to be conserved.

The system dynamic model of the Carnotor can be used as a basis for more complex systems like Otto or Diesel engine. One difficulty arises from modelling of the isobaric and isothermal processes. For both processes we need ideal conductance between Carnotor and storage tank, i.e. the numeric value of the conductance has to be infinite.

Therefore students have to make a compromise between idealization and calculability. That's the difference between the quasi-static analysis of classical thermodynamics and simulation in time domain.

10 Stirling Engine

The Stirling engine was invented and patented by Robert Stirling in 1816. A Stirling engine operates by cyclic compression and expansion of air at different temperatures. The thermodynamic principle of the Stirling engine is dscribed by the Stirling cycle. This cycle differs from the Carnot cycle through the two isochoric processes which replace the isentropic processes. Both cycles have the same efficiency if entropy is only exchanged by the two isothermal processes. Therefore, the entropy released by isochoric cooling must be thermally buffered, so that this entropy is available for isochoric heating.

In contrast to the Stirling cycle, the Stirling engine operates with two chambers, one hot and one cold. A displacer piston pushes the gas periodically between the two chambers back and forth.

Our Stirling engine is a gamma type in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder.

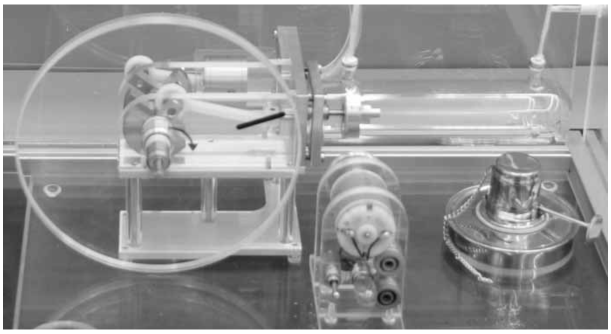

Figure 14: Stirling engine with flywheel (left), power piston (behind the flywheel), main chamber with displacer (right side).

Students can measure the temperatures in the warm and in the cold region as well as pressure and stroke of the working piston in function of time.

The temperature is measured directly at the glass cylinder. Therefore, a direct measurement of the gas temperature is not possible.

Model. We take the amount of substance of air as primary quantity. This quantity is pushed between the hot and the cold region by the pressure difference. As the second fluidlike quantity we take the energy and not the entropy. Later, we estimate the efficiency of the machine with the help of the entropy production. The mechanical part of the engine with pistons and flywheel is not modeled. Instead we give the two volumes in function of time. The rotational frequency comes from the measurement.

Figure 15 shows the flowchart of this model. In the upper part you see the balance of the amount of substances. Using the ideal gas law the pressure is calculated of volume, amount of substance and temperature. The energy level consists of a thermal (top row) and a mechanical part (two pots below). The regenerator is modeled by means of three heat accumulator with identical heat capacity. The calculation of the entropy currents, the entropy production rate and the produced entropy is not shown in Figure 15. The produced entropy can be calculated for the heat transfers in the hot and the cold chamber as well as for the convective heat transport.

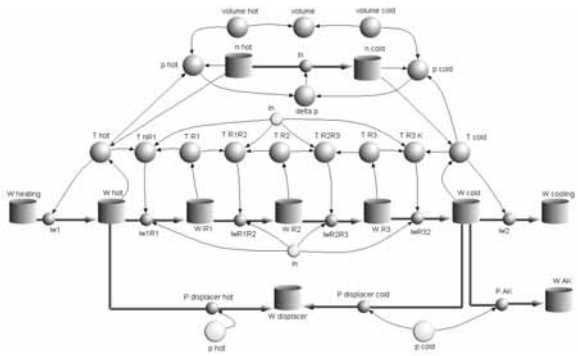

Figure 15: System dynamics model of a Stirling engine whith the energy balance (9 reservoirs) and the balance of amount of substance (two reservoirs on top).

Results. The theoretical efficiency (Carnot efficiency) is 50% at 600 K for the hot heat reservoir and 300 K for the cold heat bath. The simulation of this model gives 17%. Taking away the three heat store for the regenerator, gives only 6%. Large Stirling engines achieve an efficiency which is less than 0.5 times the Carnot efficiency. Small Stirling engines as ours achieve an efficiency that is close to zero. Therefore, the model presented here is not very valid.

But validity is not the primary goal of this laboratory course. In this modeling exercise, students will learn the basic laws of thermodynamics with a concrete example. And this goal is achieved much more than when the students solve a few simplified exercises.

An important learning objective is the correct interpretation of graphs. Figure 16 shows the pressure-volume diagram. In this diagram, the net work of the gas is equal to the area enclosed by the circle. This knowledge can also be applied to internal combustion engines and steam engines. Comparing the simulated data with the ideal cycle, we see two essential differences: expansion and compression processes are not isothermal and the four thermodynamic processes merge into one another.

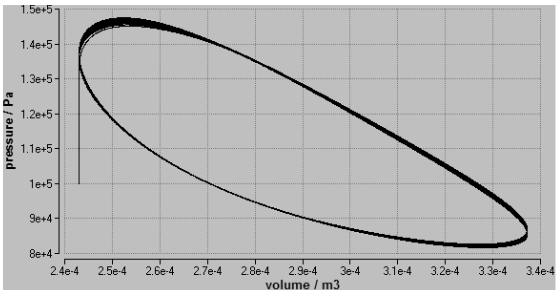

Figure 16: Simulated pressure-volume diagram of the Stirling engine.

This model of the Stirling engine allows many different studies. What happens with the effinciency if one increases the number of energy reservoirs for the regenerator? How increases the efficiency with the increase of temperature at the entrance of heat? Where is produced the most entropy? Will the entropy production decreases with increasing number of heat accumulators? The example of the Stirling engine clearly demonstrates how one can fulfill new learning objectives with modeling and simulation.

11 Summary

Systems Physics provides a consistent, coherent and relevant structure of physics. A huge number of dynamical systems can be modelled with the same heuristic approach. The equation of balance for fluidlike quantities like volume, mass, electric charge, momentum, angular momentum and entropy yields the backbone for such models. By adding the constitutive laws for accumulators and conductors we get the basic equations.

In a third step we can add energy as a second fluid-like quantity. The energy balance analysis is often useful but not necessary for simple systems. But energy conservation becomes an inevitable requirement in more complex systems like thermodynamic accumulators.

Systems Physics differs in three respects from other physics courses at colleges. First, the structure is not historically i.e. we don’t teach along the well-trodden paths. Second, we use as many analogies as possible and develop the individual domains in a uniform manner: balance equation, constitutive laws and energy as a bookkeeper. Third, we explain the laws of physics by means of modeling and simulation and not primarily by means of subtle arithmetic problems.

Electricity and heat were originally understood to be a kind of fluid, and the names of certain quantities such as current are derived from hydraulic equivalents. Therefore, the hydraulic-electrical analogy is natural and used frequently.

In thermodynamics, there are two analogies to hydraulic, the entropic and energetic. We use the entropic analogy to represent the thermodynamics in its full beauty. Waterfall picture, entropy production and Carnotor are important stones in the large mosaic of thermodynamics. The energetic analogy we use only for the thermal RC circuits such as buildings to be heated or body to be cooled.

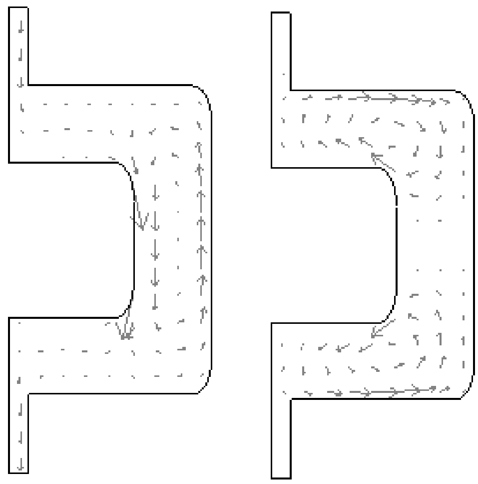

Figure 17: Momentum currents in a sheet metal under tensile stress. Each picture shows the current of a momentum component.

Mechanical-electrical analogies are introduced first by James Clerk Maxwell to explain electrical phenomena in familiar mechanical terms. However, as electrical network analysis matured it was found that certain mechanical problems could more easily be solved through an electrical analogy. Two pairs of power conjugate variables can be found: force and velocity for translational and torque and angular velocity for rotational mechanics. A deeper analysis shows that force and torque are analogous to the electric current and velocity and angular velocity are analogous to the electric potential. Each analogy has its limits. Unlike the electric charge momentum and angular momentum are vectors. Therefore, you always need a fixed coordinate system (world system) to decompose the two vector-like quantities in six fluidlike scalars.

Figure 17 shows, how you can create entirely new pictures with this idea. As a result of the tensile stress momentum flows through the piece of sheet metal (picture on the left side). Because this current is deflected, it generates eddy currents of the other components (picture on the right side). These in turn produce another eddy current of the first component (central part in the left picture). The momentum current coupling can be better explained if one also brings in the angular momentum. But that would be again a long story. This picture shows that the analogy goes much further than is assumed first. But you have to understand the continuum mechanics thoroughly in order to apply these ideas correctly.

Analogies are also important in regard to the further education of engineers. Thus one finds in textbooks on control systems the same analogy as in the Systems Physics [12]. Another line of development leads directly to the modeling tools of the latest generation such as Modelica [13]. Systems Physics has the potential to become the backbone of an entire engineering education. In such a program, we could start with a simple system dynamics tool. Then, with advancing knowledge, students could develop entire Modelica libraries. Based on past experience, we know that such training would be more sustainable than the usual formula based instruction. Unfortunately, the possibilities of this type of learning are still too little exploited.

Despite the good acceptance by the students and the excellent preparation in terms of modelling and simulation, Systems Physics isn't widely accepted.

Several reasons prevent the widespread acceptance of this approach. Most opposition comes from other teachers who don't accept that momentum can flow through material or that entropy can be seen as another word for heat. Tradition is another obstacle to progress in education. If all curricula would change, hundreds of textbooks and formulary had to be rewritten and thousands of teachers had to be re-educated.

Nevertheless, the development of Systems Physics was a real adventure. It has provided a deep insight into classical physics and paved the way for the wide application of modelling and simulation in teaching physics. Last but not least I would like to thank my friend Hans Fuchs for the innumerable fruitful discussions in developing this approach and Elisabeth Dumont for further discussion.

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Differential Equations and Carathéodory Solutions: How System Dynamics Describes Formal Dynamical Systems

Patrick Einzinger

Department of Analysis and Scientific Computing, Vienna University of Technology, Wiedner Hauptstraße 8–10, 1040 Vienna, Austria; *patrick.einzinger@tuwien.ac.at*

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Abstract. It is often informally stated that system dynamics (SD) models are equivalent to differential equation systems. This paper formalizes the concept of an SD model as a collection of rate equations, auxiliary equations, and the "flow coupling" of flows to stocks. If such a model has no causal loops that consist only of auxiliaries, then it is possible to find an equivalent differential equation system. The generalized solution concept of Carathéodory is shown to be suitable for defining the corresponding state transition map, which leads to a formal dynamical system.

Introduction

According to Hinrichsen and Pritchard [1], a dynamical system is a structure that consists of a time set (i.e., a totally ordered set of all time values) $\mathbb{T}$, an input value set U, an input function space $\mathscr{U} \subset U^{\mathbb{T}}$, a state space X, an output space Y, and two maps: the state transition map ϕ and the output map η. For every initial value $x_0 \in X$ at time point $t_0 \in \mathbb{T}$, every input signal $u \in \mathscr{U}$ and every time point $t \in \mathbb{T}$ such that $(t;t_0,x_0,u) \in D_\phi \subset \mathbb{T}^2 \times X \times \mathscr{U}$, ϕ maps to the state $x = \phi(t;t_0,x_0,u) \in X$. The output map then produces the corresponding output value $y = \eta(t,x,u(t)) \in Y$.

Four axioms must hold for the state transition map:
Interval Axiom: For every fixed initial value x_0, initial time t_0, and input signal u, ϕ is defined on an interval in $\mathbb{T}$ that contains t_0.
Consistency Axiom: For $t = t_0$, ϕ always maps to the initial value x_0.
Causality Axiom: If two input signals u and v equal each other on the interval between t_0 and t_1, then $\phi(t_1;t_0,x_0,u) = \phi(t_1;t_0,x_0,v)$.
Cocycle Property: If we "restart" the system at time $t_1 > t_0$, we get the same state at time $t_2 > t_1$ as if we go directly to t_2 from t_0, because $\phi(t_2;t_0,x_0,u) = \phi(t_2;t_1,\phi(t_1;t_0,x_0,u),u)$.

It is often informally stated that every system dynamics (SD) model is equivalent to a system of differential equations and thus a dynamical system. Basically, every stock or level stands for one differential equation, which describes the change of the stock over time. In this paper, we show formally that this is indeed true.

Note. This article is a revised version of Section 3.4 of the author's PhD thesis [2].

1 The Building Blocks of System Dynamics Models

1.1 Stocks and flows

One major advantage of SD is that only a few basic elements are necessary to build a model. Every SD model consists of *stocks* and *flows* (equivalently, they are often called *levels* and *rates*). Stocks are variables that accumulate a certain quantity. Through this accumulation, stocks represent the memory and state of the system.

Flows are the other important variable type. They have no memory, because at every time point, their value depends only on the current values of the stocks. But they represent stock changes, because flows are the sole quantities that the stocks directly accumulate. More specifically, a flow F may be an inflow of a certain stock S, in which case S is increased by F, or it may be an outflow of S, in which case S is decreased by F.

These two elements are enough to describe the entire dynamics of a system. Actually, as we will show, if the dependence of the flows on the stocks is specified through equations, the system is equivalent to a system of ordinary differential equations, where the stocks are the state variables and the flows are the right-hand sides of the differential equations. Together with initial values for the stocks, an initial value problem is given, which has a unique solution under the condition well-known from the theory of differential equations that the right-hand side is continuous in time and Lipschitz continuous in the state variable. In this regard, SD is just another way of describing differential equations.

However, the systematic way of deriving the equations is the real benefit of the method. The stock and flow structure is important on its own, even without the equations, because even it alone gives qualitative insight into the possible and probable dynamic behaviour of a system. Moreover, it has a standardized graphical notation, the *stock and flow diagram*. Figure 1 shows a simple stock and flow diagram.

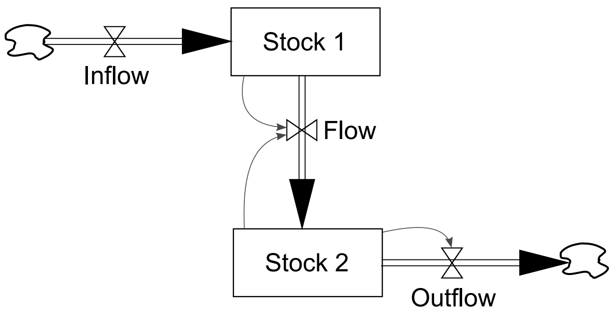

Figure 1: A stock and flow diagram that consists only of stocks (depicted as boxes) and flows (depicted as pipes with valves in the middle). If the source or sink of a flow is not important because it lies outside the system boundary, a small cloud symbol is drawn instead. Blue arrows show causal dependencies.

In the diagram, boxes depict stocks and pipes with valves in their middle depict flows. Every flow that ends in a stock is an inflow for this stock, whereas every flow that begins in a stock is an outflow. Stock 1 has one inflow that begins in a source outside the model boundary, depicted by a cloud symbol. Similarly, an outflow goes from Stock 2 into a sink. The flow in the middle is both an outflow for Stock 1 and an inflow for Stock 2.

There is an additional causal structure in the diagram. The blue arrows show on which stocks the flows depend. For example, the flow between Stock 1 and Stock 2 depends on both of them. On the other hand, it would be an error to use Stock 1 in the equation of the outflow from Stock 2, because there is no blue arrow from Stock 1 to Flow, which means that it is independent of Stock 1. Fortunately, SD simulation software is capable of automatically detecting such inconsistencies between diagram and equations.

1.2 Auxiliaries and constants

Stock and flow diagrams with only stocks, flows, and their causal dependencies along with equations could describe every possible SD model, but often different concepts and effects are involved in a flow equation. In this case, it is beneficial to include intermediary variables to state these relationships directly in the stock and flow diagram. They are called *auxiliaries* because of their not necessary but often helpful nature. Like flows, these variables can depend on stocks and other auxiliaries. It must always be possible to calculate their value from all values of the stocks.

Additionally, stock and flow diagrams can include constant values as separate quantities. Of course, it would be possible to just write these values in the equations of auxiliaries or flows, but as in computer programming the use of such "magic numbers" is considered to be bad practice. The SD methodology tries to encourage modellers to make concepts graphically explicit and to give them meaningful names.

2 Formal Definition of SD Models

Definition 2.1 (System Dynamics Model)**.** A *system dynamics model* with m stocks (levels), n flows (rates), k_a auxiliaries, and k_p parameters consists of n flow or rate equations $f_i\colon D_{f_i} \to \mathbb{R}$, $i \in \{1,\dots,n\}$, where $D_{f_i} \subset \mathbb{R}^m \times \mathbb{R}^{k_a} \times \mathbb{R}^{k_p}$, k_a auxiliary equations $g_j\colon D_{g_j} \to \mathbb{R}$, $j \in \{1,\dots,k_a\}$, where $D_{g_j} \subset \mathbb{R}^m \times \mathbb{R}^{k_a} \times \mathbb{R}^{k_p}$, and the flow coupling $FC \in \left(\{0,\dots,m\}^2 \setminus \{(i,i) : i \in \{0,\dots,m\}\}\right)^n$.

The flow coupling FC denotes which stocks a flow connects. Here, the index 0 represents a source or sink. The pair $(i,0)$ in the flow coupling stands, for example, for a flow from the i-th stock into a sink. A flow from the i-th stock into the stock with index j would be represented by the pair (i,j).

All variables of a system dynamics model have values in $\mathbb{R}$. We write $\mathbf{x}(t) \in \mathbb{R}^m$ for the state vector of stocks at time t, $\mathbf{r}(t) \in \mathbb{R}^n$ for the vector of flows, $\mathbf{a}(t) \in \mathbb{R}^{k_a}$ for the vector of auxiliaries, and $\mathbf{p} \in \mathbb{R}^{k_p}$ for the parameter vector.

3 Causal Loops

In the following, we want to find a corresponding differential or integral equation system for an SD model and define the state transition mapping and the output mapping via the solution of this equation system. This is impossible if the equations for the auxiliary variables form *algebraic loops*: Suppose that there are three auxiliary variables a_1, a_2, and a_3 in the model, and that the equations are $a_1 = g_1(\mathbf{x}, \mathbf{a}, \mathbf{p}) = a_2$, $a_2 = g_2(\mathbf{x}, \mathbf{a}, \mathbf{p}) = a_3$, and $a_3 = g_3(\mathbf{x}, \mathbf{a}, \mathbf{p}) = a_1$. Obviously, the equations are redundant and reduce to $a_1 = a_2 = a_3$, which has infinitely many possible solutions.

The question is which preconditions secure that there are no algebraic loops involving auxiliaries. This involves the concept of causal links.

Definition 3.1 (Causal Link)**.** In a system dynamics model, a variable v_1, where v_1 is a stock, an auxiliary, or a parameter, is a *direct cause* of an auxiliary or flow v_2 if the corresponding auxiliary equation g_j (or f_j) depends on v_1, that is, if the value of g_j (or f_j) is not the same for all values of v_1, where all other variables are fixed. Likewise, a flow v_1 is a direct cause of a stock v_2 if it is an outflow or inflow of v_2. In both cases, the model has a *causal link* from v_1 to v_2.

Beginning from a variable, it is possible to follow causal links.

Definition 3.2 (Causal Chain)**.** A sequence $v_1, \ldots, v_k$ of variables with $k \in \mathbb{N}$ is called a *finite causal chain* of length k beginning at v_1 if for every $i \in \mathbb{N}$ with $1 \leq i < k$ there is a causal link from v_i to v_{i+1}. Likewise, a sequence $(v_i)_{i \in \mathbb{N}}$ is called an *infinite causal chain* beginning at v_1 if it has the same property as in the finite case.

Definition 3.3 (Causal Loop)**.** A *causal loop* of length k is a finite causal chain $v_1, \ldots, v_k$ where $v_1 = v_k$ and $v_i \neq v_j$ if $1 < i < k$ or $1 < j < k$.

If and only if there is a causal loop that involves just auxiliary variables the equations form an algebraic loop.

4 The Link Matrix

We will now define a matrix that stores all causal links between auxiliaries. It is possible to see if an SD model includes a causal loop with only auxiliary variables from the structure of this matrix.

Definition 4.1 (Link Matrix)**.** The *link matrix* L of an SD model with auxiliary variables $a_1, \ldots, a_{k_a}$ is the matrix where $L_{i,j}$ is 1 if there is a causal link from a_i to a_j and 0 otherwise.

Obviously, auxiliaries that have only causal links to flows do not pose any problem. But also other auxiliaries with causal links only to these first kind of auxiliaries cannot be part of an algebraic loop. We can pursue this strategy further and thus classify them:

Definition 4.2 (Causal Order)**.** An auxiliary is of *causal order* 0 if it has no causal link to any other auxiliary. It is of order 1 if it has only causal links to auxiliaries of order 0. Generally, an auxiliary has causal order n if it has links to auxiliaries of order $n-1$, but not causal links to auxiliaries of higher order. All other auxiliaries have infinite causal order.

Lemma 4.3. *An auxiliary a_0 has infinite causal order if and only if it is part of a causal loop involving only auxiliaries or if there is a causal chain beginning at a_0 that ends in such a causal loop.*

Proof. No auxiliary in a causal loop has causal order 0, because every auxiliary in the loop has a causal link to the next auxiliary in the loop. It follows that also no auxiliary can be of order 1, because an auxiliary of order 1 only has links to order-0 auxiliaries. The same holds for every finite order. Finally, if a causal chain ends in an auxiliary that is part of a causal loop, all auxiliaries of the causal chain have infinite order, which can be seen recursively.

On the other hand, suppose that a_0 is not part of a causal loop with only auxiliaries and there is also no causal chain beginning at a_0 that ends in a loop. As there are only k_a auxiliaries and no auxiliary can be part of a causal chain twice if the chain contains no loop, every causal chain that starts at a_0 is finite. If a_0 has infinite order, at least one of the auxiliaries to whom it has a causal link, denoted by a_0', has to have infinite order too. Again, one of the auxiliaries to whom a_0' has a causal link has to have infinite order. In this way, it would be possible to construct an infinite causal chain where every auxiliary has infinite order, which is in contradiction of the fact that every causal chain starting from a_0 is finite. □

Figure 2 shows an example of a causal diagram with only auxiliary variables. All auxiliaries in the loop have infinite causal order. Additionally, a_0 has infinite causal order because it has a link to another auxiliary of infinite order. The other auxiliaries (a_5, a_6, and a_7) have finite order.

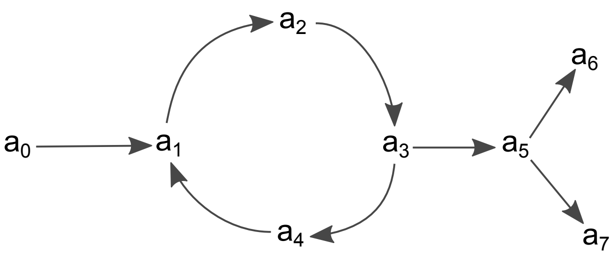

Figure 2: In this causal diagram, a_6 and a_7 have causal order 0 (they have no link to any other auxiliary). The only other variable with finite causal order is a_5, which has causal order 1 because it has only links to variables of order 0. All other auxiliaries in the diagram have infinite causal order.

Proposition 4.4. *An SD model contains a causal loop involving only auxiliaries if and only if it is not possible to renumber the auxiliaries such that the link matrix is a lower triangle matrix.*

Proof. First, suppose that the model has a causal loop involving only auxiliaries. For the link matrix to be a lower triangle matrix, a variable a_i can only have a causal link to a_j if $j < i$. One variable a' of the causal loop has to be the variable with the lowest number of all variables in the loop. As a variable in the loop, it has a causal link to the next variable in the loop. This variable must then have a lower number then a', which leads to a contradiction. Therefore, the link matrix cannot be of lower triangular form.

Now suppose that no causal loop involves only auxiliaries. Lemma 4.3 shows that then all auxiliaries must have finite causal order. We can therefore numerate the auxiliaries according to their order: First, we take all order-0 auxiliaries, then all order-1 auxiliaries, and so on. Each auxiliary can have only links to auxiliaries with lower order, which shows that the link matrix is of lower triangular form. □

5 Flow Equations of a System Dynamics Model

The last proposition gives a characterisation of the system dynamics models whose equations do not form algebraic loops. These models allow for the formation of a differential equation system which depends only on the values of stocks and parameters.

Proposition 5.1. *If a system dynamics model contains no causal loops of only auxiliaries, the flow equations can be written just in terms of stocks and parameters.*

Proof. In a system dynamics model, the flow equations might be given as functions that depend not only on stocks and parameters, but also on the values of auxiliaries. However, according to Proposition 4.4, the auxiliaries of a system dynamics model without algebraic loops can be enumerated such that the link matrix is of lower triangular form. The value of the first auxiliary a_1 depends only on stocks and parameters, that is, there is a function $g_1' : D_{g_1}' \to \mathbb{R}$ such that $g_1'(\mathbf{x}(t), \mathbf{p}) = g_1(\mathbf{x}(t), \mathbf{a}(t), \mathbf{p})$ for all $(\mathbf{x}(t), \mathbf{a}(t), \mathbf{p}) \in D_{g_1}$, where the domain D_{g_1}' is the restriction of D_{g_1} to the set $\mathbb{R}^m \times \mathbb{R}^{k_p}$. The second auxiliary a_2 may depend on a_1 as well, but as the value of a_1 is a function of only stocks and parameters, so is a_2. In general, as a_i for $1 \le i < k_a$ depends only on stocks and parameters, so does a_{i+1} .

Finally, as all auxiliaries can be written as functions of stocks and parameters, all flow equations are also only functions of stocks and parameters. □

6 The State Transition Map of a System Dynamics Model

The result from the last section guarantees that it is possible to find a differential equation system that is equivalent to the system dynamics model. Two problems could arise:

1. The differential equation system might not have a solution.
2. The differential equation might have more than one solution.

In both cases, it is not clear how to define the state transition mapping of the corresponding dynamical system. We should thus require the differential equation system to have a unique solution.

Is it enough if we allow for solutions in the classical sense? Consider, for example, the first order system

$$\frac{dy}{dt} = u - y \\ y(0) = 0 \tag{1}$$

where u is the input function and y is the output function. If u is continuous, then the right-hand side of Equation 1 is continuous and therefore the initial value problem has a solution according to the Peano existence theorem. (It is even unique because the right-hand side is Lipschitz continuous in y.) But if u is not continuous, a solution might not exist, such as in the case where the input u is the Heaviside step function

$$H\colon \mathbb{R} \to \{0,1\}$$
$$t \mapsto H(t) := \begin{cases} 1 & \text{for } t \geq 0 \\ 0 & \text{for } t < 0. \end{cases}$$

Proposition 6.1. *The initial value problem* (1) *with input $u = H$, where H is the Heaviside step function, has no solution in the classical sense.*

Proof. A solution y would have to fulfill

$$\frac{dy}{dt}(t) = \begin{cases} -y(t) & \text{for } t < 0 \\ 1 & \text{for } t = 0, \end{cases}$$

and as a differentiable function it must be continuous. Since $y(0) = 0$, for $\varepsilon > 0$ there exists a $\delta > 0$ such that $|y(t)| < \varepsilon$ for all t with $|t| < \delta$. In particular, for $\delta < t < 0$ we have $|\frac{dy}{dt}(t)| = |-y(t)| < \varepsilon$. If we choose, for example, $\varepsilon = \frac{1}{2}$, we can therefore fix a point $t_1 < 0$ such that $y(t) < \frac{1}{2}$ for all t with $t_1 \leq t < 0$. But as a derivative, $\frac{dy}{dt}$ must have the intermediate value property according to Darboux's theorem and, therefore, take all values between $\frac{dy}{dt}(t_1)$ and $\frac{dy}{dt}(0) = 1$ on the interval $[t_1, 0]$, which leads to a contradiction. □

This is unsatisfactory, as the Euler method that is typically used for the simulation of SD models does not have any problems with this system. Only the first step, which can be made arbitrarily small, is affected by the discontinuity. For all further steps, the input function equals 1.

It is possible to solve the differential equation for $t \geq 0$ with variation of constants and ignore the discontinuity at $t = 0$, which leads to the solution $y(t) = 1 - e^{-t}$. For $t < 0$, we can set $y(t) = 0$. The "solution" has the following properties:

1. It is Lipschitz continuous.
2. It fulfils the differential equation for $t \neq 0$.

It seems natural to accept this function as a solution. This leads to one kind of a generalized or weak solution concept: a solution in the sense of Carathéodory.

Definition 6.2 (Carathéodory Solution)**.** A function is a *Carathéodory solution* of an ordinary differential equation system on an interval $I \subset \mathbb{R}$ if it is absolutely continuous and satisfies the differential equations almost everywhere on I.

The function y in the example above is absolutely continuous, because it is even Lipschitz continuous, and it satisfies the differential equation everywhere apart from $t = 0$, that is, almost everywhere, thus it is a Carathéodory solution. Note that an absolutely continuous function is differentiable almost everywhere. For comparisons with other generalized solution concepts, see [3].

Definition 6.3 (State Trajectory of a System Dynamics Model)**.** Let $\mathscr{M}_{SD}$ be a system dynamics model with no algebraic loop. The differential equation system

$$\frac{d\mathbf{x}}{dt}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{p}), \tag{2}$$

where $\mathbf{x}(t)$ is the state vector containing the values of the stocks, $\mathbf{p}$ is the parameter vector, and $\mathbf{f}$ is the vector of flow equations that depends only on the stocks and the parameters as in Proposition 5.1, is called the *equivalent differential equations system* of $\mathscr{M}_{SD}$. For an initial state x_0 at time t_0, a Carathéodory solution of this system is called a *state trajectory* of the system dynamics model.

Through this definition, it is possible to specify a state transition map that corresponds to the SD model. For every fixed values of t_0 and x_0, we can set it to the value of the state trajectory on the maximum interval where a unique Carathéodory solution exists. It is permissible that this interval contains only t_0. Obviously, the state transition map obeys the other necessary properties such as consistency. Note that a system dynamics model has no separate input variables. Therefore, the input space of the corresponding dynamical system consists only of one element.

There is no single correct choice for an output map. An SD model usually has no dedicated output variables.

However, the values of all stocks and auxiliaries can be seen as output. The output space is then $\mathbb{R}^m \times \mathbb{R}^{k_a}$.

7 Conclusions

Systems theory can serve as a rigorous mathematical foundation for modelling and simulation. In this paper, we have shown that system dynamics is indeed a method that specifies dynamical systems. While differential equations are not specified directly, each feasible SD model has an equivalent differential equation system.

We can see an SD model as a collection of stocks, flows, auxiliaries, and parameters together with rate equations and auxiliary equations. Additionally, it must be specified which stocks are coupled by flows (flow coupling).

SD models are not allowed to have algebraic loops, where only auxiliary variables depend on each other without any accumulating stock in between. We have proposed formal definitions of causal links, causal chains, and causal loops, which make it possible to show that if there are no algebraic loops, (i.e., no causal loops of only auxiliaries) the flow equations of the SD model can be written just in terms of stocks and parameters. Thus, the model has an equivalent formulation as a differential equation system.

Moreover, the links between auxiliaries form a link matrix, and the model has no algebraic loops if and only if it is not possible to transform this matrix into a lower triangle form by renumbering the auxiliaries.

These findings can serve as a basis for a formal system theoretical treatment of SD models. They also show that a generalized solution concept such as the one of Carathéodory is necessary, because in applications of SD the right-hand sides can have discontinuities.

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Causality of System Dynamics Diagrams

Peter Junglas

PHWT Vechta Schlesier Str. 13, 49356 Diepholz, Deutschland; *peter@peter-junglas.de*

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Abstract. System dynamics diagrams are generally regarded as a very simple modeling tool that can be implemented easily with standard techniques. But a few examples will show that this can be more complicated than expected: The causality – i.e. the assignment of block connections to inputs or outputs – can depend on the state of the complete system. How this affects the design of system dynamics libraries will be shown for the different modeling approaches used in Modelica and Simulink.

Introduction

System dynamics diagrams are a modeling method that is used mainly for non-technical subjects like economy or ecology [1]. Commercial tools for modeling and simulation are readily available (e.g. Stella from ieee systems [2]), there even exists a free Modelica implementation [3].

In view of the basically very simple structure of the diagrams one should assume that they can be easily implemented, e.g. using Simulink to create corresponding blocks. Trying this one finds that the signal flow method can be inconvenient to reproduce certain details, because every connection of a block has to be defined beforehand as input or output, i.e. the causality of each connection is fixed. However in some examples the causality changes dynamically according to the current state of the system. For the implementation of this behaviour a modeling approach like "Physical Modeling" [4] seems to be better suited, because here the causality is dynamical in general and can only be determined in the context of the complete system.

In the following several examples are going to illustrate the basic problems, and implementations in Modelica and Simulink will show, how they can be solved. While the Simulink library is rudimentary and only serves as a proof of concept, the Modelica version is quite complete and can be useful on its own to allow for the simulation of system dynamics diagrams with physical modeling programs. It has been developped originally for a textbook [5] and is available under an open source licence from the author's homepage [6]. The already existing Modelica implementation by Cellier et al. [3] does not address the problems mentioned here, because it concentrates on the simulation of the famous world models, which are free of causality problems.

1 Basic System Dynamics Diagrams

System dynamics diagrams consist of three different types of basic building blocks: **Reservoirs** are storage elements representing state variables, which change their values – often called levels – through ingoing or outgoing flows. **Flows** work like valves and define the value of the flows, they connect reservoirs with external sources or sinks or other reservoirs. They can use the values of auxiliary variables that are computed with **converters**. Fig. 1 shows a simple diagram containing these blocks.

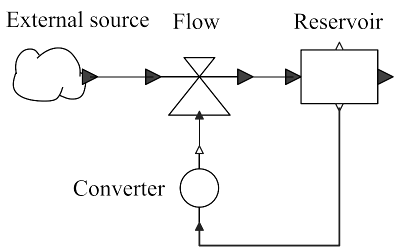

Figure 1: Basic blocks in system dynamics diagrams.

As an example we consider a simple model of population growth: The size of the population N changes according to the number of births B and deaths D per time. B is simply given by a constant rate b, whereas D

is limited by a fixed capacity N_c:

$$B = bN$$

$$D = dN \quad \text{with} \quad d = \frac{d_0}{1 - N/N_c}$$

In the complete model (cf. fig. 2) the parameters b, d_0 und N_c are defined in converters, an additional converter uses them to compute the rate d. The flows multiply their two inputs to get the flow values B and D. The diagram only shows the basic relations between the variables, the concrete formulas are hidden inside the blocks.

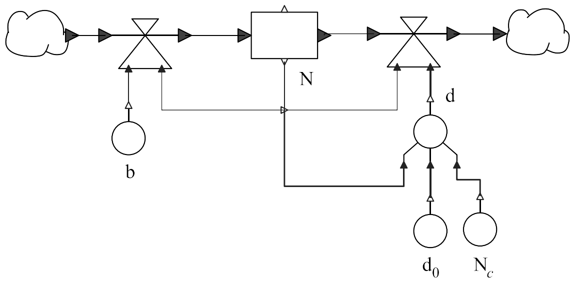

Figure 2: Model `population`.

The causality of the components is straightforward: Converters can have an arbitrary number of inputs, but only one output that is connected to other converters or the correspondig inputs of a flow. A flow block uses these inputs to compute the value of the flow and passes it as an output value to the connected reservoirs. The arrows denoting the flows in the diagram seem to contradict this view, but they only denote the (positive) direction of a flow, not the logical flow of the signal, which always proceeds from a flow to a reservoir. Finally a reservoir subtracts input and output flow and computes the value of its state variable by simple integration. This value is provided via explicit outputs, which can be used in converters or flows. This basic idea has been used in the Modelica library described in [3] and can be easily implemented in Simulink.

2 Models with Variable Causality

2.1 Stock with saturation

A reservoir has two optional parameters that define minimal and maximal level values. In the example model `sink` (cf. fig. 3) the first reservoir S_1 has a minimal value of 0 und a start value of 4, the outgoing flow is set to 0.5 by a constant converter. The result of the simulation can be seen in fig. 4: According to the constant flow the level of S_1 decreases linearly with time, until at t = 8 the minimal value is reached, and stays constant thereafter. The subsequent reservoir S_2 has the corresponding behaviour, especially it stays constant after t = 8.

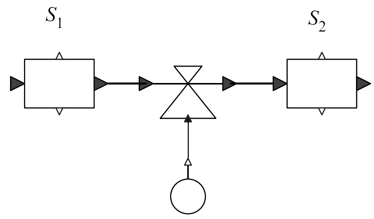

Figure 3: Model `sink`.

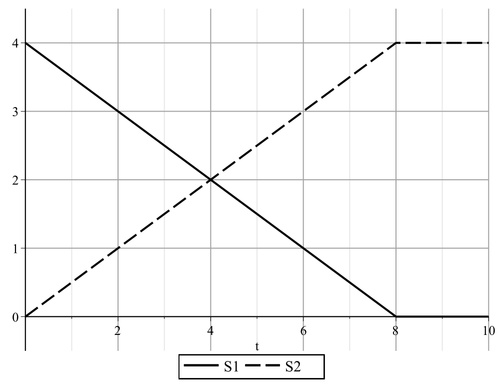

Figure 4: Simulation result of `sink`.

At first sight it seems that the model can be implemented easily by adding a saturation into the reservoir S_1. This doesn't affect the behaviour of S_2 though, its level would rise steadily after t = 8 according to the given flow value. Instead one has to guarantee that the outflow at S_1 and the corresponding inflow at S_2 change from 0.5 to 0 according to the level of S_1. This is a typical causality problem: Before t = 8 the size of the flow is defined by the flow block, afterwards it is reduced to 0 by the reservoir S_1. And the situation gets even more complicated, if S_2 has an upper limit smaller than 4: Now it is S_2 that has to change the flow value.

2.2 Simple conveyor belt model

The conveyor block models a simple conveyor belt, its input values appear at the output after a given delay.

It is a discrete element with a fixed sample time. In the test model `conveyor` (cf. fig. 5) a time varying input is transported by a conveyor and accumulated in a reservoir. Fig. 6 shows the result of the simulation, which comes as no surprise.

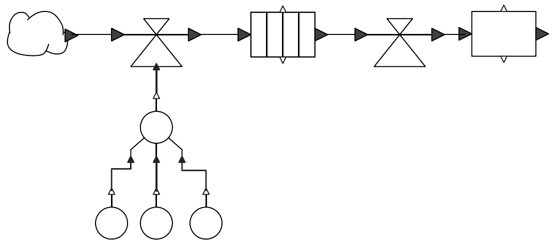

Figure 5: Model `conveyor`.

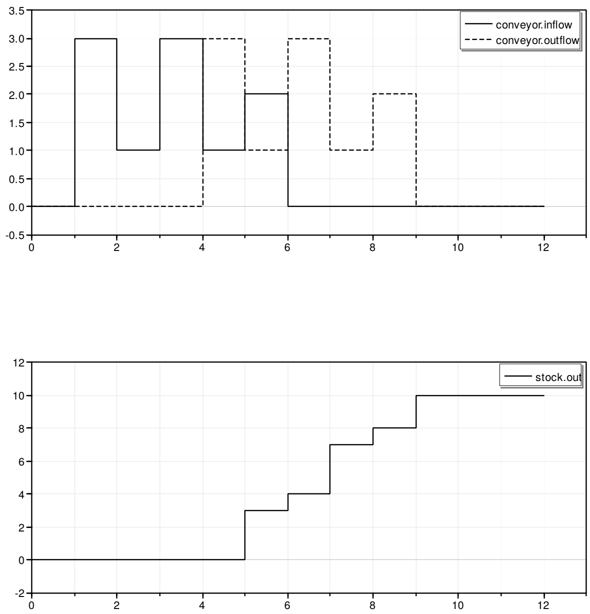

Figure 6: Simulation result of `conveyor`.

The interesting point here is the causality of the outflow: It is completely defined by the conveyor block and simply transported to the following reservoir. The value given by the flow element is disregarded completely. In this example the causality is not changing dynamically, but it has the “wrong” direction – at least compared to the standard situation defined in section 1.

2.3 Modeling a simple manufacturing machine with `Oven`

A particularly clear-cut example is the `Oven`, a discrete model for a generic manufacturing machine. It has the three parameters `initialLoad`, `capacity` and `cookingTime` and behaves like a baking tray: Initially it is loaded according to the input flow, until its capacity is reached. Subsequently the cooking time starts, at the end of which the complete content is forwarded to the output flow. The model `oven1` (cf. fig. 7) shows the basic behaviour of the component, using the parameter values `capacity = 3` and `cookingTime = 2`. The input flow has the constant value 2, the output flow the value 1.

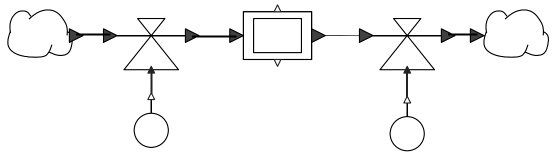

Figure 7: Model `oven1`.

The plot in fig. 8 shows the input and output flow in the upper part and the load of the `oven` in the lower part. At time t = 2 two incoming parts are stored in the `oven`, in the next step only one. At t = 3 the capacity is reached, the processing begins. Afterwards at t = 5 the complete content of three elements is released, while at the same time the next two parts arrive at the input. The concrete timing behaviour, especially the overlapping of output and input, is a matter of definition and is modelled here after the corresponding blocks in the Stella environment.

The size of the input flow depends in a complicated way on the preceding flow element and the state of the `oven`: During the loading phase the value is determined by the flow, until the capacity is reached. The input then is given as the minimum of the input flow and the remaining space in the `oven`. During the processing time the `oven` sets the input to zero. The output flow is defined by the `oven` alone: During loading and processing it is zero and rises to the full value of `capacity` only during a short discharging phase. As in the `conveyor` example the value of the successive flow element is ignored completely.

The situation gets even more complicated if one extends the model `oven1` by reservoirs S_1 and S_2 at the input and output of the `oven`: When S_1 is going to run empty – and has a minimal value of zero –, its output

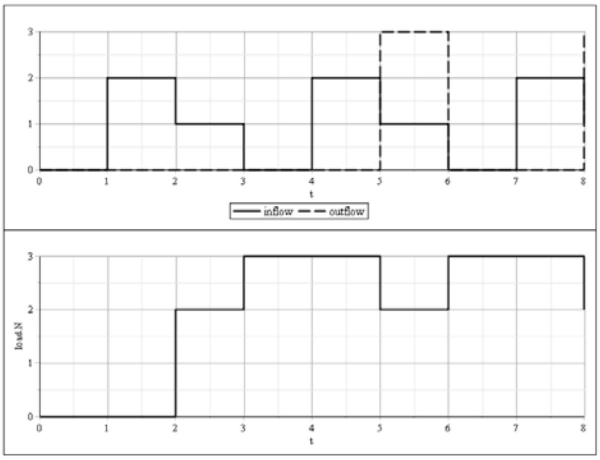

Figure 8: Simulation result of `oven1`.

flow is calculated by its last level, the (maximal) size defined by the flow element and the current state of the `oven`. Fig. 9 shows a typical simulation result for such a case.

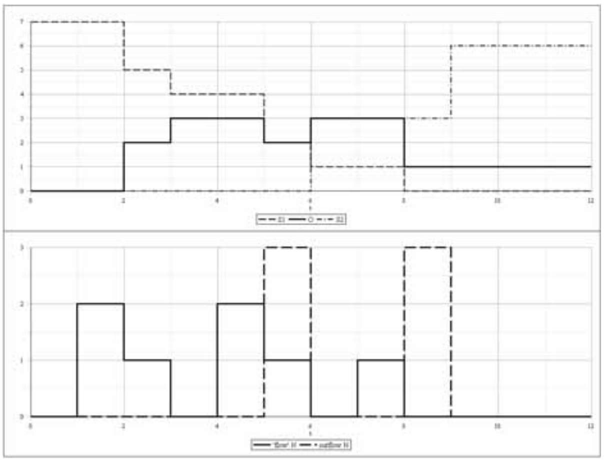

Figure 9: Simulation result of `oven2`.

And if the output reservoir S_2 has an upper saturation limit, the simulation may fail: The `oven` wants to get rid of its content, but the output storage has no room for it. Obviously this is a situation to avoid not only in the simulation.

3 Implementation of a System Dynamics Library in Modelica

3.1 Design of Modelica libraries

Physical modeling environments based on Modelica use a completely different approach to the problem of causality [4]: It is not necessary to determine, which quantities can be defined as input variables and used to compute the values of output variables. Instead one only specifies the relevant equations for a component, without solving each of them for a variable. Additional equations are generated automatically using the connections between the components. For this purpose one distinguishes two types of quantities: Flow variables add together to zero at connection points – they are often the time derivatives of conserved quantities – , whereas potential variables meeting at a connection have the same value.

How to create a simulation program out of the resulting system of equations – generally a DAE system –, is a difficult problem, but has been solved in many cases of practical interest [7]. The corresponding algorithms are implemented in Modelica based simulation programs like Dymola or MapleSim.

The high flexibility that has been reached in Modelica, comes with a price especially for library builders: Since the description of the blocks does not state explicitely where a quantity is computed, it is not guaranteed automatically, that an arbitrary combination of blocks and connections leads to a closed system, having the same number of equations and variables. A remedy for this problem has been presented in [8]: One defines an equal number of flow and potential variables at each connection point (**connector**) and provides each block with as many equations as it has external flow variables. In addition one can augment a block with "common" signal lines that are explicitely designated as input or output. In this case one needs an extra equation in the block for each output variable. Models that adhere to these conditions are called "balanced". Provably they contain an equal number of variables and equations.

3.2 Conception of the connector

These considerations will now be applied to the construction of a system dynamics library in Modelica. Starting point is the definition of a suitable connector `MassPort` that contains the size of the flow as

Modelica flow variable dm, corresponding to its integral, the state variable m. The following two questions have to be solved now:

1. Which quantity can be used as potential variable that accompanies dm?
2. How can the equations be distributed between reservoirs and flows?

Motivated by the basic systematics of system dynamics models that has been introduced in section 1 the integration of the flow shall be done inside a reservoir, which contains the following equation:

```
der(m) = inflow.dm +
outflow.dm;
```

This formulation employs the usual sign convention in Modelica: A flow variable is positiv, when it flows into the block.

Basically a flow block now computes the value of dm using its input quantities. But as section 2 has made clear, it has to take into account the levels of the adjacent reservoirs. Therefore reservoirs have to send the necessary information as a real value data that adopts the role of the potential variable. Considering the examples above there are three different possibilities, how the value of data can be used:

1. not at all, the reservoir simply accepts any value given by the flow,
2. the flow is set to data,
3. the flow is limited by data.

The first case complies with the "standard" causality. The second case corresponds to the situation at the outflow of the conveyor or oven, the third to a reservoir with saturation or the loading of the oven.

This behaviour could be implemented by setting data = 0 in the first case and using the sign of data to distinguish between the other two cases. But this idea has two drawbacks: There is no easy way to implement additional uses of data that could come up in future extensions, and the test for zero with real variables is a bad idea anyway. For that reason the connector will be extended by an integer variable info, which is used to indicate the corresponding case. This variable has a fixed causality: It is always computed by a reservoir and used inside a flow block. Therefore we need two variants of the connector, where info is designated as output or input respectively:

```
connector MassPortR
  "mass port of reservoirs"
  flow Real dm;
  Real data;
  output Integer info;
end MassPortR;

connector MassPortF
  "mass port of flows"
  flow Real dm;
  Real data;
  input Integer info;
end MassPortF;
```

3.3 Structure of the system dynamics library

After these preliminary considerations the further construction of a system dynamics library is straightforward. It consists of the following four subpackages:

- Interfaces
- Reservoirs
- Converters
- Flows

As usual the definition of the connectors, base classes and auxiliary functions are collected in Interfaces. In particular it contains the function constrainedRate that combines the external input value of a flow with the data and info variables of its two MassPorts to compute the actual flow value. This calculation is included in the base class GenericFlow and inherited by all flow components.

The subpackage Reservoirs contains the standard elements Stock and SaturatedStock together with CloudSource and CloudSink, which represent external sources or sinks. Discrete components are the by now well-known Oven and Conveyor supplemented by discrete versions StockD and SaturatedStockD.

All components in the Flows subpackage have two MassPorts to connect to surrounding reservoirs. The basic Flow has a signal input that defines the flow value in standard situations. Additionally the library provides variants with several inputs to implement commonly used simple equations and some elements for discrete simulations.

The elements in Converters exclusively have signal connections, they are defined in Modelica as block, which means that they have a fixed causality. Programs specialised to system dynamics modeling usually have only one converter and one flow block. The actual relations can be defined as parameter values, the number of inputs is adapted automatically. Unfortunately this feature cannot be implemented using Modelica. For this reason the subpackages contain several components that implement the most common relations. A special feature are the two blocks SwitchedConverter and TimeSwitchedConverter, which switch between two inputs according to a control input or the simulation time, and the GraphConverter, which implements a function by linear interpolation between table values that are read from a file. Blocks containing arbitrary relations can be created easily by inheriting from a proper base block and adding a few lines of Modelica code.

4 System Dynamics Diagrams in Simulink

In the signal flow method connections have a fixed causality, which can not change dynamically according to the state of the system. Of course this doesn't imply that one cannot implement models like the examples above, but one has to take care of the causality problems explicitely. In the following some example models in Simulink will show how this can be achieved. A simpler, but less systematic implementation is described in [5].

4.1 Modeling of continuous blocks

As has been described already in section 1 the "standard" situation has a fixed causality. Therefore it is easy to construct corresponding blocks for reservoirs, flows and converters in Simulink and create models like the population example (cf. fig. 10). No external cloud blocks have been included, since they don't represent any equations anyhow.

Unfortunately it is not possible to make the model look more like a system dynamics diagram due to a fundamental restriction of Simulink blocks: All input signals are attached to one side of a block, all output signals to the opposite side. The "upwards" orientation of the flows makes the distribution of lines a bit more pleasant, but in larger examples it is hard to avoid a hay-wire circuitry. The situation gets even worse by the additional lines that are necessary to cope with the

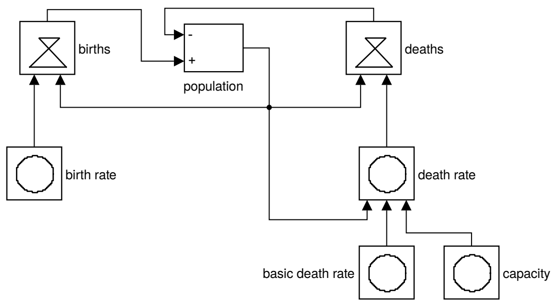

Figure 10: Model population in Simulink.

dynamical causality in the following examples.

For the implementation of a reservoir with saturation we can resort to the ideas used in Modelica before: A reservoir gets two additional outputs to signal the following flow block, when it is empty, and the preceeding flow block, when it is full. A flow block has two corresponding inputs that are connected to the surrounding reservoirs.

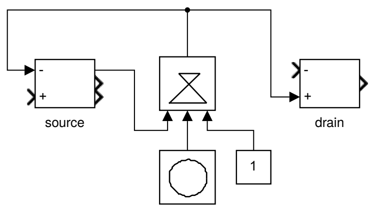

Figure 11: Model sink in Simulink.

Fig. 11 shows how this idea is used in the model sink. For simplicity the drain is realised as a simple stock without saturation. The corresponding flow input has the constant value 1 to indicate that the flow can be delivered, otherwise it would be 0. This makes the implementation of the flow block very simple: It just multiplies its three inputs.

4.2 Modeling of discrete blocks

In a discrete model a reservoir with saturation behaves differently than in the continuous case: Due to the fixed time step the inflow can be limited by the space available or the outflow by the current level. Therefore the two outputs that correspond to the data value of the Modelica connector will provide the maximal and minimal values possible instead of simply 1 or 0 as in the continuous case.

The discrete version of the flow block has to be changed accordingly: Instead of just multiplying its three inputs, it now takes their minimal value. If a connected reservoir has no saturation the unconnected data input of the flow needs a constant value of `Inf` (i.e. infinity) instead of 1. With these modifications a Simulink version of the `oven2` example with a limited reservoir at the input looks like fig. 12.

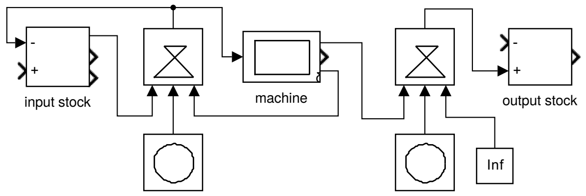

Figure 12: Modell `oven2` in Simulink.

But there is another feature still missing: The oven defines the output flow, irrespectively of the value proposed by the following flow block. One could implement this behaviour by adding another signal from the reservoir to the flow mimicking the info value in Modelica, but this would clutter the diagram with even more lines. Instead the flow block gets a boolean parameter `useFlow` that is set to `false` manually, if the flow is preceded by an `oven` or a `conveyor`. Fig. 13 shows the complete implementation of the discrete flow block. Now the model `oven2` reproduces the results of the equivalent Modelica example exactly.

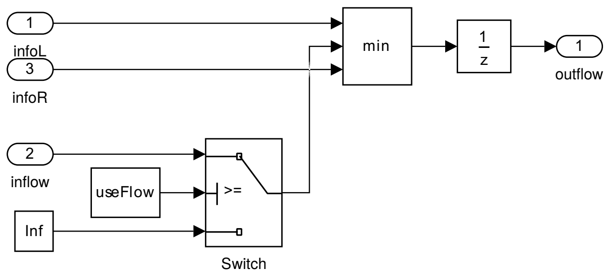

Figure 13: Implementation of the discrete `flow` block in Simulink.

The implementation of the `oven` component itself is cumbersome but straightforward, it uses three `UnitDelay` blocks representing internal variables and mimics the Modelica code completely. Alternatively one could use an S-function to program the `oven` directly in Matlab.

In contrast the `conveyor` is completely trivial, it just consists of an `Integer Delay` block. But it shows an interesting difference to its Modelica counterpart: To achieve a three step delay one sets the internal parameter to three (obviously), but in the Modelica case, which uses an array together with the `pre` operator and a `while sample()` construct, one has to set the parameter to four to get the same result. Apparently the detailed timing of an event is handled differently in Modelica and Simulink.

Though all example models have been successfully implemented in Simulink, the results lack the simplicity and flexibility of the Modelica version. This is only partly due to the dynamic causality, but mainly – and trivially – to the restrictive placement rules for connections on Simulink blocks.

5 Conclusions

The development of a flexible system dynamics library is much easier using the dynamic causality of physical modeling environments. Nevertheless it is possible to mimic it completely in Simulink using a larger number of signal lines between the blocks. Reversing the argument one could define the flow and potential variables in the `MassPort` connectors with a fixed causality, since `dm` is always computed in a flow, `data` in a reservoir. This shows that the idea of “dynamical causality” in system dynamics diagrams is mainly a matter of convenience and depends on the definition of “one connection”.

In modeling courses a presentation of the ideas behind the two different implementations will clarify the notion of causality and broaden the modeling skills of the students. An interesting point here, which will need further clarification, is the different behaviour of the `pre` operator in Modelica and the 1/z block in Simulink.

Compared to dedicated system dynamics environments users of the Modelica library have to cope with limitations of their tools. A main point is the missing of the feature to input formulas directly as parameters. Even if components for the most common relations are provided and more can be created by a few lines of Modelica, the typical user of system dynamics software has little intention to write explicit code. In any case the Modelica library presented here is a simple and cheap replacement for specialised tools - at least for teaching purposes.

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Toward Useful System Dynamics Models of Physician Reimbursement and Population Health

Patrick Einzinger

Inst. of Analysis and Scientific Computing, Vienna University of Technology, Wiedner Haupstraße 8-10, 1040 Vienna, Austria; *patrick.einzinger@tuwien.ac.at*

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Abstract. System dynamics models are widely used for applications in health care. Modelling of different reimbursement systems is a comparatively new field of application. This paper tries to identify the core dynamic structures and feedback loops that drive such models. We created a simplified model of physician reimbursement that includes the interaction between patients, their disease state, and the pressures on physician behaviour from reimbursement and their workload.
Several simulated scenarios show that its behaviour is plausible and in line with theories on the influence of different reimbursement systems.

Introduction

In the past, system dynamics (SD) has found many areas of application. Health care is one example. Homer and Hirsch [1] list various health care topics where system dynamics has been applied, from disease epidemiology and drug addiction to patient flows in emergency departments and health care capacity planning.

They also suggest that system dynamics could be helpful in creating more complete models of population health, which might incorporate multiple interacting diseases.

One field of study where no standard modelling approach has been established yet is the analysis of different reimbursement systems for providers of health care.

Models in this area of application should answer the question of which schemes of payment for doctors are optimal and what possible consequences of each scheme could be. They must be able to incorporate, for example, the influence of reimbursement on treatment decisions and health consequences for patients. All diseases that lead to the consumption of health services play a role in this problem (not just one as in typical decision-analytic modelling of isolated health care interventions), which makes it even harder to deal with.

First applications of simulation modelling of physician reimbursement include a system dynamics model of group practices [2] and an agent-based model for the study on per case flat rates in the extramural health care sector, the GAP-DRG model [3]. In this paper, we investigate the core dynamic structures that drive those models. Every epidemic model, for example, uses the positive feedback loop caused by more infectious people infecting even more additional individuals who in turn become infectious, even though implementation can differ depending on the modelling method.

It would be beneficial if such core dynamic structures could be also identified for health care reimbursement systems. We use the structured modelling process of SD in order to create a simplified model of physician reimbursement that includes the interaction between patients, their disease state, and the pressures on physician behaviour from reimbursement and their workload. The focus lies on the dynamic structure. Parameters are set to plausible values, but not parametrized from data.

Note. This article is a revised and shortened version of Chapter 6 of the author's PhD thesis [4].

1 Problem and Textual Model Description

A good modelling study starts with a description of the problem or research question that should be answered. In the case of reimbursement systems in extramural health care, one of the central questions is how different reimbursement systems influence the amount of provided health services, the quality of service, and the costs for the payer as well as how an optimal reimbursement system should be designed. According to Czypionka et al. [5], most of the theory of optimal service reimbursement is based upon the work of Ellis and McGuire [6], who develop an analytical model and derive conclusions from solving for an optimum of the physicians' utility function, which includes their profit (more specifically, the profit of the hospitals where they are employed) and the benefit to the patients.

Such models do not study dynamic behaviour and how physicians react over time to potentially changing pressures in the system. Physicians' treatment decisions can produce feedback by changing the future need of the patients, which in turn influences their decisions (e.g., if their workload changes). Therefore, dynamic simulation models might add additional insight to the already available theory. The central research question is thus which dynamic behaviour physician's choice of service extent shows under different reimbursement systems and how it influences patient health (i.e., which quality is achieved).

It follows that a model must include at minimum the health state of the population, its influence on the physicians and their treatment decisions (which amount of services they provide), and the feedback of the treatment to the health of the population. There are many different factors influencing medical decision making [7], but we focus on two of them, physician income and workload.

1.1 The health of the population

Consider a fixed population of n individuals. People with good health are part of the *healthy population* (HP). They may become symptomatically ill with an *average incidence rate* (IR), which depends on a *fractional incidence rate* (fir) after which they belong to the *sick population seeking treatment* ($SPST$). In this state, individuals are in need of medical treatment and will consult physicians.

Patients who get *successful treatments* (ST) become healthy again. However, there are also *unsuccessful treatments* (UT) that do not fully cure them. Such individuals are then part of the *latently sick population* (LSP). As such, they do not immediately need medical treatment, but after *relapses* (R), which take on average the *time to relapse* (ttr), they become again *sick population seeking treatment*.

This model structure keeps track of diseased individuals. It also allows that they stay ill without immediately seeking treatment. However, the kind of disease or the occurrence of multiple parallel diseases are not considered. Furthermore, the model does not explicitly keep track of chronic diseases that may never heal. These simplifications are due to the focus on dynamics instead of detail, which could be added in later modelling steps but would complicate the models in a first step and thus hinder insight.

What is new in this model structure, compared to the models in [2] and [3], is the possibility of taking quality into account. Higher quality manifests in a higher *fraction of success* (FOS) of treatments. In the GAP-DRG model, medical services have no influence on patients' state of health, and the group practice model does not consider the health of the patients explicitly.

1.2 Cases and services per doctor

Persons in the *sick population seeking treatment* generate a certain amount of *cases* (C) for physicians per day at a *case rate per person* ($crpp$). For every case, an individual changes his or her state to either healthy or latently sick.

1.3 Workload and reimbursement

It is assumed that the more services per day a physician has to perform the higher his *workload* (W), which is measured relative to a *standard service volume* (ssv), is. However, doctors do not instantaneously adapt their *perceived workload* (PW), upon which their reactions are based, but only after a certain *time to perceive workload* ($ttpw$).

In general, reimbursement is some mixture of per case flat rates and fee-for-service payment. The *reimbursement per doctor* (RPD) thus consists of the *case reimbursement* (CR), which is calculated from the *cases per doctor* and the *per case flat rate* ($pcfr$), and the *service reimbursement* (SR), which equals the *services per doctor* times the *average service tariff* (ast).

Again, doctors adapt their *perceived reimbursement* (PR) after a certain *time to perceive reimbursement* ($ttpr$). The *normalized reimbursement* (NR) is then the reimbursement relative to some *standard reimbursement* (sr).

1.4 Service extent and its influence on the success of treatment

The service extent measures how many services doctors provide relative to the true service need per doctor. Thus, values under 1 correspond to under-provision and value above 1 to over-provision of services.

Both the perceived reimbursement and workload of a doctor influence his or her service extent. If both assume their standard values they exercise the *standard effect of reimbursement on service extent* ($serse$) and the *standard effect of workload on service extent* ($sewse$). In this case, the *effect of reimbursement on service extent* ($ERSE$) and the *effect of workload on service extent* ($EWSE$) both assume the value 1. If reimbursement increases, its effect on *service extent* decreases, because doctors do not have to work as much to reach their target income. Furthermore, if workload increases, its effect on *service extent* also decreases, because doctors try to spend less time on each patient to reduce their workload.

The model assumes that there is both a *positve effect of service extent* ($PESE$) and a *harmful effect of service extent* ($HESE$). If the service extent equals 1 the *fraction of success* equals the *optimal fraction of success* ($ofos$). A lower service extent decreases the *positive effect of service extent*, because doctors do not provide all necessary services. Conversely, a higher service extent leads to a *harmful effect of service extent*. In both cases, the resulting *fraction of success* will be sub-optimal.

2 Feedback in the Model

The described structure includes several feedback loops. Figure 1 shows a simplified causal loop diagram of the model.

The most obvious feedback loops B1 (Target Income) and B2 (Desired Workload) are balancing loops through service extent and reimbursement or workload:

Balancing loop B1 (target income)

The more services per case doctors provide, the higher the reimbursement. When they perceive an increase in reimbursement they in turn reduce their service extent.

Balancing loop B2 (desired workload):

In the same manner as with reimbursement, doctors who perceive an increased workload decrease their service extent.

There is also a reinforcing loop R1 (Prevention), which involves the health of the population and the positive effect of service extent on the fraction of success. On the other hand, B3 (Bad Treatment) is another balancing loop and involves the harmful effects of overtreatment.

Reinforcing loop R1 (prevention)

If service extent increases and more individuals become healthy through the positive effects of service extent, physicians' workload and reimbursement decrease, because future cases are prevented. Thus, they have more time and motivation to increase their service extent. Note that this feedback loop is only active if the service extent is below the optimal level.

Balancing loop B3 (bad treatment)

This feedback loop, on the contrary, becomes active if the service extent is above the optimal level. The harmful effects of services increase and thus more people become latently sick. In the long term, this leads to more relapses and more cases. Workload and reimbursement increase, which provokes a decrease in service extent.

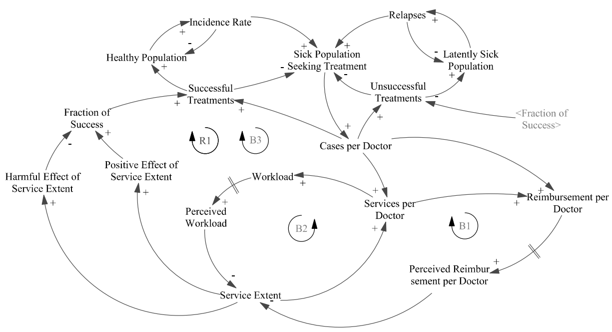

Figure 1: Simplified causal diagram of the physician reimbursement model.

3 Stock and Flow Structure

After the creation of a causal diagram, it is necessary to determine which variables are stocks or flows. The model mainly includes the stocks of healthy individuals, sick individuals seeking treatment, and latently sick individuals. It follows that flows are the variables that influence these stocks.

Physicians perceive their workload and reimbursement only with a delay (they average the input over time). If these delays are, for example, first order exponential delays, then their implementation also involves a stock. Thus, the model includes three explicit and two implicit stocks. For a detailed description of model equations and parameters, see [4]. Plausible values based on educated guesses were chosen for the parameters.

Initial values for the stocks in the model are also necessary. For a theoretical analysis, a useful assumption is that the system should be in equilibrium, where the in- and outflows to each stock cancel each other out. This leads to an equation system, which was solved in order to derive the equilibrium values for stocks and delays (see Table 1).

Variable/Parameter	Equilibrium Value	Unit
Healthy Population	85 628.44	Person
Sick Population S. Treatm.	10 015.02	Person
Latently Sick Population	4 356.53	Person
Standard Reimbursement	560.84	Euro/(Doctor*Day)
Standard Service Volume	60.09	Service/(Doctor*Day)

Table 1: Equilibrium values for the physician reimbursement model.

4 Simulation Scenarios

4.1 Base run

In the base run, the model is in equilibrium and thus all variables stay at their equilibrium values. Normalized reimbursement as well as perceived workload are constantly 1.

4.2 Per case flat rates

Per case flat rates do not reimburse single services, but only cases. The average service tariff, ast, is therefore zero in this scenario. On the other hand, the per case flat rate, $pcfr$, must be higher to compensate for the missing service reimbursement. We set it to 56 euros, because this equals the assumed per case flat rate in the base run (20 euros) plus the assumed average service tariff (6 euros) multiplied by the service extent in equilibrium (1.2) and the service need per case (5).

The second effect is that now the service extent does not have a direct influence on reimbursement. Therefore, it does not make sense for a physician to increase it in order to receive more payment (or decrease it if he or she has more than enough). This cuts the causal loop B1 (Target Income), such that the effect of reimbursement on service extent is always 1, which lowers the service extent in comparison to the base run (where standard service extent is 1.2).

Figure 2 and Figure 3 show the results for the sick population and physician reimbursement, workload, and service extent. Only the perceived workload influences the service extent, so it is below the optimal value instead of too high as in the base run. Thus, the doctors provide fewer services to the patients, and their perceived workload decreases. In turn, they increase the service extent slightly. Additionally, the new level of the service extent is more beneficial to the patients than it is in the base run, which causes the number of latently sick patients to drop.

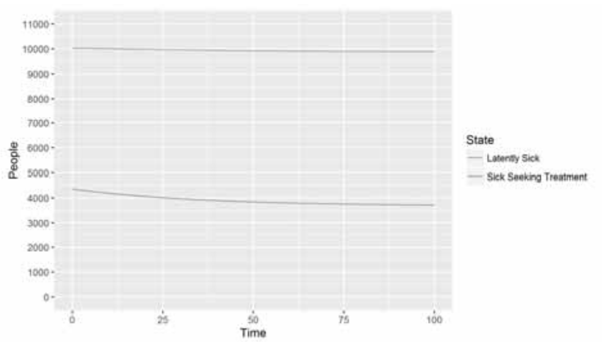

Figure 2: The number of persons who are sick seeking treatment or latently sick in the scenario with per case flat rates as the reimbursement system.

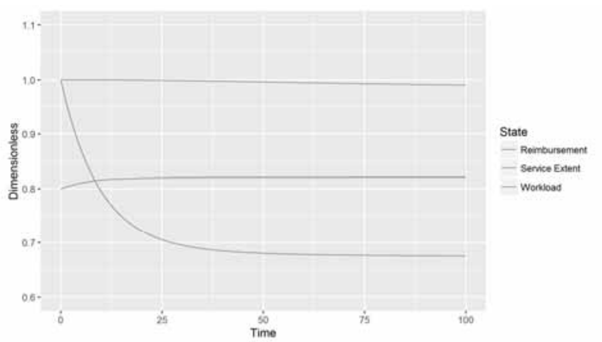

Figure 3: Normalized Reimbursement, perceived workload, and service extent in the scenario with per case flat rates as the reimbursement system.

4.3 Increase of incidence rate

An important test of system behaviour is the reaction to a certain change of an input or a parameter. In this scenario, we assume that the fractional incidence rate doubles from 0.01 to 0.02 after 10 days, which leads to far more individuals getting sick (e.g., during a pandemic).

Figure 4 and Figure 5 show the results. As expected, the number of sick individuals seeking treatment increases sharply after the change in the fractional incidence rate. It saturates at a bit more than 17 thousand. The latently sick population increases nearly linearly.

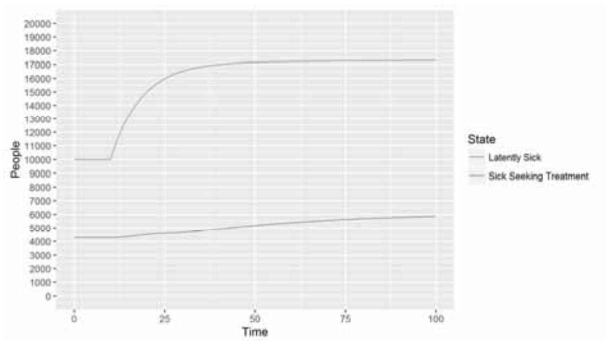

Figure 4: The number of persons who are sick seeking treatment or latently sick in the scenario where the fractional incidence rate changes from 0.01 to 0.02 after 10 days.

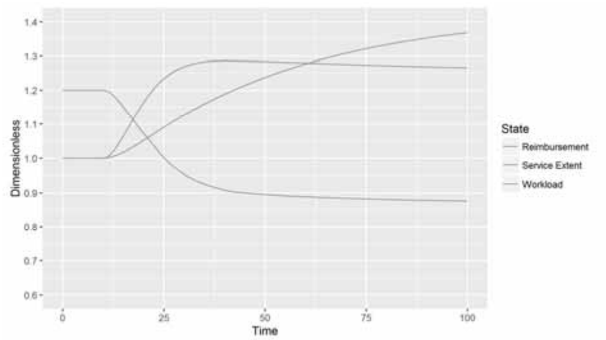

Figure 5: Normalized Reimbursement, perceived workload, and service extent in the scenario where the fractional incidence rate changes from 0.01 to 0.02 after 10 days.

As a result, the perceived workload and reimbursement of the doctors also increase sharply. This causes them to lower the service extent. At about time 50, the perceived workload starts to decrease again.

4.4 Increase of incidence with per case flat rates

Reimbursement with per case flat rates can potentially change the reaction of the system to a higher incidence rate in the population. Thus, this section studies a scenario with both a higher incidence rate and per case flat rates for reimbursement.

Figure **6** and Figure **7** show the corresponding results. The perceived workload of the doctors drops initially because of the lower service extent, which is provoked by the different reimbursement system. However, the perceived workload (and the reimbursement) increases sharply after the change in incidence.

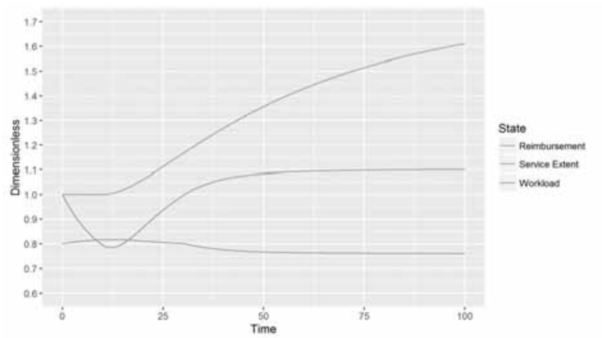

Figure 6: The number of persons who are sick seeking treatment or latently sick in the scenario with an increase in the fractional incidence rate and a per case flat rate reimbursement system.

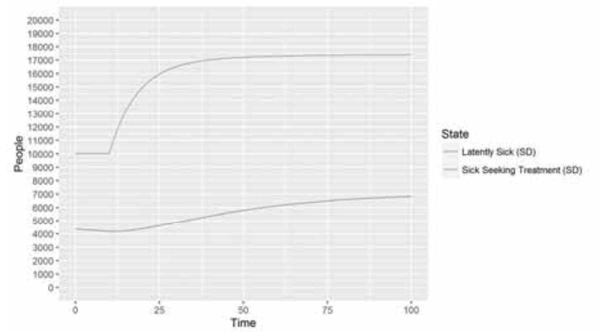

Figure 7: Normalized Reimbursement, perceived workload, and service extent in the scenario with an increase in the fractional incidence rate and a per case flat rate reimbursement system.

This causes service extent to decrease even more. Thus, the treatment is worse than it was in the last section. As a consequence, there are about a thousand more latently sick individuals at the end of simulation than without the per case flat rate reimbursement system. This shows that under the assumptions of the models, the system reacts better under the mixed system of per case flat rates and single service reimbursement.

5 Conclusions

The physician reimbursement model depicts the most important properties of both the GAP-DRG and the group practice model. It incorporates epidemiology (people who develop diseases) as well as physician behaviour based on their workload and their reimbursement, which depends on the applied reimbursement system. However, the model was built to be as simplified and abstract as possible in order to favour dynamic complexity over detail complexity. This facilitates the utilization of the SD modelling process, although it is possible to transform the result into an equivalent agent-based model (see [4]).

The simulation results are plausible and in line with theories on physician behaviour. However, the identification and quantification of the causal effects that are part of a feedback structure from observational data will be a further important area for future research. Robins and Hernán [7] present causal inference methods that allow for the analysis of the causal effect of a time-varying exposure on an outcome, where the exposure is allowed to depend on the former values of measured covariates and vice versa, that is, exposure and confounders form feedback loops. Such methods might therefore also prove valuable for the parametrization of system dynamics simulation models such as the one presented in this paper.

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Treatment Strategies for the Prevalence of Obesity in Austria Modelled with System Dynamics

B. Glock[1*], P. Einzinger[1, 2]

[1] dwh simulation services, dwh GmbH, Neustiftgasse 57-59, 1070 Vienna, Austria; *barbara.glock@dwh.at

[2] Department of Analysis and Scientific Computing, Vienna University of Technology, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria

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Abstract. In Austria, especially among children, the prevalence of obesity has increased since 1999. Therefore, a System Dynamics model, simulating the prevalence of obesity, has been developed. The modular architecture allows separate analysis of the model parts and also adding and connecting different modules, like for example a cost module or a module for an obesity-related disease to the existing population model and the disease model of obesity. Three interventions, treating obesity with an increase in caloric expenditure and/or a reduction of caloric intake, are tested, analysed and compared. The results show that a reduction of caloric intake reduces the prevalence of obesity and overweight until 2050 (intervention 1). Furthermore, a reduction for the doubled amount of kilocalories per day doesn't have the doubled effect on the reduction of the prevalence (intervention 2 compared to 1). Last, but not least, intervention 3 compared to intervention 2 shows that physical activity together with a reduction of caloric intake reduces the prevalence much more than a single reduction of caloric intake in the amount of kilocalories due to physical activity and eating less together.

Introduction

Obesity is a health concern of paramount importance. Especially in Austria more than one third of the population is obese or overweight and not only the adult population suffers from this disease, but also children [1]. It has long list of co-morbidities such as orthopeadic problem or cancer. Obesity is measured by the *Body Mass Index* (BMI) that is calculated by dividing body mass in kilogram through the square of body height in centimetre, as seen in equation (1).

$$BMI = \frac{body\ mass\ [kg]}{body\ height^2\ [cm]} \tag{1}$$

The main classification for adults according to the World Health Organization [2] is shown in Table 1.

Classification	BMI
underweight	< 18,50
normal weight	18,50 – 24,99
overweight	25,00 – 29,99
obese	≥ 30,00

Table 1. Classification of obesity and overweight according to the WHO [2] measured through the BMI.

For children the percentiles of the reference curves according to Kromeyer-Hauschild [3] are used and therfore the classification is slightly different.

The model's architecture is modular consisting of a population module that simulates the demographic development and of a disease module simulating the prevalence of the disease over time. Furthermore a connection in eating and physical activity habits of children to that of their parents is implemented as well [4].

There are three interventions that are compared:

1. A **reduction of the caloric intake of 80 kcal/day** in the adult obese and overweight population
2. A **reduction of the caloric intake of 160 kcal/day** in the adult obese and overweight population
3. A **reduction of the caloric intake of 80 kcal/day** and an additional increase in physical activity by an **increase of caloric expenditure of 80 kcal/day** in the adult obese and overweight population

It is researched if a reduction of the doubled amount of caloric intake reduces the prevalence of obesity twice as much (comparison of 1 and 2). Also the effect of physical activity in comparison to the effect of a reduction of caloric intake is evaluated (2 compared to 3).

1 Method: System Dynamics

System dynamics was originally developed in 1951 by J. Forrester [5] who used this top-down modelling technique for complex management systems. He furthermore applied this technique to social systems and used it to simulate complex causal links.

It is a graphic notation and is based on differential equations. Basically, the population is divided into *stocks* that are connected by *flows*. Each stock represents a differential equation in accordance to time *t*. These flows, going in or out of the stock are regulated through a valve that can be dependent on *parameters* or stocks. Additionally *auxiliaries* can be used to represent algebraic equations. A very simple stock and flow diagram can be seen in Figure 1.

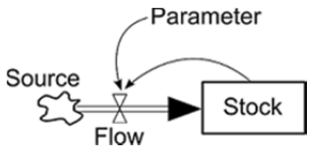

Figure 1. A simple stock and flow diagram. The flow is dependent on the stock and a parameter, represented by the smaller arrows.

Sources are the boundaries of the system. This small example can also be written as the differential equation as seen in equation (2) and (3).

$$\dot{Stock}(t) = Flow\,(t) \tag{2}$$
$$Flow(t) = Parameter\ \cdot Stock(t) \tag{3}$$

These differential equations can also be written as integrals and each stock represents the state of the system. The example in Figure1 can be interpreted as the stock being a population, where in accordance to the fertility rate (being the parameter) births (being the flow) increase the population. The births are calculated by multiplying the fertility rate with the stock.

2 Architecture of the Model

The model is set up **modular**. This means that a *population model* is used for the simulation of the demographic development of the population. A *disease model* simulates the development of obesity over time until 2050. These two parts are connected by a special defined *interface*. This modular setup is very useful, because error analysis is much easier. Other required model parts for cost calculation or co-morbidities can be connected through special defined interfaces.

2.1 Population model

The population is divided into 192 stocks for 96 age classes (0-94, 95+) and two sexes (male, female). Each stock can be changed by flows for *aging*, *death* and *migration*. The stock of the age class 0 additionally can be changed by flows of *births*, as seen in Figure 2.

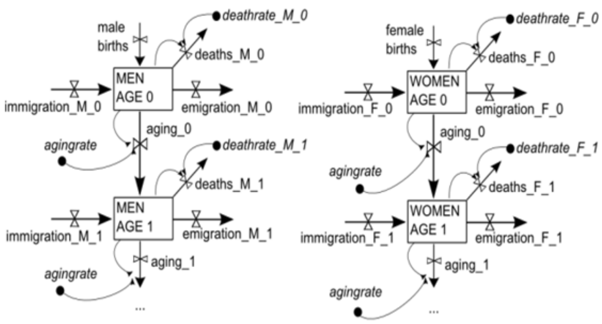

Figure 2. Structure of the population model.

The deaths are dependent on the death rate and the connected stock, which can be seen by the small arrows pointing at the valve of deaths. Migration, on the other side, is not dependent on the size of the population and is given as a net in- respectively out-flow. The births are calculated by multiplying the one-year age specific fertility rates with the stocks of fertile women (aged 15-45). This calculation is not shown in this figure, except for the already calculated total *births (male births, female births*).

The data is provided by Statistics Austria [6]. For death rates r the death probabilities p from death tables (regular tables for 1999 until 2010 and prognostic tables for the years 2010 until 2050) are used and transformed into rates as seen in equation (4).

$$r = -\ln(1-p) \tag{4}$$

The birth rates are given as one-year *age specific fertility rates*, being the number of total life-births per 1.000 women for the years 1999 until 2010.

For the forecast years 2011 until 2050 there are only the estimated *total fertility* rate, being the number of children a women would birth in her life, if there are the same fertility conditions in her future life as they are now, and the estimated *average fertility age* available. These are used to calculate an estimation of the one-year age specific fertility rates for the forecast years. Data for migration is also provided and estimated by Statistics Austria.

2.2 Disease model

The demographic development is calculated in the population model. Therefore the development of the disease itself is calculated in the disease model. The population is split into ten age classes, sex (because there are differences in the basal metabolic rates for men and women) and the four BMI categories representing the severity of obesity. This means that people can only change between stocks within one age class and sex of adjacent BMI categories as seen in Figure 3.

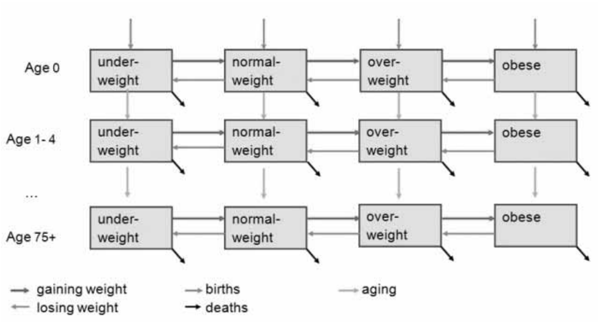

Figure 3. Flows between adjacent BMI categories in the disease model.

The rates, regulating the amount of the flows, stay constant in the base run and change in 2010 if an intervention is tested. An intervention only calculates *caloric* changes. Therefore, the core part of the disease model is the translation of *changes in energy balance* within a stock to *changes of rates* between the BMI-categories between the stocks.

The energy balance is calculated by energy intake minus energy expenditure. The Energy intake is calculated by the kilocalories taken in by eating food or drinking beverages. The energy expenditure EE is calculated as shown in equation (5).

$$EE = BMR + TEF + PA \tag{5}$$

The basal metabolic rate (BMR) depicts the energy the body needs to maintain the basal functions each day at indifference temperature of 28 degrees Celsius and with empty stomach. The estimation of the BMR requires age, weight, height and gender of the person. The Revised Harris-Benedict equations [7] shown in equation 6 and equation 7, are used.

The factors for weight and height are larger for men than for women resulting in a larger BMR for men than for women. The thermic effect of foods (TEF) is the energy that is used to process the food a person eats (usually 10% of the value of caloric intake). Physical activity (PA) also contributes to the energy expenditure.

$$BMR_{Men} = 88{,}362\ kcal + \left(13{,}397\ \frac{kcal}{kg} \cdot \boldsymbol{weight}\ [kg]\right) + \left(4{,}799\ \frac{kcal}{cm} \cdot \boldsymbol{height}\ [cm]\right) - \left(5{,}677\ \frac{kcal}{year} \cdot \boldsymbol{age}\ [years]\right) \tag{6}$$

$$BMR_{woman} = 447{,}593 kcal + \left(9{,}247\ \frac{kcal}{kg} \cdot \boldsymbol{weight}\ [kg]\right) + \left(3{,}098\ \frac{kcal}{cm} \cdot \boldsymbol{height}\ [cm]\right) - \left(4{,}330\ \frac{kcal}{year} \cdot \boldsymbol{age}\ [years]\right) \tag{7}$$

Each stock in the disease model has an average ener-gy balance, calculated as mentioned above. The energy balance in 1999, at simulation start, is given and then used to calculate the change of energy balance (ΔK) throughout the simulation, which is then transformed into a *change of rates* (ΔF) between the BMI-categories as seen in equation 8.

$$\Delta F = MAX\left\{0;\ 0{,}5 \cdot \frac{\Delta K}{(b_c - b_m) \cdot (h_m)^2 \cdot k} \cdot \frac{365}{12}\right\} \tag{8}$$

This equation was adapted from a paper by Homer et al. [8] and includes the BMI-cut-off points b_c to the adjacent BMI-category, the average BMI b_m in each category, the average height h_m in each sex, age class and BMI-category specific stock and furthermore, an empiric estimation of the average kilocalories per kilogram of weight-change k (8.050 kcal/kg) according to Forbes [9].

There is a correlation between energy intake and energy expenditure from parents to that of their children. Therefore, a weighted average of energy expenditure, respectively energy intake, over all parentsages (19-64 years) and severity degrees is calculated. The percentage of the caloric change during simulation to the initial value in 1999 is then translated to a change in the energy expenditure, respectively energy intake, within the age classes of the children (0-18 years). For example, if the energy intake of parents increases for 2% then the energy intake of children will increase for 2% as well. This average over all age classes and BMI-categories is used, because there is no data available on how many adults, categorized by their BMI, actually do have children at a specific age.

The weighting of this average value is done in a manner that 'younger' parents with probably 'younger' children have a greater influence on their children than 'older' parents do have on their 'older' children. Furthermore, the percentage of, for example, overweight parents having overweight children is not known as well.

There are two kinds of rates between the BMI-categories, the *upflow rates*, calculating the change of stocks from a lower BMI-category to a higher BMI-category, and the *downflow rates*, calculating the change of stocks from a higher BMI-category to a lower BMI-category (see Figure 3). During the simulation these rates are changed in a manner that was mentioned before by matching the change of energy balance to a change of rates. This means that an initial value of the rates has to be provided. There was no data on changes of weight within a year for the Austrian population available that would describe weight gaining or weight losing. Therefore the downflow rates are estimated out of data from the National Health and Nutrition Survey (NHANES) [10] from the USA. This dataset includes person specific data for age, weight, height, sex and, most important, for the estimated weight one year ago. Out of this data the BMI and the BMI one year ago can be calculated and used for an estimation of the rates for a downwards BMI-category change. The upflow rates in the model were then calibrated. A dataset depicting the state of the system, meaning the distribution of BMI-category within the population in 2006/2007 [11], was used for minimizing the objective function, the difference between the simulated prevalence of obesity in Austria and the actual prevalence in 2006/2007.

2.3 Interface

The population model and the disease model are connected by an interface that calculates the changes of the stocks due to births, aging, migration and deaths in the population model and transfers them to the stocks of the disease model. The structure of the population model differs from the structure of the disease model. The first one has 96 age classes, 2 sexes and no difference in BMI-category, whereas the latter one has only 10 age classes, 2 sexes, but 4 BMI-categories. Therefore, the changes of the stocks in the population model are aggregated for each sex according to the age classes in the disease model. Then they are split up into the stocks of the BMI-categories in the disease model within this age class and sex.

This is done in a manner that the distribution of the BMI-categories of the changes from the interface show the same distribution of BMI-categories as in the disease model: If there are 50% people normal weight and 20% overweight in the disease model at this time, then the changes of the stocks of the population model are split up and 70% are transferred to the stock of normal weight people and 20% are transferred to the stock of overweight people.

In this model there is no connection from the disease model back to the population model, since no obesity-related deaths are simulated. The reason for that is that there are no direct obesity related deaths. Usually no one dies because of overweight, but sometimes because of obesity *associated* diseases, like problems with the heart. The modular setup allows coupling other model parts simulating co-morbidities. If such a model part, simulating an obesity associated disease, is connected, it is possible to redefine the interface or to define an interface from that model part to the population model and then allow informationflows to the population model and also simulate disease related deaths.

3 Results

The base run shows an increase in the prevalence of obesity and overweight in 2050. According to the simulation there are 338.110 obese male aged 19-64 in 2050, whereas in 1999 there were 217.983 obese male people. Within the female adult population the number increased from 198.933 in 1999 to 326.361 in 2050. Of course this result includes the demographic development as well, but there is still an increase of the prevalence of obesity within the relative numbers.

3.1 Intervention 1: Reduction of caloric intake for 80 kcal per day

If there is a reduction of the caloric intake for 80 kilocalories per day starting in 2010 within the adult obese and overweight population, there is a reduction of the prevalence of obesity and overweight in 2050. The comparison of the base run to intervention 1 is shown in Figure 4 for the obese male and female population together. The results are depicted for some age classes and the vertical axis shows the absolute number of obese people in 2050.

3.2 Intervention 2: Reduction of caloric intake for 160 kcal per day (doubled amount)

In intervention 2 the caloric intake is reduced for 160 kilocalories per day in the obese and overweight adult population. Due to the fact that a dependency between adult eating behaviour and that of children is implemented, a decrease of the caloric intake in adults also reduces the caloric intake within children. The prevalence of obesity and overweight reduces as well as in intervention 1, but the effect of the reduction compared to the effort of reducing the caloric intake for twice as much, is for intervention 2 smaller than for intervention 1, as seen in Table 2.

	Intervention 1 vs. base run	Intervention 2 vs. base run
Children 2 - 18 years	-32%	-44%
Adults 19 - 64 years	-18%	-31%

Table 2. Comparison of the reduction of the prevalence of obesity due to intervention 1 to that due to intervention 2.

In intervention 1 the prevalence of obesity was re-duced for 32% within children, whereas in intervention 2 only a reduction of 44% can be shown, both compared to the base run. This effect is not twice as much as the effort of reducing the doubled amount of caloric intake.

This means that the effect of a decrease of the prevalence of obesity, and it is the same for overweight, reduces relatively to the effort.

3.3 Intervention 3: Reduction of caloric intake for 80 kcal per day and additional increase of physical activity for the amount of 80 kcal per day

In intervention 3 the caloric intake is reduced for 80 kilocalories per day for the obese and overweight population together with an increase of physical activity of the amount of 80 kilocalories of energy expenditure per day. This means that each day people have 160 kilocalories less than they have in the base run. This looks like it is the same reduction of calories as in intervention 2. A comparison of intervention 2 and 3 show that the prevalence of obesity in intervention 3 is reduced as well, but, as seen in Figure 5, additional physical activity instead of eating less has a larger effect on the prevalence of obesity. The prevalence of obesity in intervention 3 is slightly more reduced than the prevalence of obesity in intervention 2.

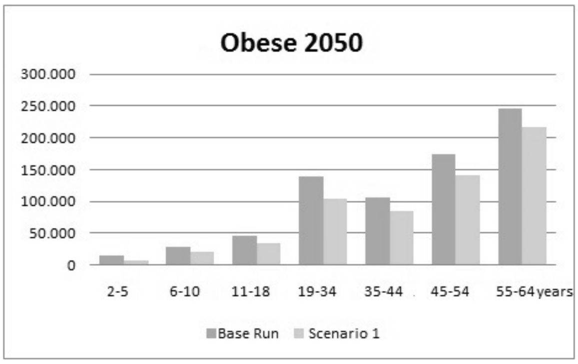

Figure 4. Prevalences of people with obesity in base run compared to intervention 1.

Figure 5. Prevalences of people with obesity in intervention 2 compared to intervention 3 for some age classes.

The reason why intervention 3 has a better effect is the thermic effect of foods: by eating more in inter-vention 3 the thermic effect of foods is higher than that in intervention 2 and therefore the energy balance is reduced slightly more by the thermic effect of foods, although the overall reduction of kilocalories, by physical activity or eating less, is in both interventions the same.

4 Validation

There are a lot of different methods that can be used to validate a model, but nevertheless, a model will never be validated for 100%. In this case there are two validation methods used, a *cross-model* validation for the population model itself and a *probabilistic sensitivity analysis* for the disease model.

4.1 Cross-model validation

The results of the population model are compared to the prognosis data of Statistics Austria and the difference in 2050 is less than 3.3% [4]. This means that the validation of the population model via another model is acceptable.

4.2 Probabilistic sensitivity analysis

A probabilistic sensitivity analysis (PSA) is done for the parameters of the up- and downflow rates which are the parameters with the biggest uncertainty due to the fact that they are partially calculated out of the NHANES study and partially calibrated. The PSA is done in the following way:

- For each of the 120 parameters a set of 400 probabilistic samples is calculated using the original estimateed value as mean of a normal distribution and 10% of the mean as standard deviation.
- For each of the 400 parameter sets a simulation run is done for base run, intervention 1, 2 and 3.
- The prevalences of obesity and overweight for each parameter set for all age classes and male and females are saved.
- Finally, a qualitative comparison of the results for each of the three interventions compared to the base run for each parameter set is done.

The results of the PSA [4] show that for each parameter set all interventions reduce the prevalence of obesity and overweight compared to the base run for every age class and sex. This means that the model output is not dependent on the parameters used in the PSA or that the range in which the parameters are varied is too small.

5 Conclusion

Each intervention leads to a decrease of the prevalence of obesity and overweight. It can be shown that a reduction of caloric intake is effective, but a further reduction is not that effective as the reduction at the beginning. Furthermore, due to the thermic effect of foods, a combined treatment with physical activity and a reduction of caloric intake is more effective than reducing intake.

Furthermore, the modular setup allows a high degree of reusability of model parts. For example the population model can be used in another model where the demographic development of a population is required. The parameterization can be changed to that of another population, if another population is researched. Obesity is a disease with a long list of co-morbidities, like diabetes or hypertension, and the modular setup allows an integration of other model parts that can be connected through another interface.

This also means that other influences can be modelled as well. A cost model, calculating the costs of the disease due to medication or surgery, can also be connected.

This model makes qualitative statements for treatment strategies of obesity and overweight and provides a high degree of reusability for model parts due to the modular setup.

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A Model of 'Breaking Bad': An Economic Model of Drugs and Population Dynamics Predicts how the TV Series Feeds Back to the Drug Market

Christiane Rössler, Magdalena Witzmann*, Thomas Schmickl

*Department for Zoology, University of Graz, 8010 Graz, Austria; magdalena.witzmann@edu.uni-graz.at

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Abstract. The discusssed stock&flow-model predicts population dynamics of Crystal Meth addicts related to the price development of drugs, the society and the market that is affected by the popularity of the TV series 'Breaking Bad': The potential impact of the broadcasting of the TV series on the system is tested by using sudden (pulsed) changes of selected flows and rates to reveal sensitivity of selected variables: 'Addicts', 'price relationship', 'dealers' saturation' and 'Stock of Crystal Meth'. While consumption, purchase and production show strong responses to such perturbations, other variables like 'getting_addicted' and 'weaning_off' show only weak responses. These reactions to pulsed changes of model parameters are analysed and their significance is discussed.

Introduction and Motivation of the Model Study

Nowadays there are various addiction problems that are related to all types of different drugs. One dilemma is given by the fact that one cannot precisely illustrate how many drugs are circulating in the population due to the presence of the illegal drug market. Even though the police invest much effort into performing razzias, drug controls as well as fighting the drug war, the illegal drug market persists with its vast sum of different drugs [1-3].

Economy, however, exploits the 'popularity' of the drug war to produce films or series, although it might be sociologically beneficial [4] to produce educational or documentary films that explain the drug problematic as well as creating awareness to get down to the root of the trouble which is lack of knowledge and downplaying drug effects [1].

Such alternative programs could help to avoid drug addiction or to abandon drugs [1,4].

The presence of these illegal substances causes a huge amount of different effects. On the one hand some agents make a huge profit out of their famousness, while others profit from selling drugs.

On the other hand there is a vast amount of people affected by the drug problematic via illnesses, gang shootings, financial ruin, and many other problems. [1-3]

The methamphetamine Crystal Meth is a long known substance [5] that suddenly increased its fame in the year 2008, due to the TV show 'Breaking Bad' (2008-2012) [3,5-7]. This TV series shows a school chemistry teacher who starts producing and selling Crystal Meth in order to earn money. Blake Ewing, an assistant district attorney, once said: '*I'll continue to wonder about the long term effects of mainstreaming such a dangerous drug into popular culture'* [8].

In 2012 the Crystal Meth consumption increased and exceeded the number of heroin users [9]. We hypothesise that series like 'Breaking Bad' (2008-2012) may have catalysed this increase of Crystal Meth, as series like 'Breaking Bad' (2008-2012) are assumed make drugs more tempting for teenagers or potential sellers and thus increase the addiction rate ultimately.

In general it is extremely difficult to examine how drug availability itself or hypes induced by series like 'Breaking Bad' (2008-2012) affect a population's use of drugs.

In order to gain insights into the socioeconomics of the drug market we built a mathematical model (Figure 1) and ran multiple analyses to describe this kind of dilemma in quantitative predictions.

1 The Model

Our mathematical model (Figure 1) is based on a simple economic model representing the dynamic ratio of supply and demand. It predicts flows of drugs to and from addicts and drug dynamics in correlation to the given price development assuming that the latter regulates the established market by making drug-selling more attractive due to a greater demand. We used this mathematical model to predict the system's sensitivity to outside influences such as the influence of the TV series 'Breaking Bad' on the modelled drug market is assumed to have. We tested this hypothesis based on the assumption that, due to the series broadcast the amount of people cooking or trying out Crystal Meth will change. We furthermore assumed that the number of dealers who switch to selling this drug will be affected in consequence of the TV series. These sudden extrinsic perturbances of the beforehand established equilibria of the system variables were simulated by PULSE functions which are defined by (1), whereby t is the time where the data are observed, t_{start} defines the begin of the PULSE, *dur* defines the length and *amp* defines the amplitude of the PULSE.

It is important to understand that our article does not model the fictional drug market based on what is shown in the TV series. Instead we elaborated an economic model of the real-world drug market and tested the effect of the hype that a series like 'Breaking Bad' may have on this market system.

1.1 Methods

The stock&flow-model [10,11] is built in Vensim 5.11A [11]. This programme is available as free download on http://vensim.com/free-download/ [11]. The model works with data that are parameterised with data from the world drug report [12], and other literature sources [13,14].

The model runs for 120 months, integration type is Euler [14] and time step is defined with $\Delta t=0.1$ month. Units for CrystalMeth. are [g], units for *Addicts* (N_a) and *Non_Addicted* (N_{na}) are [persons]. The models' main structure is shown in Figure 1. The total *Stock of Crystal Meth* (C_{stock}) is specified by (2) where α is the *intrinsic production rate*, g represents the *smuggled goods*, β is the *actual purchasing rate* and C_{circ} is the amount of *Crystal Meth in Circulation*. *Crystal Meth in Circulation* is defined by (3) that follows from the constant *actual purchasing rate* β, *consumption rate* γ and *distribution rate* λ.

The dynamics of N_{na} are modelled by (4), where the *actual growth rate* is δ, *normal death rate* is ε, *weaning off rate* is μ, *addiction rate* is φ and the *dealers' saturation of crystal meth* is s.

Equation 5 determines the dynamics of N_a that grow in number with φ and s and drop with μ and drug related death rate ω. The *purchasing price relationship* p is a regulator for the drug flow; it is defined by supply – C_{stock} - and demand – N_a, s, γ and r- the *daily requirement*. The *price elasticity* a is a measurement for the responsiveness of a good to a change in its price. These relationships are described in (6).

The *dealers' saturation* s has influence on *consumption* and on p, as apparent from (7). The *dealers' saturation* also regulates the *getting_addicted* and the *weaning_off* flow. A 100% dealers' saturation implies a maximum addiction rate. Thus forming the link between drugs and addicts. *Equation 7* is given by (7) where C_{circ} is given in (3) and k is the *dealers' maximum capacity*.

A PULSE function (1) was used to test the drug system's sensitivity to the series' influence. The series ran for 5 years, thus we applied the PULSE for 5 years to perturb the system with different strengths (0% to +50%). Therefore (1) was used, where the data at $t=73$ are observed, t_{start} is 13 [month], duration is 60 [month] and the amplitudes are the different strengths multiplied to the *default value*, thus a factor of 1.0 represents 0% and a factor of 1.5 represents +50% of perturbation strength. So this pulse function changes a chosen flow in a defined time interval of duration *dur* ranging from t_{start} to (t_{start} + *dur*) by multiplication. For example: We enhance the production of Crystal Meth about 20% in every time step for a defined time-period.

1.2 Experiments

In order to predict the effect of the broadcast of the TV series onto the various system components we performed a set of perturbation experiments. *Equation 8* describes in general how the PULSE function (1) was used to change a chosen system variable by applying a *perturbation factor* (*pf*). Whereby we used the *default values* (*dv*) given in *table 1* for every perturbed system variable.

We assume that the broadcast of the TV show and its popular reception can make the drug more attractive, lower the barriers to get the drug and thus will increase the probability of potential consumers to become addicts. This is expressed by perturbing the variable '*getting_addicted*' as described by (9).

We supposed that due to the broadcast of the TV show the tendency to wean off drugs might decrease because being addicted becomes popular. This is expressed by perturbing the variable '*weaning off*' in the following way, see (10).

We further assumed that the TV series can increase consumption since more people want to try out this popular drug. This is expressed by perturbing the variable '*consumption*' in the way as is described by (11).

We assumed that 'Breaking Bad' makes it attractive for dealers to switch to selling meth instead of other drugs. This is expressed by perturbing the variable '*purchase*' in the way as it is described by (12).

We also supposed that the TV series motivates people to establish their own 'Meth-lab' [16]. This is expressed by perturbing the system variable '*production*' in the way, as it is described by (13).

Following these assumptions we did four experiments to test how variables react to our assumed effects of the series.

Experiment 1: We disturbed the flows (as described above) with different amplitudes of perturbation PULSEs and examined how *Addicts* react on these disturbances.

Experiment 2: We observed the *purchasing price relationship* while disturbing flows (as described above) via different amplitudes of perturbation PULSEs.

Experiment 3: We disturbed the flows (as described above) with different amplitudes of perturbation PULSEs and studied how *dealers' saturation of crystal meth* was influenced.

Experiment 4: We investigated the *Stock of Crystal Meth* while disturbing the flows, which are described above, via different amplitudes of perturbation PULSEs.

1.3 Results

Figure 2 shows the reactions of *Addicts*, *purchasing price relationship, dealers' saturation* and *Stock of Crystal Meth* after the PULSE influenced the affected flows. The abscissa shows the increase and the decrease of the PULSE effect relative to the starting conditions. The ordinate shows the relative change of the observed variables. In general, responses are almost linear.

Experiment 1: When changing the *getting_addicted* flow the stock of *Addicts* reacts by increasing in number, while a change of *consumption* decreases *Addicts*. *Purchase* and *production* show less reaction and similar linear scaling of reaction.

Experiment 2: The *price relationship* increases with a positive change in purchase and decreases with a rise in *production*. *Getting_addicted* shows a slight increase, while *production* is reacting least to a change.

Experiment 3: *Dealers' saturation* grows strongest with a rise in *production* and decreases with an increase in *consumption*; with changes in *getting_addicted* and *purchase. Dealers' saturation* shows little decrease.

Experiment 4: The *Stock of Crystal Meth* is most influenced by increased *production* volumes and by decreased *purchase*. The *consumption* and *production* flow show similar linear responses, but on a low level.

None of the observed variables react to changes in *weaning_off*; this flow remains constant throughout all perturbation experiments.

1.4 Discussion

System Dynamics is a method for analysing complex and dynamic systems to understand and if necessary to manipulate a systems' behaviour [10]. Therefore it is applicable in many scientific disciplines such as biology, sociology and economic sciences. The System Dynamics approach aims for recognising essential and global contexts. Vensim PLE is a simulation software for developing, analysing, and packaging dynamic feedback models. [11] It was chosen due to its simplicity in setup and application. Furthermore profound / extensive mathematical skills can be neglected for the benefit of joined-up thinking / system comprehension. Therefore it perfectly fits for beginners to get an insight into the modelling process.

The model itself is based on basic economic regulations concerning supply, demand and price-development – if demand and supply are equal, the market is stable established by the price, which is the balancing variable. Secondly, population dynamics are simply described by birth and dying events - outside influences such as immigration are disregarded in order to maintain a closed system. Due to these facts the modelled system reacts due to system-intrinsic feedback loops. On the one hand, we showed that the modelled drug market is intrinsically stable in response to extrinsic perturbations.

On the other hand, significant medium-term effects of perturbations are predicted, as they can be caused by the TV series itself. These responses, which are shifts of equilibria during the perturbed period, have been analysed systematically in a quantitative way generating testable hypotheses.

Results show different sensitivities of analysed observed variables to the changes in parameters governing important flows in the system: The more *consumption* increases, the more *dealers' saturation* decreases. Consequently the *price relationship* and *Addicts* decrease. This seems implausible at first sight but it is accurate according to the model's hypothesis of market regulation. Since demand is determined by the *consumption rate* and not by the *consumption* flow, the *price relationship* does not react as one might initially expect. The saturation reacts with a time delay, which is a result of the multi-stock structure of the modelled system. With regard to *production*, the model's behaviour is governed by the feedback loop '*Stock of Crystal Meth to purchase*', which prevents oversaturation.

The growing *purchase* flow reacts with an enhancement of *Addicts*, *price relationship* and *dealers' saturation* while *Stock of Crystal Meth* decreases. This is consistent to the underlying hypothesis of market regulation.

A positive change in *getting_addicted* leads to an increase in *Addicts*. As *price relationship* is not very responsive to small changes, it grows subtly, due to a remote growth in supply (*Stock of Crystal Meth*).

Dealers' saturation decreases with higher *consumption* caused by more *Addicts*. *Weaning_off* conspicuously is insensitive in consequence of a low *weaning_off rate*.

Since there are no over-proportional changes the system is considered to be stable. This stability is caused by the negative feedback loop established by the interaction of demand and *price relationship*. The higher the *price elasticity* (6) is, the more stable the system becomes due to a higher flexibility in the *price relationship*, which induces an enhancement of the negative feedback loop.

One simulated perturbation of the drug market was found to be the effect of the broadcast of the series itself [8]. In agreement to our model predictions, the UNODC reports an increase in *Stock of Crystal Meth*, *Addicts* and *Crystal Meth in Circulation* between 2008-2012 [12, Fig. 49.].

Based on our results it can be assumed that 'Breaking Bad' still has an impact on the rise in meth-use. State-Time plots (not shown here) indicate long-term effects, concerning the ratio of *Non-addicted* to *Addicts* without a decrease of total population. *Addicts* become more while *Non-Addicted* decline in amount. Apart from these changes the model - in the long term - finds back to its starting conditions. We did not consider the fact that the series is still in circulation (e.g. streaming sites) and thus its effects may endure even longer.

It is remarkable that the *price relationship* always reaches its equilibrium after the pulse-shaped disturbance of the system ceases to act on an altered flow. This is a consequence of (6) which varies the terminal point by alternating the *price elasticity a* in a self-stabilizing way.

Since there is no data that strictly reports about a correlation between the series and the increase of seizures of *CrystalMeth* reported by the UNODC the model cannot be strongly validated by directly comparing to empirical data. However, we think the model's mechanisms are generalizable to any hype-affected drug market thus useful future work can replace *CrystalMeth* by Marihuana- since more data is available due to its actuality concerning legalisation. By doing this, the effects of such a legalising could be modelled and then be compared with data of countries that already legalised it- such as, for example, Portugal. The core piece of work, a solid but still simple economic drug market model, is developed and analysed in the current paper.

Acknowledgements

This work was initially started as a final semester project of a mathematical modelling lab course at Karl-Franzens University of Graz, Austria by Christiane Rössler and Magdalena Witzmann. The teacher of this course, Thomas Schmickl, motivated the two master students to write a scientific article about their work and to submit it to the international **MATHMOD 2015** conference in Vienna. The paper was accepted at the conference as a poster, which then won the 'best student-poster award' at the conference. This ultimately led to invitation to submit an extended version of the article to **SNE - Simulation Notes Europe.**

2 Model Equations

$$PULSE(t, t_{start}, dur, amp) = \begin{cases} 0 & if\ t < t_{start} \\ amp & if\ t_{start} \leq t < (t_{start} + dur) \\ 0 & else \end{cases} \quad (1)$$

$$\frac{\Delta C_{stock}}{\Delta t} = +\alpha(t) * C_{stock} + g(t) - \beta(t) * C_{stock} * (1 - \frac{C_{circ}}{k(t)}) \quad (2)$$

$$\frac{\Delta C_{circ}}{\Delta t} = +\beta(t) * C_{stock} * \left(1 - \frac{C_{circ}}{k(t)}\right) - MIN\begin{Bmatrix} C_{circ} * d \\ \gamma(t) * N_a * s(t) \end{Bmatrix} \quad (3)$$

$$\frac{\Delta N_{na}}{\Delta t} = +\delta(t) * N_{na} + \mu(t) * N_a * (1 - s(t)) - \varphi(t) * N_{na} * s(t) \quad (4)$$

$$\frac{\Delta N_a}{\Delta t} = +\varphi(t) * N_{na} * s(t) - \mu(t) * N_a * (1 - s(t)) - \omega(t) * N_a \quad (5)$$

$$p = \frac{a * \frac{N_a * (1 - s(t)) * \gamma(t) * r(t)}{C_{stock} + 1}}{\sqrt{1 + (a * \frac{N_a * (1 - s(t)) * \gamma(t) * r(t)}{C_{stock} + 1})^2}} \quad (6)$$

$$s = \frac{C_{circ}}{k(t)} \quad (7)$$

$$pf(t) = dv * PULSE(t, t_{start}, dur, amp) \quad (8)$$

$$getting\_addicted(t) = N_{na} * \varphi * s * PULSE(t, t_{start}, dur, amp) \quad (9)$$

$$weaning\_off(t) = N_a * \mu * s * PULSE(t, t_{start}, dur, amp) \quad (10)$$

$$consumption(t) = \lambda * C_{circ} * s * \gamma * PULSE(t, t_{start}, dur, amp) \quad (11)$$

$$purchase(t) = \beta * k * C_{stock} * C_{circ} * PULSE(t, t_{start}, dur, amp) \quad (12)$$

$$production(t) = \alpha * C_{stock} * PULSE(t, t_{start}, dur, amp) \quad (13)$$

3 Figures

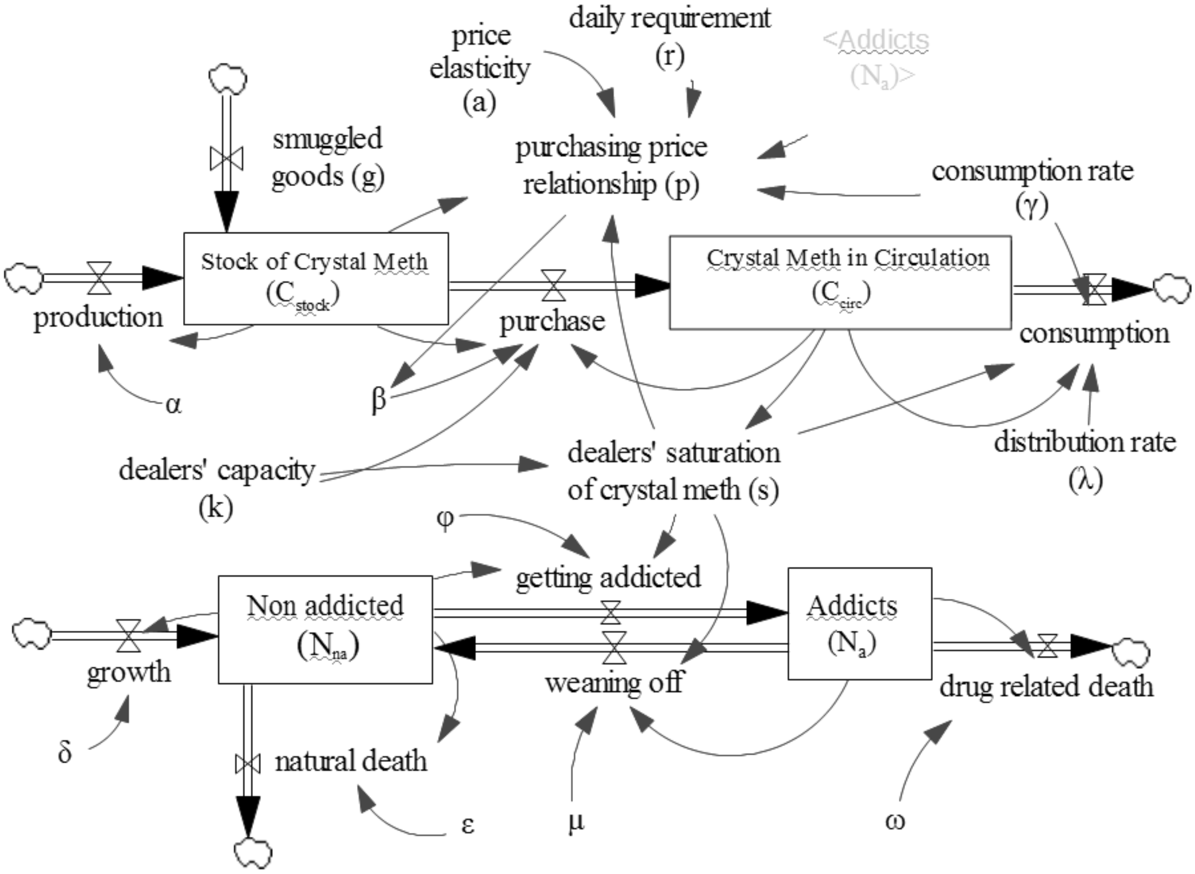

Figure 1: Excerpt of the stock&flow-model of drugs and population dynamics, showing the main structure of its system components:

Rectanglular boxes depict stocks, that are system components that model quantities that can only change through flows (double arrows) that bring quantities from sources (cloud symbols) into the system or via sinks (cloud symbols) out of the system. The whole chain of sources, flows, stocks and sinks guarantees conservation of mass in the system. Thin singular arrows indicate positive or negative direct dependencies between system components, which can be either constants (greek letters) or variables (latin letters). For further details, see text.

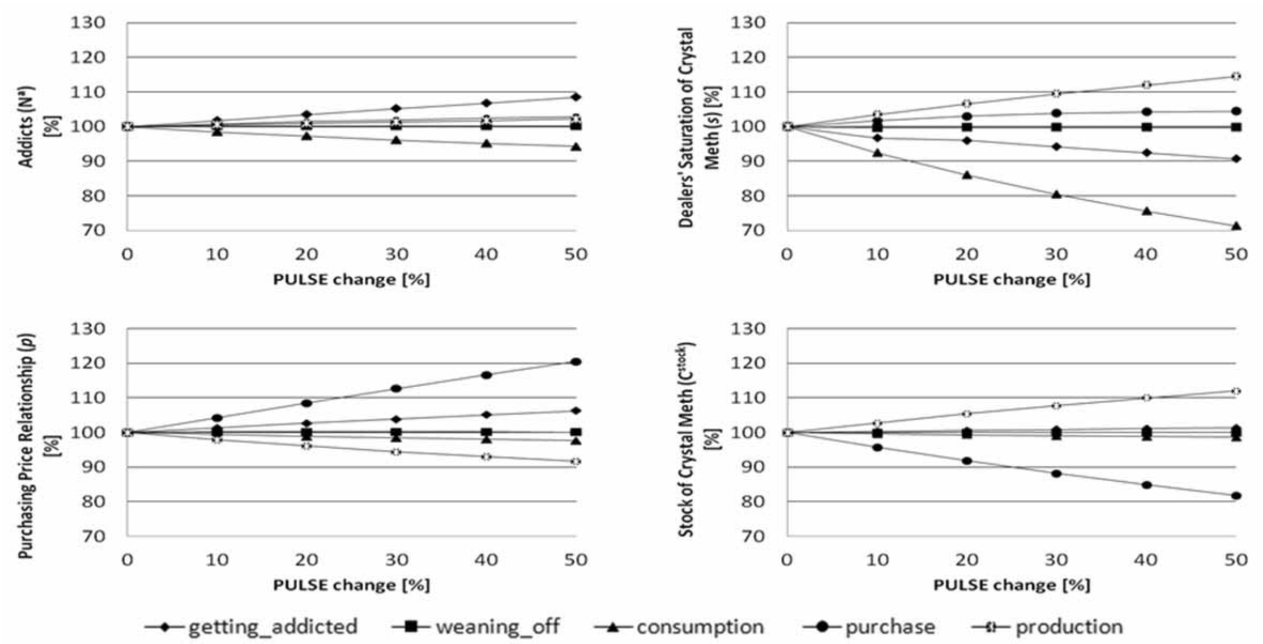

Figure 2: Results of sensitivity tested by a pulsed disturbance of model parameters: Each picture depicts the effect of the applied pulse distribution on the abscissa. a) The stock of *Addicts*, b) the variables *Purchasing Price Relationship*, c) the variable *Dealer' Saturation of Crystal Meth*, and d) the *Stock of Crystal Meth* are depicted on the ordinate. All values are in percent. For further details, see text.

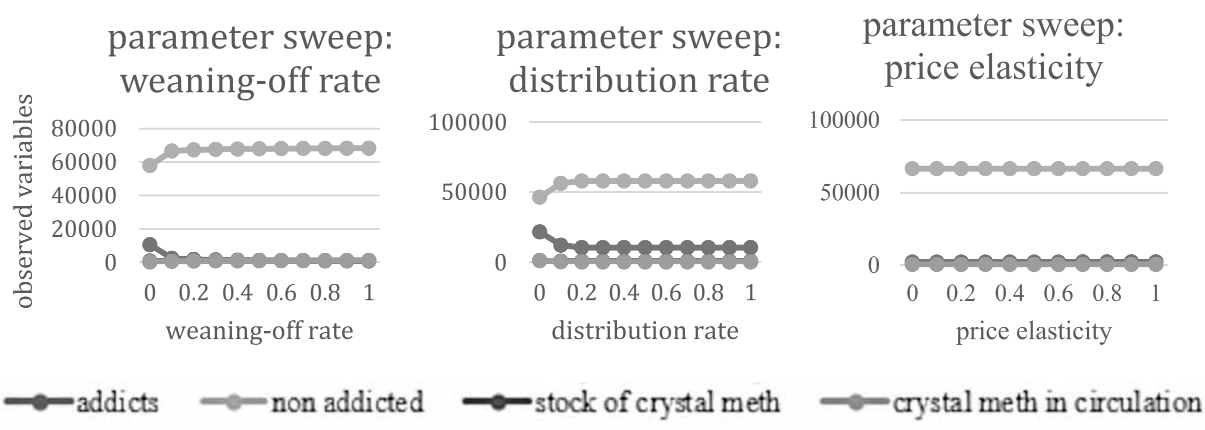

Figure 3: Parameter sweeps of the parameters weaning-off rate, *distribution rate and price elasticity* in the standard-model. We analysed how the stocks in our model react to different rates ranging from 0.0-1.0 (x-axis). The y-axis shows the observed data of *Addicts*, *Non-addicted, Stock of Crystal Meth* and *Crystal Meth in Circulation* at t=73. In the range of 0.0 and 0.2 of the varied parameter the observed variables are most sensitive to changes.

4 Used Parameters

Variable	Initial value	Unit	Literature sources
Actual growth rate (of non addicts) δ	0.011668	1/Month	0.014/Year [14]
Addiction rate φ	0.01	1/Month	0.012/Year [12]
Basic purchasing rate β	0.4	1/Month	50.000g/500.000 Addicts/Week [12]
Consumption rate γ	0.04	g/Person/ Month	15mg/Person/Day [12]
Daily requirement r	15mg	1/Person	15mg/Person/Day [15]
Dealers' capacity k	300	g	[15]
Distribution rate λ	0.5	1/Month	Free parameter[1]
Drug related death ω	0.00001	1/Month	0.000147 Persons/Year [15]
Intrinsic production rate α	0.8	1/Month	10 tons/Year [15]
Normal death rate ε	0.000683	1/Month	0.0082/Year [14]
Price elasticity a	1	dmnl	0nly price relationship is sensitive
Smuggled goods g	16000	g/Month	0.2 tons/Year [12]
Weaning off rate μ	0.1	1/Month	Free parameter[1]

Table 1: Variables, initial values , units and literature sources used in the model. Data originates from the World Drug report 2014 [12], the United States Census Bureau [13] and Härtel-Petri and Haupt [14].
[1] model is highly sensitive in [0.0-0.2] and insensitive in [0.2-1] to those parameters. The parameter sweeps are depicted in Figure 3-5.

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Exploring the Advantages of Multi-Method Modelling in the Use Case of a Large Socio-Technical Infrastructure System: The Airport City

Barbara Glock[1*], Niki Popper[1], Felix Breitenecker[2]

[1]dwh GmbH, dwh Simulation Services, Neustiftgasse 57-59, 1070 Vienna, Austria; *barbara.glock@dwh.at

[2]Institute for Analysis and Scientific Computing, Vienna University of Technology, Wiedner Hauptstraße 8-10, 1040 Vienna, Austria;

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Abstract. Modelling large socio-technical infrastructure systems tends to be tricky. In the past either one 'best fitting' modelling technique was used to model the system or a small part of the system was modelled. This lead to many tradeoffs, where the chosen modelling method got to its limits: by modelling a small part, effects from outside were ignored and modelling the whole system with one method lead to either much detail - where micro-based methods were applied - where it was not required which further lead to high computation times. Using a macro-based approach lead to less detail where it would have been needed. Different parts of the Airport City are modelled with the best fitting modelling technique. These parts are researched for their coupling mechanisms to model the whole system and see how effects in one part evolve and pass to the next subsystem. An agent based model of the landside with a modal split of passenger arrival, a Discrete Events terminal model, a multi-method agent-based model with an integrated System Dynamics model representing the retail area of an airport and an agent based model of the airside are developed and their advantages and disadvantages are being explored.

Introduction

The planning of big infrastructure developments is getting more challenging due to more complex structures and an increased number of construction standards. Large infrastructure systems can be decomposed into subsystems that are somehow interconnected and correspond on different levels with each other.

This makes an analysis more difficult. Furthermore, there are different views on the system that need to be addressed and satisfied: stakeholders, planners, consumers, decision makers, etc. On the one side questions addressing profit arise, and on the other side consumers want a specific level of quality. Also ecologic aspects need to be kept in mind. In general this calls for modelling and simulation. These large systems, broken into pieces, consist of different subsystems with much more detail, each of them with its own dynamic effects. This gives an opportunity for multi-method modelling (MMM) to use all advantages of each method in combination.

Applying multi-method modelling techniques to model large infrastructure systems hasn't been properly researched yet, since the focus of most modellers has lien in increasing know-how on the singular methods themselves and additionally the computational power hasn't been that advanced in the past then it is nowadays to meet this challenge. Most literature focuses on comparing the available modelling method in their research area to find the best fitting [1] or discuss what the advantages and disadvantages are [2], but also how a model in one paradigm can be transformed into a model of another paradigm [3]. Especially under what circumstances, mathematically described, this is allowed.

But, as mentioned before, rather few publications try to combine the advantages of different modelling paradigms: System Dynamics (SD), a rather old approach, developed in the 1950s by Jay W. Forrester [4] has been researched very well [5].

Discrete Events Simulation (DES) [6] has been researched very well too. Literature on so-called hybrid models, where these two modelling paradigms are being combined, coupling continuous and discrete models, can be found [7].

When it comes to agent-based modelling (ABM), this being a rather new approach [8], modellers are still struggling with finding a 'right' definition – different definitions exist! [9] -, than thinking of how to combine for example agent-based methods with other modelling paradigms like System Dynamics. Researching literature revealed some works on first attempts and implementations where agent-based models are coupled with System Dynamics models [9] and one paper on a classification attempt for combining SD and ABM was found [10].

1 Aim and Goals

The aim of this dissertation project is to research different multi-method modelling techniques for modelling large socio-technical infrastructure systems as airports, to reveal their advantages and disadvantages and to give some guidance on how to apply these different modelling paradigms. Macro-based and micro-based modelling paradigms are different in view and offer different advantages. *The one modelling method's advantage is the other ones disadvantage. So why not combine their advantages?*

The focus will lie on ABM combined with SD and on DES combined with SD, since these two different modelling paradigms are a little bit trickier to combine. The use case where this will be tested is the Airport City, since this is a large, decomposable system and yields a lot of possibilities to apply multi-method modelling techniques.

2 Modelling Methods

Multi-method modelling with the following three modelling methods are researched and used in the application of airport planning, because these methods are, according to literature, used most often in this area and are also applicable to model the subsystem to answer specific research questions.

2.1 System Dynamics

In this macro-based modelling paradigm the point of view is from above, where only aggregated levels are looked at. It was developed in the 1950s by Jay W. Forrester, who applied it first in management systems [4]. He then transferred this methodology to social systems. Nowadays diverse literature on System Dynamics and Systems Thinking exists [5]. A SD model consists of six basic elements, as seen in table 1.

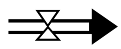
Element	Representation	Description
Stocks (Levels)		Describe the state of the system at each time and represent aggregates
Flows		Describe the changes of the stocks; are basically auxiliaries and are only allowed between stocks and stocks and sinks/sources
Parameters		Are constants and represent rates on which changes of stocks are dependent
Auxiliaries		Are helpful for a better understanding of the model and represent algebraic equations
Sink/ Source		Describe the boundaries of the system
Links		Describe the causalities of other elements

Table 1: Basic elements of System Dynamics.

A System Dynamics model basically represents a set of differential and algebraic equations. A simple example can be seen in Figure 1 and possible related equations in equations (1) and (2).

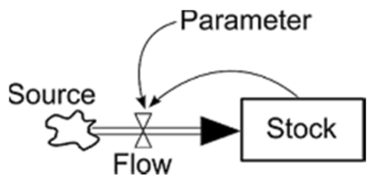


Figure 1: Simple stock and flow structure of SD.

Possible equation for time t:

$$\frac{d\,Stock(t)}{dt} = Flow\ (t) \tag{1}$$

$$Flow(t) = Stock(t) \cdot Parameter \tag{2}$$

The dynamics of the system emerge from causal links of the modelled variables that often form feedback loops. Such loops can be **balancing** or **reinforcing** driving the dynamics of the system.

Application areas are amongst others economics, health care and policy design.

2.2 Agent-based modelling

Agent-based modelling is a rather new approach and several properties of agents can be found in literature [9]. A selection of those is:

- **Proactiveness**, **purposefulness**: ability to take the initiative in order to achieve goals
- **Situatedness**: an agent is embedded in its environment and senses and acts on it
- **Reactiveness, responsiveness**: ability to react in a timely fashion to changes in the environment
- **Autonomy**: ability to interaction and communication with other agents, sometimes even awareness of other agents
- **Anthromorphity**: having human-like attributes like beliefes and intentions
- **Learning**: ability to increase performance over time based on previous experience
- **Mobility**: ability to move around in the simulated physical space, sometimes even between different machines
- **Specific purpose**: designed to accomplish well-defined tasks

Not every agent-based system has all of those properties [9] and depending on the agent's purpose one should not speak of agents and non-agents, but speak of a **continuum of agency**: The more agent characteristics an entity possess and the more developed those are, the higher the degree of agency it has.

2.3 Discrete events simulation

Discrete Events Simulation models are similar to agents, but the entity modelled here is not like an agent autonomous. It is passively led through the system instead. Furthermore, changes in the state of the system happen due to events at discrete points in time [11].

Between two consecutive events the state remains unchanged. Basic elements of DES are:

- **Entities**: have discrete properties and can be arranged in sets or lists
- **Events**: is an instantaneous happening that changes the state of the system. Events are arranged in an event list and are scheduled by using event notices that provide different information like tye or time of event.
- **Clock**: is a global variable that represents the simulated time. There are activities (time spans of certain length already know by simulation start) and delays (time spans of uncertain length like waiting time of a passenger in a queue). The clock can be forwarded in different manners.
- **Scheduler**: handels the event list, forwards the events to the event processing routine, also reschedules events if necessary and updates the clock.

This kind of modelling is mostly used in logistics and transportation.

3 Classification of MMM

Researching literature revealed that few attempts in multi-method modelling were done, but only one paper was found that tried to classify models that used ABM and SD modelling to model the whole system. There are three proposed categories [10].

Two coupled submodels are called **interfaced** if they have some point of interaction like communication between elements.

The submodels run alternating and independently (see Figure 2). There is no direct feedback between the submodels.

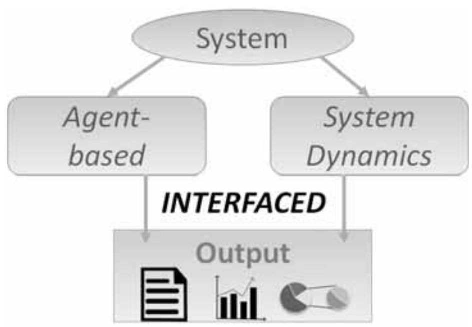


Figure 2: Interfaced multi-method model.

Two submodels are **sequential** if one submodel needs the output of another as input (see Figure 3).

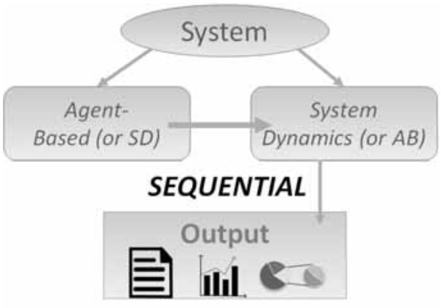


Figure 3: Sequential multi-method model.

In an **integrated** multi-method model the submodels interact with each other in some way, as can be seen in Figure 4.

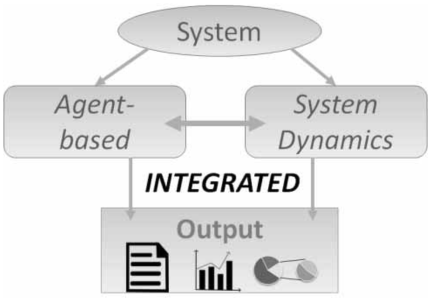


Figure 4: Integrated multi-method model.

According to Swinerd and McNaught [10] there are three ways to model an integrated design:

- **Agents with rich internal structure:** within each agent an SD model exists (see model on retail area). One can think of the SD model within an agent as the agent's 'brain' that 'tells' him what to do in a dynamic way. Here, influences from both sides can be considered: ABM submodel passes informa-tion to the SD submodel and vice versa.
- **Stocked agents**: a level within an SD model is used to bind an aggregate measure of an ABM. This could be an SD submodel that calculates production costs on car sales and the influence of fuel price on consumer choice of vehicle technology where consumers are modelled in the AB submodel. Here only influences from SD to ABM are modelled, but not the other way round.
- **Parameters with emergent behaviour**: a parameter of an SD model is calculated by an ABM. An example is an agent-based submodel where demographic development is modelled with agents together with their individual properties (age, sex, maybe socio-economic factors). Out of these properties the value of a parameter for a coupled SD submodel is calculated.

There is a fine line between the classes of multi-method models. The modeller has to decide what fits best. It is also dependent on where the system boundaries lie. This classification approach is very useful as a starting point in researching multi-method modelling, since it is also applicable not only for SD and ABM modelling but also for other modelling methods.

4 Use Case: Airport City

The Airport City is a good example of a **large socio-technical infrastructure system** to model, since on the one hand passenger demand forecasts predict an increase in the long term growth of transported passengers of avg. 4% per year [12] and on the other hand the system can be decomposed to smaller subsystems, that are somehow interconnected to each other on different levels. In Figure 5 a selection of important areas of the Airport City can be seen.

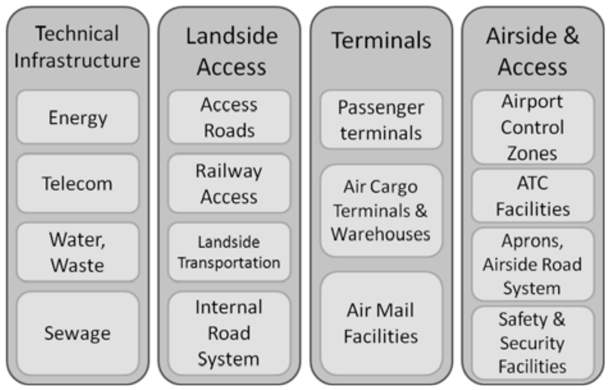


Figure 5: Selection of areas in the Airport City. (Source: adapted from company AI-MS Aviation Infrastructure Management Systems).

Also different views need to be satisfied here as well: planners, consumers, and stakeholders. A terminal model modelled with Discrete Events and a model of the retail area as an integrated ABM-SD model with rich internal structure has been developed. Furthermore, an agent-based model of the landside and the integration of a network-based agent-based model of the airside have been developed. Still planned is a SD model to calculate costs/profit and CO2 emission of airplanes and passenger demand forecasts. The advantages and disadvantages together with the possible coupling mechanisms are being researched. The described models are implemented in AnyLogic 7 [13].

4.1 Terminal model with discrete events

The terminal area is after the landside area the second area where departing passengers go to. The processes going on include check-in, security controls, passport controls and proceed to gate through retail area [14]. These processes are dependent on specific features of the passenger, like if he/she is business or tourist passenger (only hand luggage or not), or what his destination is (if within Schengen the passenger can proceed without passport control) or if he is handicapped or not. This submodel also includes transfer passengers, meaning passengers arriving at the airport by plane, going through passport control if necessary and proceeding to gate after going through retail area. This circumstance shows on the one hand, that this submodel gets input from the landside as well as from the airside and if some delays or other effects happen in the parts of the airport not represented in the terminal submodel it has an effect on the terminal submodel.

The research question in this model is if resources like personnel and number of open counters is enough at each time to maintain the quality standards measured in waiting time of passengers. This being a simple server-queue question is modeled best using Discrete Events with counters and personnel being resources and passengers being entities.

The DES model has already been implemented, as seen in Figure 6. This model includes the basic servers in such a process (check-in, security, passport control and transfer). In AnyLogic simple blocks for creating (sources), processing (server), and queuing (queue) entities are used. Resources are created via a (scheduled) resource pool.

Interfaces to possible coupled models like the adjacent landside model (not described here) are marked in orange. From an ABM-landside model agents enter the terminal system via an *Enter*-block. The agent based model modelling the landside can be coupled by this rule: every time an agent (passenger) exits the landside model, an entity (it is possible to pass other information as well) in the DES model is generated. Other interface from and to this terminal model are the connection to the retail area, transfer to the airside or if the flight was missed the exit to the landside to go back home.

4.2 Retail area with integrated ABM-SD model

The retail area is economically seen a very important part of the airport since most of the profit is gained here. The retail area is a shopping area after having passed the controls in the terminal where passengers go through when they proceed to the gate to depart.

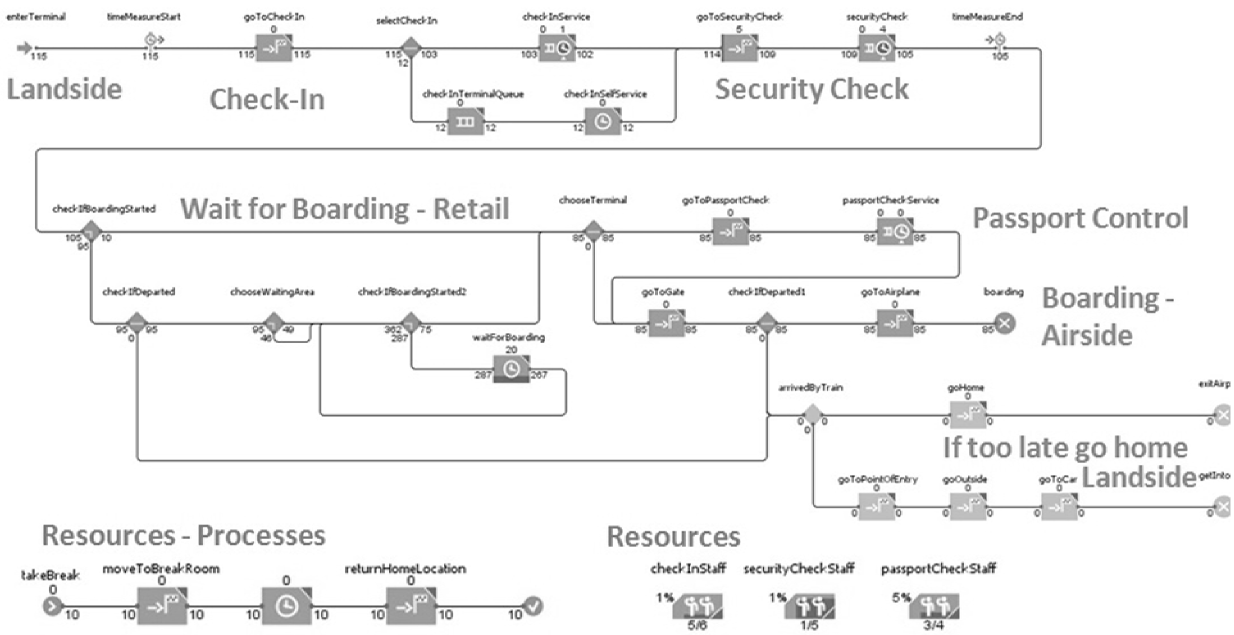


Figure 6: Discrete Events Simulation of the Terminal.

One main research question in this area is to maximize profit by guaranteeing a specific level of quality for passengers like a short way to the gate or attractive sales. Here also spatial information is needed.

The processes are dependent on an individual's behaviour: he/she reacts to the environment and other passengers; therefore an ABM submodel that includes spatial information (map of the shops) is used.

The environment is the retail area with the shops. The inner parts of an agent should be dynamically changing, since this is more realistic: next to some individual parameters like age, economic status and gender as well as flight information, the agent consists of an SD submodel that models the need to eat and the need to buy other things.

In this case the retail area submodel is itself **an integrated model of agents with rich internal structure.** Each agent follows rules like:

- Proceed to gate in time
- If hungry and still in time to departure, then look for eating store and eat
- In dependence of attractiveness of store and in dependence of estimated income buy something if there is still time to departure and the need to buy something exceeds a specific threshold

These rules always take into account the by the SD model calculated need to buy something. This means there is communication from the SD module to the agent based module (tell him where to go). In return the need is dynamically calculated by the SD module by using individual information from the agent (age, gender, time until departure), but also using information from the environment of the AB module, like the attractiveness of the store that has some 'basic attractiveness' and furthermore is calculated by the number of people inside (if there are no people inside it may be something wrong with it, if there are too much people inside it is overcrowded).

A first version of this submodel has been developed (by M. Obermair and B. Glock), as seen in the 3D version of the animation in Figure 7. A network is applied to a ground floor and passenger agents interact on this plan with the shops trying to satisfy their goals that are modelled with SD, which can be seen in Figure 8.

Clearly, this multi-method approach allows agents to develop their needs dynamically and not by discrete rules, which gives a more realistic picture of the world.

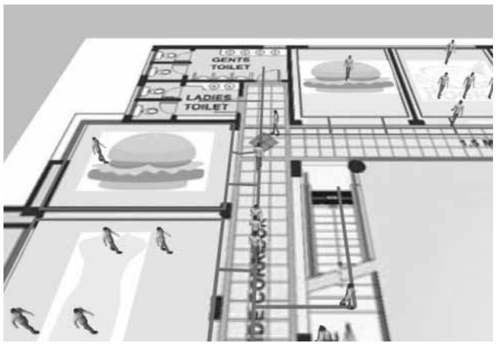


Figure 7: Integrated multi-method model of retail area – agents with rich internal structure (agents).

To explore the disadvantages and advantages more specific, currently, a version of the retail area with single-method modelling approach is in development to have direct comparision. Therefore, measure variables are defined and compared.

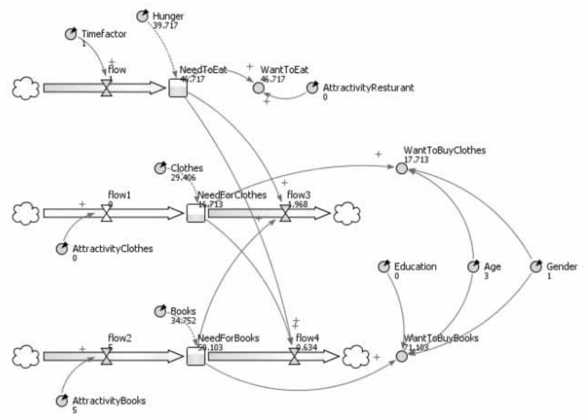


Figure 8: Integrated multi-method model of retail area – agents with rich internal structure (SD model within each agent).

4.3 Airside

The airside of the airport is the part where diverse processes take place that deal with outgoing and incoming planes, like it is shown in Figure 9.

The so called ground handling processes include all processes around the plane. After touchdown (landing of the plane), the taxi arrives to get the passengers. After that the unloading and water refill starts. There are some limitations like cleaning and catering have to start after disembarking or fuelling after unloading luggage that need to be considered as well. In this submodel the spatial context plays an important role since travelling times contribute to quality measurements for passengers and the calculation of optimizations regarding the ground handling process itself.

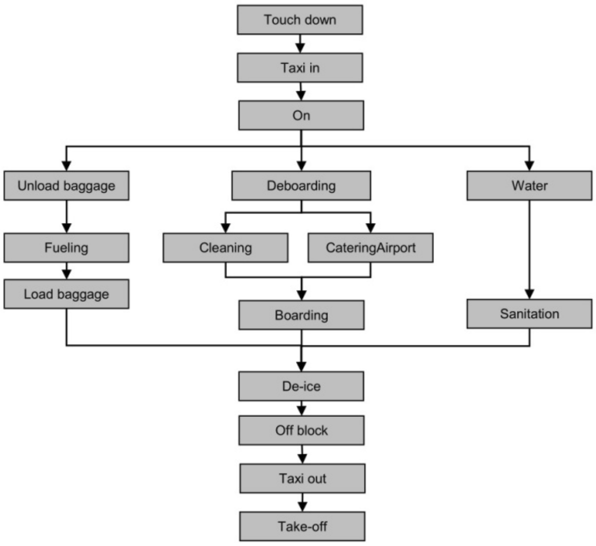


Figure 9: Ground handling process [15].

The so called ground handling processes include all processes around the plane. After touchdown (landing of the plane), the taxi arrives to get the passengers. After that the unloading and water refill starts. There are some limitations like cleaning and catering have to start after disembarking or fuelling after unloading luggage that need to be considered as well.

In this submodel the spatial context plays an important role since travelling times contribute to quality measurements for passengers and the calculation of optimizations regarding the ground handling process itself.

The amount of flights is increasing and space on the airside where passengers can board (directly through the gate vie boarding bridges or on the apron) is limited. Therefore, in this case an AB submodel is used with a given network on which the agents can operate.

Different types of agents interact with each other on an environment like the network (selection):

- ♦ Planes
- ♦ Mobile stairs
- ♦ Catering vehicle
- ♦ Belt loader
- ♦ Baggage cart, ...

They have one overall goal to get the plane as soon as possible up in the air again.

4.4 Further submodels

Next a submodel modelling the landside with agents where the type of agents is different (cars, and not passengers) is in development and a submodel modelling the CO2 emission (with SD) as an integrated design is planned, where the agent-based and Discrete Event submodels have an influence on parameters of the SD model (classification of parameters with emergent behaviour) together with a single method approach of the retail area to compare differences directly.

5 The Big Modelling Picture

Summarizing the proposed submodels as seen in Figure 10 there is a terminal submodel with DES that interacts with the multi-method retail area submodel modelled with ABM, which itself is a multi-method model as the 'brain' of each agent is a SD model. The retail area submodel will be connected to the airside submodel. A submodel of the landside will be integrated.

Passengers proceed not only from landside to the airside, but also from airside to the landside, if they are arriving. Transfer passengers are included as well. So, we can see that those submodels are from integrated form all along, because these submodels have to exchange information (e.g. the agent or entity being passed on). The further planned SD submodel, calculating profit and CO2 emission requires information from the other submodels. Somehow, this SD model will give (delayed) some information back to the submodels (dotted lines in Figure 10), since the effect of the CO2 development will have an effect on the structures of the airport implemented with the submodels

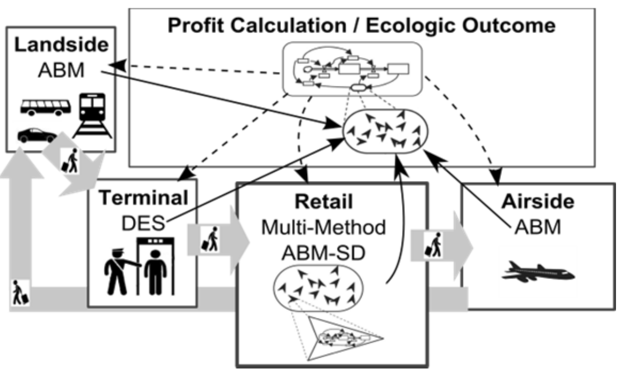


Figure 10: The Coupling Schema of the Modelled and Planned Submodels.

The advantages of this multi-method modelling tech-nique clearly are that the model gets more realistic by also including individual's properties. The disadvantage is that it can get more complex. On the other hand due to the modular architecture verification and validation will be, compared to a whole ABM model, easier.

6 Conclusions and Outlook

Using multi-method models is getting more and more important [16], since large infrastructure systems like airports get more complex and larger. Errors by using only one method for the large system can accumulate over time resulting in difficult decision making. By using different (best fitting) modelling methods for different subsystems and utilizing all their advantages a more realistic presentation of the model can be created. This also makes communication to decision makers easier and accumulating errors are eliminated to some extent. Furthermore, calculation times of the simulation models can be reduced as well.

Next (interesting) steps in this project include building and integrating a CO2-emission submodel and a profit calculation model that interact with the former described submodels and an airside and a landside model together with the comparison of the single method approach to the multi-method approach in the retail area.

Acknowledgement

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System Dynamics for Modelling Emotions: from Laura - Petrarch to Nowadays Couple

Felix Breitenecker[1*], Andreas Körner[1], Niki Popper[2]

[1]Institute for Analysis and Scientific Computing, Vienna University of Technology, Wiedner Haupstrasse 8-10, 1040 Vienna, Austria; *Felix.Breitenecker@tuwien.ac.t*

[2]dwh GmbH, dwh Simulation Services, Neustiftgasse 57-59, 1070 Vienna, Austria

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Abstract. F. J. Jones – a scientist for literary – analyzed Petrarch's 'Sonnets to Laura' with respect to positive and negative emotions and recognized in the changes between love and despair an oscillating behaviour, which he called Petrarch's emotional cycle. The mathematician S. Rinaldi investigated this cycle from viewpoint of stability, established a nonlinear ODE model for this oscillating emotions and inspiration.

This contribution makes use of 'System Dynamics' – SD - to set up a model for the emotional relations between a couple, first for the couple Laura–Petrarch, and second, for a nowadays couple, by extending the states of the system.

In principle, emotions and inspiration emerge from a source, and are fading into a sink – best suited for the SD modelling paradigm. The rate variables and the controlling parameters for increase and decrease of emotions create a broad variety of emotional behaviour and of degree of inspiration, and require nonlinear approaches for driving forces for the emotions, especially in the feedback between Laura and Petrarch (in SD nonlinear auxiliary variables).

Using Jones' emotional cycle as data, parameters in the 'Laura-Petrarch Model' can be identified. Interestingly, again the poems help determining at least the qualitative size of some parameters. Changes some of these historic parameters describe nice case studies: Laura's emotions are fading faster, or positive appeal of Petrarch changes emotion behaviour qualitatively.

The Laura-Petrarch SD model allows to develop a 'Nowadays Couple Model' by extending states in the SD model (taking into account the equality of woman and man nowadays). The historic parameters from the 'Laura-Petrarch Model' can be used as basis for parameters in the 'Nowadays Couple' SD model, – allowing some nice simulation experiments for the development of emotions, from ecstatic up and down to never-ending languidness, from attraction to denial, from natural course to course intervention by aesthetic surgery.

Figure 1: Portraits of Laura and Petrarch, from Biblioteca Medici Laurenziana, Ms. Plut. cc. VIIIv- IX, Florence, Italy (courtesy of Ministero per i Bene Culturali e Ambientali), from [2].

Introduction

Francis Petrarch (1304-1374), is the author of the *Canzoniere*, a collection of 366 poems (sonnets, songs, sestinas, ballads, and madrigals). History tells: in Avignon, at the age of 23, he met Laura, a beautiful but married lady (Figure 1); he immediately fell in love with her which lasted longer than Laura's life; although this love was not really reciprocated (he never met her), he addressed more than 200 poems to her over the next 21 years. Indeed, the poems express bouts of ardour and despair, snubs and reconciliations, making Petrarch the most lovesick poet of all time.

F. J. Jones – a scientist for literary – analysed Petrarch's *Sonnets to Laura* with respect to positive and negative emotions and recognised in the changes between love and despair an oscillating behaviour, which he called *Petrarch's emotional cycle* ([1].

The mathematician S. Rinaldi investigated this cycle and established a nonlinear ODE model for this oscillation, with Laura's emotion, with Petrarch's emotion, and with Petrarch's inspiration as state variables – based on classical mathematical analysis and stability considerations in ODE systems ([2]).

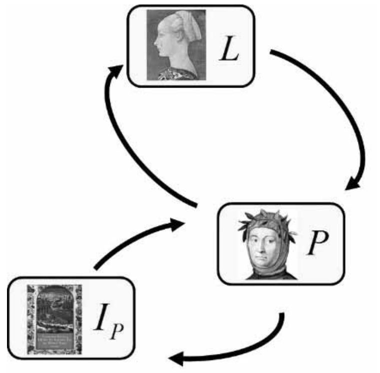

Figure 2: Causal loop diagram between Laura's and Petrarch's emotions and Petrarch's inspiration.

Petrarch's emotions – and Laura's 'counter'-emotions, expressed indirectly in the poems, aggregate over time flowing from sources to a sink, driven by feedback from each other: the key words aggregation, flow, source, sink, feedback almost request for *System Dynamics* as modelling tool for the dynamics of emotion.

System Dynamics (SD) is a well-known modelling and simulation approach, introduced by J. Forrester [5]. The modelling procedure is based on three steps:

- First, a *causal loop diagram* (CLD) visualizes the relations between the aggregated variables qualitatively- Figure 2 shows the principle feedbacks within Laura's emotion, Petrarch's emotion, and Petrarch's inspiration,
- then a stock and flow diagram (SFD) describes the relations quantitatively by flows and feedbacks,
- and additionally the SFD can be directly implemented for computer simulation (nowadays automatically by simulators which understand SD modelling).

Indeed SD turns out to be a good choice as modelling tool (see [3]), but SD is also a good basis for analysis and simulation. On the other side, the principle basic structure of SD with flow and feedback is related to transfer functions, which alternatively can be used as graphical modelling approach for an emotional cycle as discussed in a related contribution [4].

1 Petrarch's Emotional Cycle

Petrarch's poems express 'bouts of ardour and despair', and change drastically in time. Unfortunately, only few lyrics of the Canzoniere are dated. In 1995, Frederic Jones presented an interesting approach to the chronological ordering problem of Petrarch's poems in his book *The Structure of Petrarch's Canzoniere* ([1]).

Jones concentrated on Petrarch's poems written at lifetime of Laura (the first, sonnet X, was written in 1330 and the last, sonnet CCXII, in 1347). First, he analysed 23 poems with fairly secure date. After a careful linguistic and lyrical analysis, he assigned grades for the poems, ranging from -1 to +1, establishing *Petrarch's emotional cycle*: the maximum grade (+1) stands for ecstatic love, while very negative grades correspond to deep despair.

The following examples illustrate this grading (in quotations, the English version is taken from an English translation of the *Canzoniere* by Frederic Jones):

- Sonnet LXXVI, great love → grade: +0.6
  Amor con sue promesse lunsingando,
  mi ricondusse alla prigione antica
  [*Love's promises so softly flattering me*
  have led me back to my old prison's thrall.]
- Sonnet LXXIX, great despair → grade: -0.6
  Cosi mancando vo di giorno in giorno,
  si chiusamente, ch'i' sol me ne accorgo
  et quella che guardando il cor mi strugge.
  [*Therefore my strength is ebbing day by day,*
  which I alone can secretly survey,
  and she whose very glance will
  scourge my heart.]

In a second step, F. Jones analysed and 'graded' all the other poems with unknown date and checked, in which part of the cycle they could fit. Taking into account additional historical information, he could date these poems.

Displaying the grades over time (Figure 3), F. Jones detected an oscillating behaviour of the grade values, which he called *Petrarch's emotional cycle E*(t), with a period of about four years.

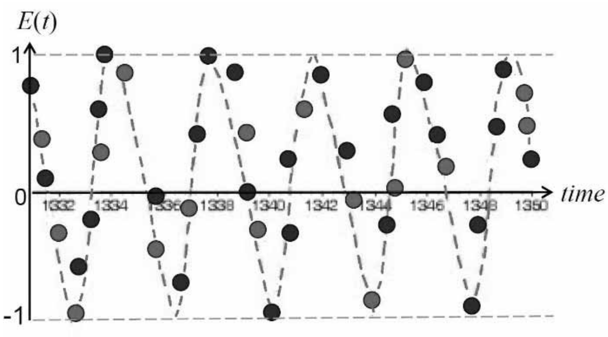

Figure 3: Petrarch's emotional cycle *E(t)* – dashed line, with 'graded' poems; red dots for securely dated poems, blue dots s for poems dated on indirect data (sketch).

2 Model Approach by System Dynamics

System Dynamics (SD) is a well-known modelling approach, introduced by J. Forrester ([5]). SD is a methodology for studying and managing complex feedback systems, such as one finds in business and other social systems. In fact it has been used to address practically every sort of feedback system between aggregated states. Feedback refers to the situation of X affecting Y and Y in turn affecting X e.g. by a chain of causes.

System Dynamics is more than a modelling method – SD diagrams can directly implemented as computer models for simulation experiments.

2.1 Causal loop diagram model

For modelling, SD starts at qualitative level with a causal loop diagram. A *causal loop diagram* (CLD) is a diagram that aids in visualizing how interrelated variables affect one another.

The CLD consists of a set of nodes representing the variables connected together by causal links (Figure 2, causal links between emotions and inspiration in the Laura–Petrarch model). The relationships between these variables, represented by arrows, can be labelled as positive '+' or negative '–'. Positive causal links '+' means that the two nodes move in the same direction, i.e. if the node in which the link start increases, the other node also increases. Similarly, if the node in which the link starts decreases, the other node decreases. Negative causal links '–' are links in which the nodes change in opposite directions (an increase causes a decrease in the other node, or a decrease causes an increase in another node). Sometimes the relations are indefinite '+–'

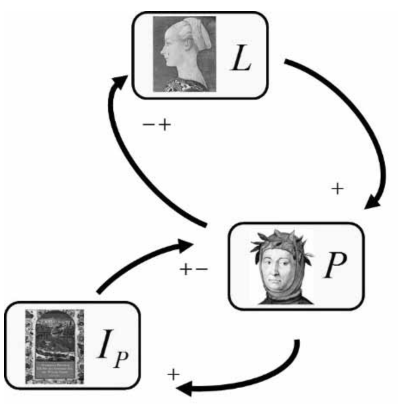

Figure 4: Fully labelled causal loop diagram between Laura's and Petrarch's emotions and Petrarch's inspiration.

In case of Laura's and Petrarch's emotions $L(t)$ and $P(t)$, and Petrarch's inspiration $I_P(t)$, the causal relations are evident and can be partly labelled (Figure 4), but two links are indefinite.

2.2 Stock and flow diagram model

SD continues the modelling process now at the quantitative level by a *stock and flow diagram* (SFD), sometimes also called *level and rate diagram*. Nowadays diverse literature on SD exists, e.g. [6]. A SD model consists of six basic elements summarized in Table 1.

Element	Representation	Description
Stocks (Levels)	Stock Name	Describe the state of the system at each time and represent aggregates
Flows		Describe the changes of the stocks; are basically auxiliaries and are only allowed between stocks and stocks and sinks/sources
Parameters		Are constants and represent rates on which changes of stocks are dependent
Auxiliaries		Are necessary to describe more complex relations combining more inputs
Sink/ Source		Describe the boundaries of the system
Links		Describe the causalities of other elements

Table 1: Basic elements of System Dynamics.

A *stock* variable is measured at one specific time. It represents a quantity existing at a given point in time, which may have been accumulated in the past. A *flow* variable is measured over an interval of time. Therefore a flow would be measured *per unit of time*. The variables in the CLD must be identified either as stock (level) or flow (rate) – or as auxiliary, and each stock (level) is connected in the SFD with its inflow – coming from a source- and by its outflow to a sink; flows are represented by double arrows and flow-controlling valves (rates). The causal links from the CLD are found in the SFD as characterising influences from stocks to flows (or from parameters and auxiliaries to flows). SD makes use of auxiliaries to define more complex feedbacks; auxiliaries may have more than one input, and very often they are table functions defined by data.

3 Laura-Petrarch SD Model

For the dynamics of emotion and inspiration under investigation, Laura's emotion $L(t)$, Petrarch's emotion $P(t)$, and Petrarch's inspiration and $I_P(t)$ are considered as stocks. The basic element of the SFD is the behaviour of emotion and inspiration – they are fading when time goes on – they decrease with respect to their intensity (feedback of stock to output flow; Figure 5).

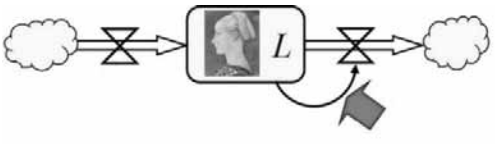

Figure 5: Basic stock and flow diagram for emotions.

Emotions and inspiration are driven by stimulations – input flow of the stock. Petrarch's emotion $P(t)$ is driven by Laura's emotion $L(t)$ (feedback from stock Laura to input flow Petrarch; Figure 6), and by his inspiration $I_P(t)$ (feedback from stock Inspiration to input flow Petrarch; Figure 6). Laura's emotion $L(t)$ is driven by Petrarch's emotion $P(t)$ (feedback from stock Petrarch to input flow Laura; Figure 6), and the inspiration $I_P(t)$ is driven by Petrarch's emotion $P(t)$ (feedback from stock Petrarch to input flow Inspiration; Figure 6). So a first simple SFD (Figure 6) for the dynamics shows the feedback structures for the driving stimulations and for the decrease by fading (Figure 6).

SD's modelling procedures now quantify the qualitative SFD by introducing parameters and auxiliaries for the causal links and for the influences on the flows. Laura's and Petrarch's emotions and Petrarch's intuition are fading with certain celerity, characterised by the gain parameters α_L, α_P, and α_{IP} in the direct feedbacks.

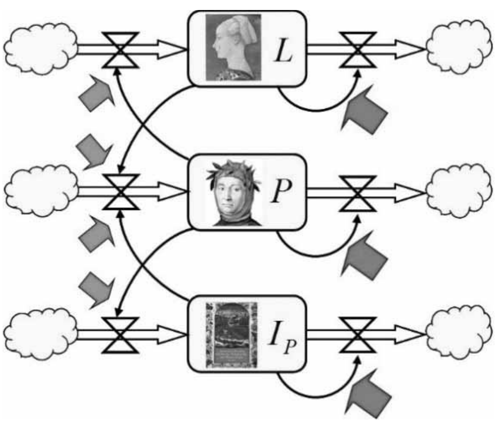

Figure 6: Qualitative stock and flow diagram for Laura's and Petrarch's emotions and for Petrarch's inspiration.

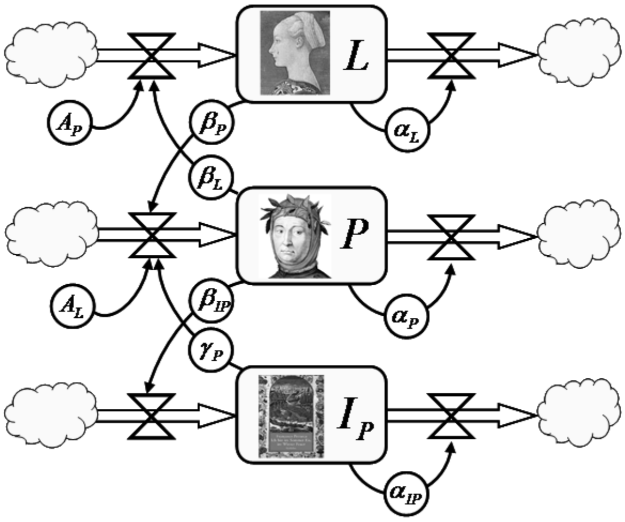

Figure 7: Stock and flow diagram for Laura's and Petrarch's emotions and for Petrarch's inspiration with only linear influences.

The driving stimulations for the emotions $L(t)$ and $P(t)$ are given by a general appeal (A_L Laura's appeal, A_P Petrarch's appeal) and by the respective gained 'counter'-emotion, which is for first a proportion of the respective emotion, characterized by gaining parameters β_P and β_L in the feedbacks: Petrarch's emotion is stimulated by an additional feedback from inspiration, a feedback from inspiration, characterized by a gaining parameters γ_P in the feedback. The driving stimulation for inspiration $I_P(t)$ is a proportion of Petrarch's emotion, characterized by gaining parameter β_{IP} in the feedback.

The resulting SFD for the dynamics of emotion and inspiration in Figure 7 shows all basic feedbacks and direct inputs for the flows, gained with parameters or simple 'gaining' auxiliaries. This structure is a classic linear one: the ODE system shows only linear behaviour, and is therefore only a first approach for the more complex relations.

But two of the driving stimulations turn out to be more complex, Laura's reaction on Petrarch's emotion, and Laura's appeal to Petrarch – the 'simple' gaining with a parameter and the simple constant appeal A_L are not sufficient.

Complexity of Laura's reaction. First, the reaction feedbacks between the emotions need further investigations. The 'linear' approach more or less says, that individuals love to be loved and hate to be hated, and that they expect a 'linear' feedback from the other. This 'simple' behaviour is evident for Petrarch, since in his poems the poet has very intense reactions to the most relevant signs of antagonism from Laura.

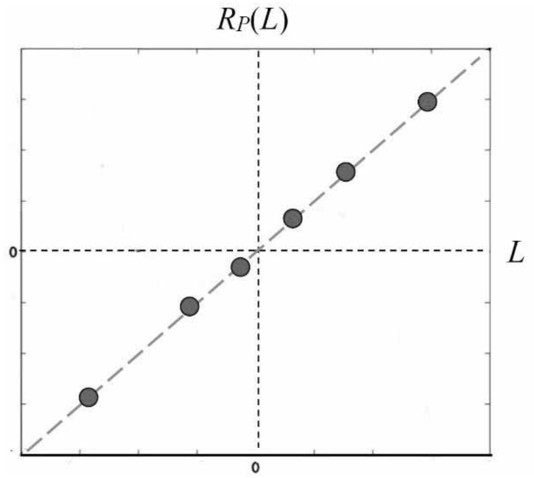

Figure 8: Petrarch's reaction on Laura's emotion
– red dots tabulated function'
– dashed line as interpolating linear line.

So indeed this emotion directly follows the emotion shown by Laura, displayed in Figure 8 as table function (red dots with tabulated values, dashed line as interpolating curve), or given in mathematical terms:

$$R_P = \beta_P \cdot L\,.$$

Laura evolves a more complex reaction to Petrarch's emotion – summarized in Figure 9 (red dots with tabulated values, dashed line as approximation curve). A 'linear' reaction function is not appropriate for Laura, except for little emotions, thus interpreting the natural inclination of a beautiful high-society lady to stimulate harmless flirtations (Figure 9, first blue dots left and right from zero). But Laura never goes too far beyond gestures of pure courtesy: she smiles and glances.

However, when Petrarch becomes more demanding and puts pressure on her, even indirectly when his poems are sung in public, she reacts very promptly and rebuffs him. This is not an assumption, this behaviour can be read more or less explicitly in a number of poems, e.g. in Sonnet XXI:

- In Sonnet XXI, Petrarch claims:

  Mille fiate, o dolce mia guerrera,
  per aver co' begli occhi vostri pace
  v'aggio proferto il cor; ma voi non piace
  mirar si basso colla mente altera.

  [*A thousand times, o my sweet enemy,*
  to come to terms with your enchanting eyes
  I've offered you my heart, yet you despise
  aiming so low with mind both proud and free.]

Consequently, the reaction function $R_L(P)$ should, for positive emotions of Petrarch, first increase, and then decrease (Figure 9, blue dots right from zero).

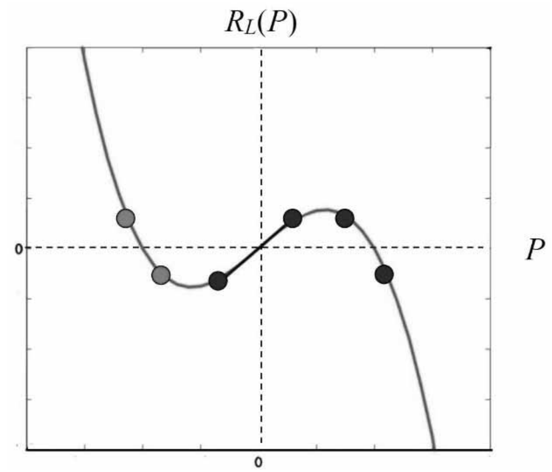

Figure 9: Laura's reaction on Petrarch's emotion
– red and blue dots: tabulated function'
– dashed line: approximating curve
(cubic function).

But Laura' reaction is also more complex ('nonlinear') for Petrarch in despair (negative emotions of Petrarch). Indeed, when the poet despairs, Laura feels very sorry for him, showing despair herself. Following her genuine Catholic ethic she arrives at the point of overcoming her antagonism by strong feelings of pity, thus reversing her reaction to the passion of the poet. This behavioural characteristic of Laura is repeatedly described in the *Canzoniere*, e.g. in Sonnet LXII

- In Sonnet LXIII Petrarch writes:

  Volgendo gli occhi al mio novo colore
  che fa di morte rimembrar la gente,
  pieta vi mosse; onde, benignamente
  salutando, teneste in vita il core.

  [*Casting your eyes upon my pallor new,*
  which thoughts of death recalls to all mankind,
  pity in you I've stirred; whence, by your kind
  greetings, my heart to life's kept true.]

Consequently, the reaction function $R_L(P)$ should for negative emotions of Petrarch first decrease, and then increase (Figure 9, blue dot and red dots left from zero).

Combining both branches of this the heuristic feedback results first in a table function with few n heuristically derived tabulated values, which directly can be used as auxiliary in SD models:

$$R_L(P) = TAB\left(\left(P_1, R_{L,1}\right), \dots, \left(P_n, R_{L,n}\right); P\right)$$

Mathematically this table function can be approximated by a cubic function (displayed in Figure 9 as dashed curve), which alternatively can be used as auxiliary in the SD model, or for analytical investigations:

$$R_L(P) = P \cdot \left(1 - \left(\frac{P}{\gamma_L}\right)^2\right)$$

Complexity of Laura's appeal. Laura's appeal A_L to Petrarch evolves also complex behaviour, it depends on inspiration $I_P(t)$, which indirectly expresses, whether Petrarch's desire is poetic or passionate. And there is no doubt that the tensions between Petrarch and Laura are of a passionate nature, expressed in Petrarch's work:

- In Sonnet XXII, Petrarch writes:
  Con lei foss'io da che si parte il sole,
  et non ci vedess' altri che le stelle,
  sol una nocte, et mai non fosse l'alba.
  [*Would I were with her when first sets the sun, and*
  no one else could see us but the stars,
  one night alone, and it were never dawn.]
- And in his *Posteritati*, Petrarch confesses:
  Libidem me prorsus expertem dicere
  posse optarem quidem, sed si dicat mentiar.
  [*I would truly like to say absolutely that*
  I was without libidinousness, but if I said
  so I would be lying].

These investigations in Petrach's writing conclude, that Laura's appeal to Petrarch depends on antagonism between lyric inspiration and desire, taking into account the well-established fact that high moral tensions, like those associated with artistic inspiration, attenuate the role of the most basic instincts. The Appeal A_L becomes dependent on the inspiration $I_P(t)$.

Figure 10 sketches the assumed correlation: the less inspiration (and the less time used for writing), the higher the desire lets increase the appeal (Figure 10, left red dots); and the more inspiration (and the more time for poetry), the lower the passionate part in the appeal (Figure 10, right blue dots).

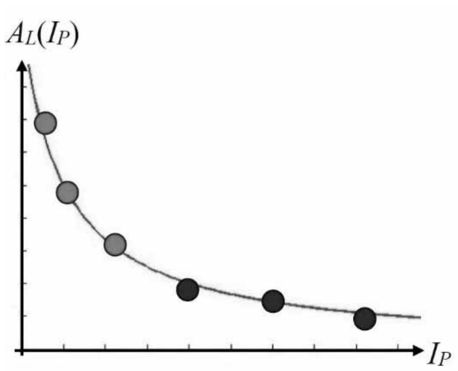

Figure 10: Laura's appeal to Petrarch's dependent inspiration: poetic vs. passionate desire
- blue and red dots: heuristic tabulated values
- dashed curve: approximating hyperbolic function.

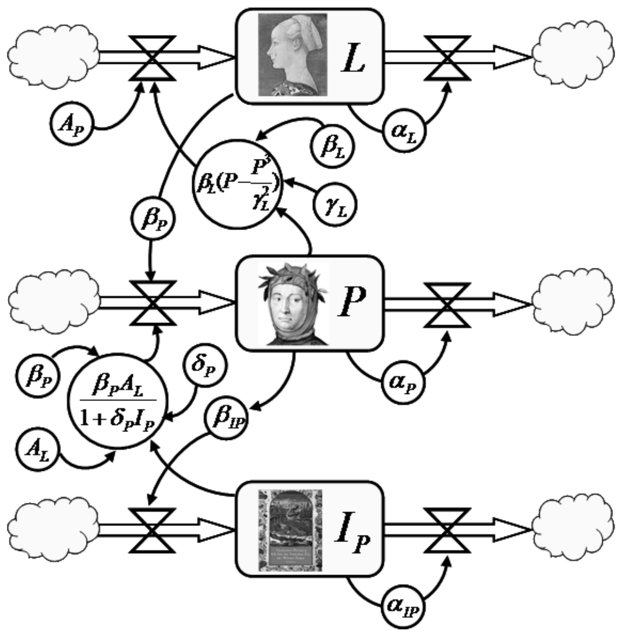

Figure 11: Full stock and flow diagram SD model for Laura's and Petrarch's emotions and for Petrarch's inspiration.

These considerations result first in a table function with few m heuristically derived tabulated values, which directly can be used as auxiliary in SD models:

$$A_{L,I_P}(I_P) = TAB\left(\left(A_{L,1}, I_{P,1}\right), \dots, \left(A_{L,m}, I_{P,m}\right); I_P\right)$$

Mathematically this table function can be approximated by a hyperbolic function (displayed in Figure 10 as dashed curve), which alternatively can be used as auxiliary in the SD model, or for analytical investigations:

$$A_{L,I_P}(I_P) = \frac{A_L}{1 + \delta_P \cdot I_P}$$

Full stock and flow diagram model. With table functions or with analytical functions for Laura's reaction on Petrarch's emotion $R_L(P)$ and Laura's appeal for Petrarch A_{L,I_P} now the full SFD model can be compile, as given in Figure 11.

The 'nonlinear' relations for Laura's appeal and reaction are of different quality. Choosing in the nonlinear cubic-like gain for Laura's reaction $R_L(P)$ a big value for the parameter γ_L, the nonlinear auxiliary becomes almost linear (the nominator is bounded, usually less than 1). The nonlinear auxiliary for Laura's appeal A_L becomes linear, if the parameter δ_P is set to zero, letting the influence of Petrarch's poetic inspiration vanish.

The SFD model allows to derive the ODE model, which in this case is given by

$$\frac{dL}{dt} = -\alpha_L \cdot L + \beta_L \cdot TAB\left(\left(P_{i1}, R_{L,i}\right); P\right) + \beta_L \cdot A_P$$
$$\frac{dP}{dt} = -\alpha_P \cdot P + \beta_P L + \beta_P \cdot TAB\left(\left(A_{L,i}, I_{P,i}\right); I_P\right)$$
$$\frac{dI_P}{dt} = -\alpha_{IP} \cdot I + \beta_{IP} P \qquad or\ by$$
$$\frac{dL}{dt} = -\alpha_L \cdot L + \beta_L \cdot P \cdot \left(1 - \left(\frac{P}{\gamma_L}\right)^2\right) + \beta_L \cdot A_P$$
$$\frac{dP}{dt} = -\alpha_P \cdot P + \beta_P L + \beta_P \cdot \frac{A_L}{1 + \delta_P \cdot I_P}$$
$$\frac{dI_P}{dt} = -\alpha_{IP} \cdot I + \beta_{IP} P$$

This ODE system can be generated automatically by an appropriate SD simulation system, sometimes it is directly translated into a discrete model using Euler integration formula.

4 Identification of Laura–Petrarch SD Model

The big challenge is to identify the model parameters in the nonlinear *Laura-Petrarch Model*, with two appeal parameters, with three gains, with three time constants, and with two parameters for the nonlinearity – in sum ten parameters. A brute-force identification starting with arbitrary values for these parameters is not successful, especially as the appeals may also be negative.

Consequently first the size of the parameters and relations between them should be qualitatively analysed, following S. Rinaldi ([2]). The time constants α_L, α_P, and α_{IP} describe the forgetting processes. For Laura and Petrarch obviously $\alpha_L > \alpha_P$ holds, because Laura never appears to be strongly involved, while the poet definitely has a tenacious attachment, documented by poems:

- In sonnet XXXV Petrarch claims:
  Solo et pensoso i piu deserti campi
  vo mesurando a passi tardi e lenti,
  …….
  Ma pur si aspre vie ne' si selvage
  cercar non so ch' Amor non venga sempre
  ragionando con meco, et io col'lui.
  [*Alone and lost in thought, each lonely strand*
  I measure out with slow and laggard step,
  ………
  Yet I cannot find such harsh and savage trails
  where love does not pursue me as I go,
  with me communing, as with him do I.]

The inspiration of the poet wanes very slowly, because Petrarch continues to write (over one hundred poems) for more than ten years after the death of Laura. The main theme of these lyrics is not his passion for Laura, which has long since faded, but the memory for her and the invocation of death:

- In Sonnet CCLXVIII, written about two years after Laura's demise, Petrarch remembers:
  Tempo e ben di morire,
  et o tardato piu ch'i non vorrei.
  Madonna e morta, et a
  seco il mio core;
  e volendol seguire,
  interromper conven quest'anni rei,
  perche mai veder lei
  di qua non spero, et l'aspettar
  m'e noia.
  [*It's time indeed to die,*
  and I have lingered more than I desire.
  My lady's dead, and with her my heart lies;
  and, keen with her to fly,
  I now would from this wicked world retire,
  since I can no more aspire
  on earth to see her, and delay will me destroy.]

Consequently between the time constants α_{IP} and α_p the relation $\alpha_{IP} < \alpha_p$ must hold. As Petrarch's inspiration holds about ten years, whereas Laura forgets Petrarch in about four months, and Petrarch's passion fades in one year, suitable relations and values are

$$\alpha_L \sim 3 \cdot \alpha_P,\ \alpha_P \sim 10 \cdot \alpha_{IP},\ \alpha_P \sim 1$$

The gains or reaction parameters β_L, β_p, and β_{IP} also can be estimated qualitatively, with respect to the time constants:

$$\beta_L \sim \alpha_P,\ \beta_P \sim 5 \cdot \alpha_P,\ \beta_{IP} \sim 10 \cdot \alpha_P$$

Here the assumption is that Laura's reaction equals the forgetting time of Petrarch, and Petrarch reacts five times stronger. For simplicity, the parameters γ_L and δ_P are normalised to one, since it is always possible to scale $P(t)$ and $I_P(t)$ suitably.

The choice of the appeal parameters A_L and A_P is crucial, because these parameters determine the qualitative behaviour of emotion dynamics – cyclic nonlinear behaviour, or damped oscillation toward an equilibrium. In case of Laura and Petrarch, cyclic love dynamics are expected in order to meet the experimentally founded emotional cycle $E(t)$ of Petrarch.

Clearly, Petrarch loves Laura, so for the basic appeal $A_L > 0$ must hold and indeed Laura is a beautiful woman – Figure 12 shows some historic portraits.

Figure 12: Portraits of Laura and Petrarch, from Internet resources.

It is to be noted, that the Laura's basic appeal A_L is modified by the before given hyperbolic function to Laura's inspiration-dependent appeal $A_{L,I_P}(I_P)$.

By contrast, Petrarch is a 'cold scholar interested in history and letters'. He is appointed a *cappellanus continuus commensalis* by Cardinal Giovanni Colonna, and this ecclesiastic appointment brings him frequently to Avignon, where Laura lives. Consequently Petrarch's appeal A_P is assumed to be negative. Appropriate choices for the appeals A_L and A_P are:

$$A_L \sim 2,\ \ A_P \sim -1$$

The negativity of the appeal of Petrarch (see also the portraits in Figure 12) is somehow recognized by the poet himself:

- In sonnet XLV, while Petrarch is talking about Laura's mirror, he says
  Il mio adversario in cui veder solete
  gli occhi vostri ch'Amore
  e'l ciel honora, …
  [*My rival in whose depths*
  you're wont to see
  your own dear eyes which
  Love and heaven apprize, ...]

The above estimated ten parameter values, together with zero initial values for emotion dynamics and for the poetic inspiration, are a good choice for identification. For identification, a least squares method can be used, which minimizes the difference between the data (the grades given by the emotional cycle E_K) and Petrarch's emotion $P(t_k)$ from the SD model at defined time instants t_k, using the parameter relation derived before:

$$\sum (P(t_k) - E_k)^2 \quad \rightarrow \quad \min$$

Figure 9 shows an identification result for Petrarch's emotions $P(t)$ vs. Petrarch's emotional cycle with data $E(t_k)$ ('graded' poems).

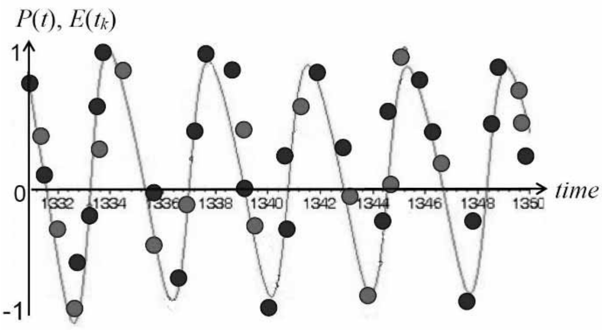

Figure 13: Result of model identification: love dynamics *P(t)* for Petrarch coinciding with data from Petrarch's emotional cycle *E(t$_k$)*, with data E_k (blue and red dots).

Figure 14 shows all results for the identified parameters, structured within a graphical user interface for experimenting with parameter changes. The results of the numerical solution are qualitatively in full agreement with the *Canzoniere* and with the analysis of Frederic Jones. Petrarch's emotion $P(t)$ tends toward a regular cycle characterised by alternate positive and negative peaks. Also, Laura's emotion $L(t)$ and Petrarch's poetic inspiration $I_P(t)$ tend towards a cyclic pattern.

At the beginning, Petrarch's inspiration $I_P(t)$ rises much more slowly than his emotion and then remains positive during the entire period. This might explain why Petrarch wrote his first poem more than three years after he has met Laura, but then continues to produce lyrics without any significant interruption.

By contrast, Laura's emotion is always negative. This is in perfect agreement with the *Canzoniere*, where Laura is repeatedly described as adverse:

- In sonnet XXI, Petrarch calls Laura
  dolce mia guerrera
  [*my sweet enemy*].
- But in sonnet XLIV Petrarch says:
  ne lagrima pero discese anchora
  da' be' vostr'occhi, ma disdegno et ira.
  [*and still no tears your lovely eyes assail,*
  nothing as yet, but anger and disdain.]

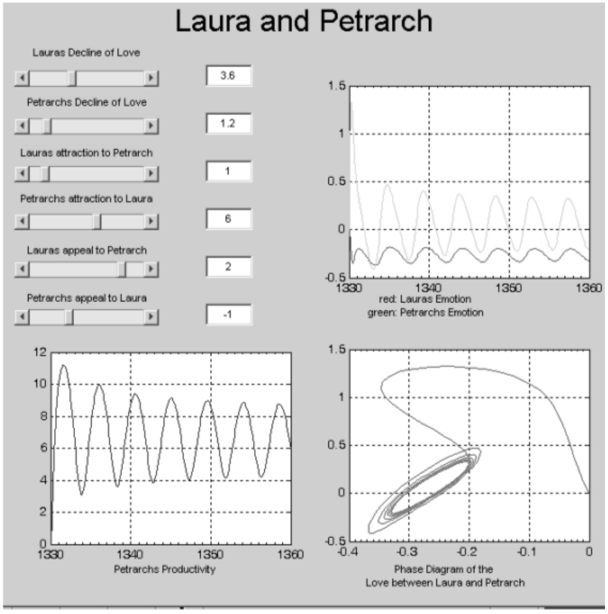

Figure 14: GUI for experimenting with the Laura-Petrarch Model, with parameter values from identification:
i) above left: sliders for gain β_L, time constant α_L, gain β_P, time constant α_P, and appeals A_L and A_P;
ii) upper right: Laura's emotion L (green) and Petrarch's emotion *P* (red) over time period 1130 - 1360;
iii) lower left: Petrarch's inspiration I_P, (blue) over time -
iv) lower right: phase portrait *P(L)* of love dynamics of Petrarch and Laura – *P* over *L* with nonlinear cycle.

5 Experiments with Laura-Petrarch SD Model

Experiments with the parameters show, that the cyclic emotional dynamics may change to a damped oscillation converging to equilibrium. It is difficult to find out which parameter quality causes a cyclic behaviour, and which the damped oscillations. Rinaldi ([2]) has investigated the behaviour carefully, finding a Hopf bifurcation which switches from cyclic to converging stable behaviour. Here two results from simulations with parameter change are shown

5.1 Laura's fast fading emotions

Starting with the classic Laura–Petrarch parameters, an increase of only one parameter α_L by a factor of 2.5 changes the qualitative behaviour essentially (Figure 15) – this parameter change means, that Laura forgets Petrarch in about half time than before. Result is a strongly damped behaviour converging to equilibrium with very small positive and negatives value for *P* and *L*, resp.

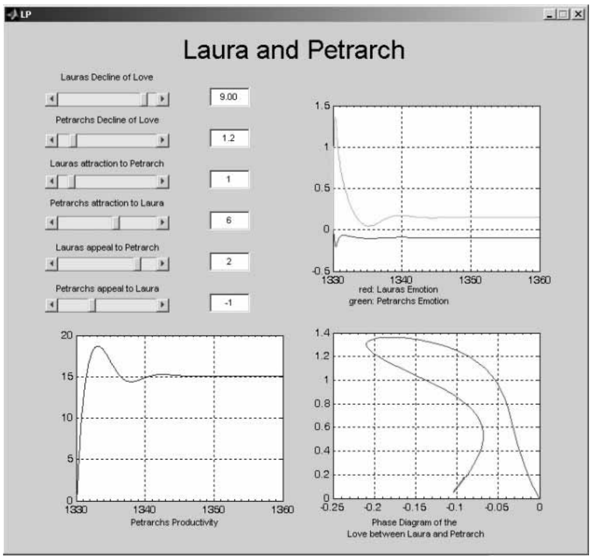

Figure 15: Experiment with Laura-Petrarch Model: Laura's fast fading emotions.

5.2 Petrarch with positive appeal

An interesting experiment is the case of an attractive Petrarch. Supposing e.g. that Petrarch is a young beautiful men, almost like Apollo, he may have the appeal $A_L \sim 6$ to Laura, three times the appeal of Laura to him (all other parameters unchanged).

Figure 16 shows the results: emotions and inspiration are very strongly damped and converge to steady states with relative high positive values – but this is a boring development. This surprising results may conclude, that for non-boring emotions it is necessary, that appeal is opposite.

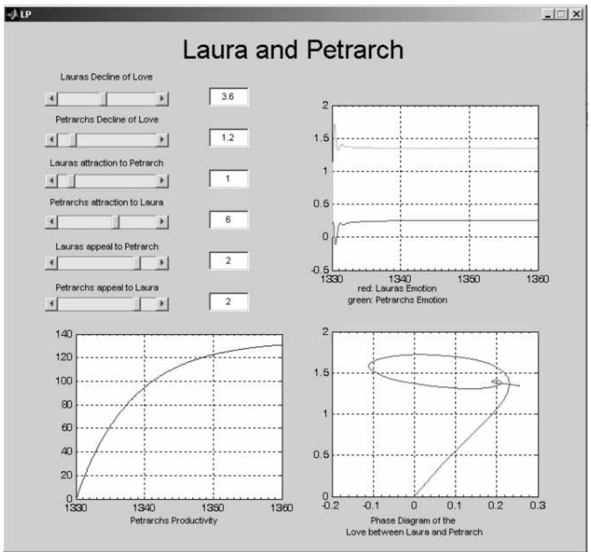

Figure 16: Experiment with Laura-Petrarch Model: Petrarch with positive appeal.

6 Nowadays Couple SD Model

In times of gender equality women as well as men may play an active part in a love affair. Consequently also women express their love by poems or other media, and they confess their love to public. By this, an additional stock with flow for the woman's inspiration can be introduced easily. For Laura and Petrarch this would mean, that also Laura writes poems, that Petrarch's appeal is influenced by Laura's poetic inspiration, and that Petrarch shows more sensibility in his reaction to Laura. Consequently, the structure of the System Dynamics model (Figure 17) suggests a genuine and natural extension: symmetric stocks, flows, and feedbacks gains as well for 'Petrarch' and for 'Laura', which should now generally represent a man and a women who show emotions to each other.

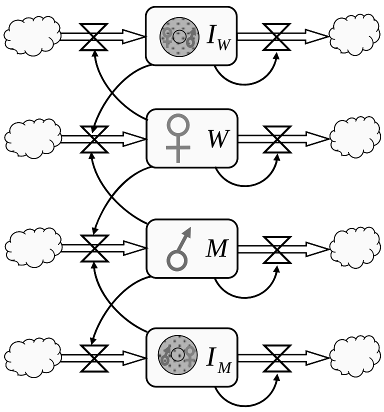

Figure 17: Qualitative SFD model for emotions and inspirations in Nowadays Couple Model.

6.1 Full Nowadays-Couple SD model

The *Nowadays Couple* SD model describes the emotion dynamics $W(t)$ for a woman, and $M(t)$ for a man both falling in love to each other; love inspires both the communicate their love to public, in letters, in videos, with CDs and DVDs, etc. – represented by the inspiration variables $I_W(t)$ and $I_M(t)$.

Also men are now following the more sensitive but more complex behaviour in the reactions to the partner's emotions. Now, because of the symmetry in emotions and inspirations, the model makes use of two nonlinear cubic-like reaction functions for woman's and man's reaction to each other, and of two nonlinear relations between inspiration, appeal, and emotion.

Figure 16 presents the complete nonlinear *Nowadays Couple* SD model in SFD notation,

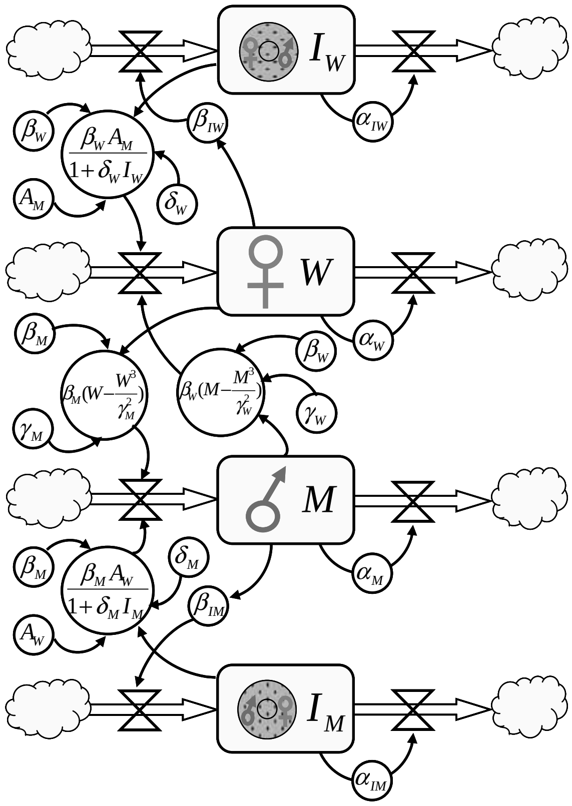

Figure 18: SD Stock and flow diagram for *Nowadays Couple Model* with nonlinear reactions and appeal.

Compared with the *Laura-Petrarch Model*, the *Nowadays-Couple Model* must make use of an increased number of parameters: four fading parameters (instead of three), four (linear) weighting factors for the cross-feedbacks (instead of three), two appeal parameters (instead of one), and four parameters in the nonlinear functions (instead of two) – in sum 14 parameters.

A theoretical analysis of this model is almost impossible, but numerical experiments may give interesting insight into emotion dynamics. The ODE model derived from the SFD (Figure 18) shows – as the SFD – a symmetric structure:

$$\frac{dW(t)}{dt} = -\alpha_L W(t) + \beta_W M\left(1 - \left(\frac{M}{\gamma_W}\right)^2\right) + \beta_W \frac{A_M}{1 + \delta_W I_W(t)}$$

$$\frac{dI_W(t)}{dt} = -\alpha_{IW} I_W(t) + \beta_{IW} W(t)$$

$$\frac{dM(t)}{dt} = -\alpha_M M(t) + \beta_M W\left(1 - \left(\frac{W}{\gamma_M}\right)^2\right) + \beta_M \frac{A_W}{1 + \delta_M I_M(t)}$$

$$\frac{dI_M(t)}{dt} = -\alpha_{IM} I_M(t) + \beta_{IM} M(t)$$

6.2 Experiments with Nowadays-Couple SD model

As with the *Laura–Petrarch Model*, the *Nowadays Couple Model* has been implemented in a graphical user interface (GUI) for experimenting with parameters and displaying solutions: emotion dynamics with cycle limit, convergence to stable constant emotion limit (with few or many waves, with positive and / or negative limit value for emotion), etc. Among 14 parameters, it is difficult to find parameters for specific behaviour.

For demonstration purposes, therefore a simplified GUI has been developed, which allows selection of certain specific cases with predefined parameters. Figure 19 and Figure 20 present two of these case studies:

- 'Everyday Boring': Almost no waves in the emotions, fast convergence to a stable constant emotion value (positive for women, negative for man)
- 'Pretty and Ugly': Opposite parameters (one pretty, one ugly) result in a fast waves in both emotions for the first five years, then convergence to a relatively high constant emotion value for both.

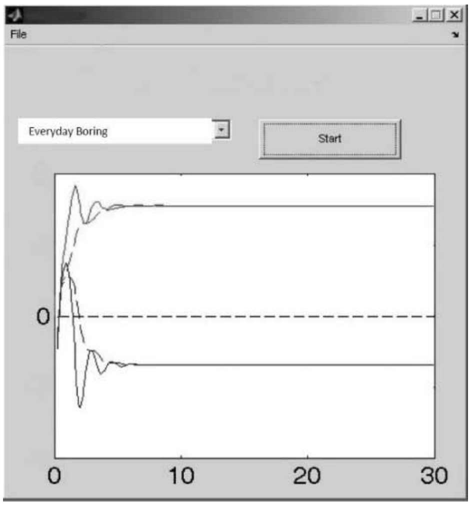

Figure 19: Nowadays Couple Model
Experiment 'Everyday Boring'
- red/blue – woman's/men's emotion;
- red/blue dashed – woman's/men's inspiration).

Time-dependent appeals. Does the *Nowadays Couple Model* reflect reality? The model is able to mimicry different situations, but with one assumption: the general appeal parameters A_M and A_W are constant up to now (note: they are multiplied by the hyperbolic functions depending on inspiration, but themselves they are constant). This assumption may not meet reality; the appeal for each other may change over time, e.g. aging, and they also may be manipulated and controlled.

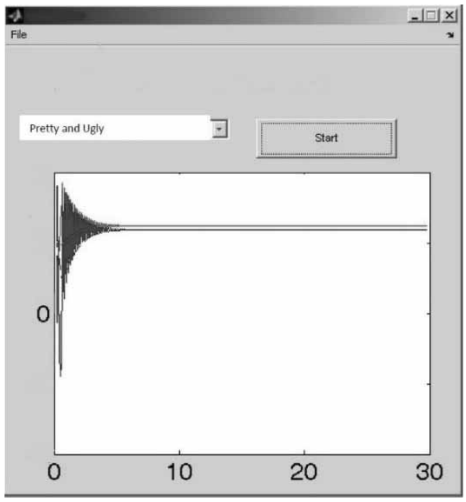

Figure 20: Nowadays Couple Model
Experiment 'Pretty and Ugly
- red/blue – woman's/men's emotion.

A dynamic appeal can be easily modelled by time-dependent general appeal variables $A_M(t)$ and $A_W(t)$, either by a specific mathematical time function, or simply by an only time-dependent table function):

$$A_M(t) = TAB\left(\left(A_{M,1}, t_1\right), \ldots, \left(A_{M,n}, t_n\right); t\right)$$

Case studies may become now very complicated, because not only 14 parameters have to be chosen appropriately, but also the function $A_M(t)$ and $A_W(t)$ have to be provided meaningful.

An extended version of the GUI presented in the two figures before allows additionally providing predefined appeal functions. Figure 21 and Figure 22 show results for perhaps interesting cases:

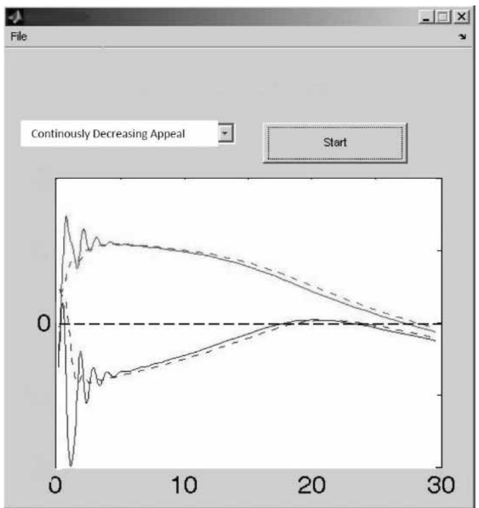

Figure 21: Nowadays Couple Model
Experiment 'Continuously Decreasing Appeal'
- red/blue – woman's/man's love emotion;
- red/blue dashed – woman's/man's inspiration).

- 'Continuously Decreasing Appeal': the appeals decreases exponentially, resulting in a convergence of the emotions to small values
- 'Jump in Appeal – Aesthetic Surgery': after ten years of fading emotions, e. g. an aesthetic surgery increases the women's appeal, resulting in a jump of emotions – into positive for her, into negative for him, but followed by same emotion fading than before.

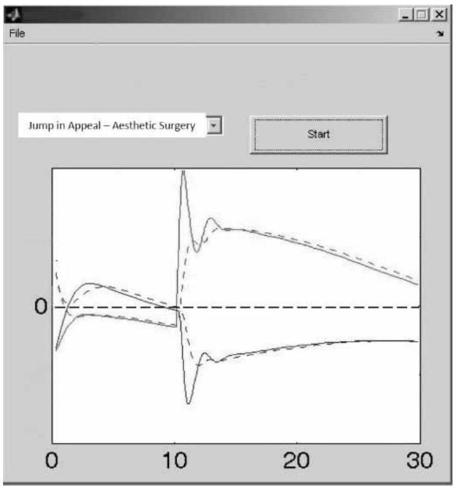

Figure 22: Nowadays Couple Model
Experiment 'Jump in Appeal – Aesthetic Surgery'
- red/blue – woman's/man's love emotion;
- red/blue dashed – woman's/man's inspiration.

7 Conclusion

The method of *System Dynamics* is indeed a valuable tool for modelling social systems – as the investigated system of emotions. In contrary to engineering, no precise forecasts can be made, only scenarios can help for better understanding.

Of course, this contribution presents serious investigations. But is it possible to investigate the dynamics of emotions, perhaps the most important phenomenon concerning our lives, seriously by methods of mathematics and engineering? One could also conclude, it might be better not to tackle the secrets of love, because described and controlled by formula, it is not love anymore longer. In this view, the contribution might be seen as reference to Petrarch and the most beautiful love poems the author ever read.

Modelling methodology provides a classification for models – where also the type *Verbal Model* can be found. On occasion of Petrarch's 800th birthday, his sarcophagus was opened, and near to Petrarch's skull a bottle was found (Figure 23), with a manuscript of a sonnet:

Figure 23: Bottle with manuscript of sonnet, in Petrarch's sarcophagus.

- *Benedette le voci tante ch'io*
  chiamando il nome de mia donna ò spare,
  e I suspire, et le lagrime, e 'l desio;
  et benedette sian tutte le carte
  ov'io fama l'acquisto, e 'l pensier mio,
  ch'è sol di lei, sí ch'altra non v'à parte.
- *[And blessed be all of the poetry*
  I scattered, calling out my lady's name,
  and all the sighs, and tears, and the desire;
  blessed be all the paper upon which
  I earn her fame, and every thought of mine,
  only of her, and shared with no one else.]

Perhaps this sonnet is the best model for the emotions expressed in poems – the *Verbal Model* for the emotions is the sonnet itself.

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SNE Repres.	Felix Breitenecker *felix.breitenecker@tuwien.ac.at*

SNE – Simulation Notes Europe. SNE is a scientific journal with reviewed contributions as well as a membership newsletter for **EUROSIM** with information from the societies in the *News Section*. **EUROSIM** societies are offered to distribute to their members the journal **SNE** as official membership journal. **SNE** Publishers are **EUROSIM**, ARGESIM and ASIM.

Editor-in-chief	Felix Breitenecker *felix.breitenecker@tuwien.ac.at*

→ *www.sne-journal.org,*
office@sne-journal.org

EUROSIM Congress. **EUROSIM** is running the triennial conference series **EUROSIM** Congress. The congress is organised by one of the **EUROSIM** societies.

EUROSIM 2016 will be organised by SIMS in Oulu, Finland, September 16-20, 2016.

Chairs / Team EUROSIM 2016
Esko Juuso EUROSIM President, *esko.juuso@oulu.fi* Erik Dahlquist SIMS President, *erik.dahlquist@mdh.se* Kauko Leiviskä EUROSIM 2016 Chair, *kauko.leiviska@oulu.fi*

→ *www.eurosim.info*
office@automaatioseura.fi

EUROSIM Member Societies

ASIM
German Simulation Society
Arbeitsgemeinschaft Simulation

ASIM (Arbeitsgemeinschaft Simulation) is the association for simulation in the German speaking area, servicing mainly Germany, Switzerland and Austria. ASIM was founded in 1981 and has now about 700 individual members, and 30 institutional or industrial members.

→ *www.asim-gi.org* with members' area

info@asim-gi.org, admin@asim-gi.org

ASIM – Inst. f. Analysis and Scientific Computing
Vienna University of Technology
Wiedner Hauptstraße 8-10, 1040 Vienna, Austria

ASIM Officers	
President	Felix Breitenecker *felix.breitenecker@tuwien.ac.at*
Vice presidents	Sigrid Wenzel, *s.wenzel@uni-kassel.de*
	T. Pawletta, *pawel@mb.hs-wismar.de*
Secretary	Ch. Deatcu, *christina.deatcu@hs-wismar.de*
Treasurer	Anna Mathe, *anna.mathe@tuwien.ac.at*
Membership Affairs	S. Wenzel, *s.wenzel@uni-kassel.de*
	W. Maurer, *werner.maurer@zhwin.ch*
	Ch. Deatcu, *christina.deatcu@hs-wismar.de*
	F. Breitenecker, *felix.breitenecker@tuwien.ac.at*
Universities / Research Inst.	S. Wenzel, *s.wenzel@uni-kassel.de*
	W. Wiechert, *W.Wiechert@fz-juelich.de*
	J. Haase, *Joachim.Haase@eas.iis.fraunhofer.de*
	Katharina Nöh, *k.noeh@fz-juelich.de*
Industry	S. Wenzel, *s.wenzel@uni-kassel.de*
	K. Panreck, *Klaus.Panreck@hella.com*
Conferences	Klaus Panreck *Klaus.Panreck@hella.com*
	J. Wittmann, *wittmann@htw-berlin.de*
Publications	Th. Pawletta, *pawel@mb.hs-wismar.de*
	Ch. Deatcu, *christina.deatcu@hs-wismar.de*
	F. Breitenecker, *felix.breitenecker@tuwien.ac.at*
Repr. EUROSIM	F. Breitenecker, *felix.breitenecker@tuwien.ac.at*
	A. Körner, *andreas.koerner@tuwien.ac.at*
Education / Teaching	A. Körner, *andreas.koerner@tuwien.ac.at*
	S. Winkler, *stefanie.winkler@tuwien.ac.at*
	Katharina Nöh, *k.noeh@fz-juelich.de*
Int. Affairs – GI Contact	N. Popper, *niki.popper@drahtwarenhandlung.at*
	O. Rose, *Oliver.Rose@tu-dresden.de*
Editorial Board SNE	T. Pawletta, *pawel@mb.hs-wismar.de*
	Ch. Deatcu, *christina.deatcu@hs-wismar.de*
Web EUROSIM	A. Körner, *andreas.koerner@tuwien.ac.at*

Last data update June 2016

ASIM Working Committee	
GMMS	Methods in Modelling and Simulation Th. Pawletta, *pawel@mb.hs-wismar.de*
SUG	Simulation in Environmental Systems Wittmann, *wittmann@informatik.uni-hamburg.de*
STS	Simulation of Technical Systems H.T.Mammen, *Heinz-Theo.Mammen@hella.com*
SPL	Simulation in Production and Logistics Sigrid Wenzel, *s.wenzel@uni-kassel.de*
EDU	Simulation in Education/Education in Simulation A. Körner, *andreas.koerner@tuwien.ac.at*
DATA	Working Group Data-driven Simulation in Life Sciences; *niki.popper@drahtwarenhandlung.at*
	Working Groups for Simulation in Business Administration, in Traffic Systems, for Standardisation, etc.

CEA-SMSG – Spanish Modelling and Simulation Group

CEA is the Spanish Society on Automation and Control and it is the national member of IFAC (International Federation of Automatic Control) in Spain. Since 1968 CEA-IFAC looks after the development of the Automation in Spain, in its different issues: automatic control, robotics, SIMULATION, etc. In order to improve the efficiency and to deep into the different fields of Automation. The association is divided into national thematic groups, one of which is centered on Modeling, Simulation and Optimization, constituting the CEA Spanish Modeling and Simulation Group (CEA-SMSG). It looks after the development of the Modelling and Simulation (M&S) in Spain, working basically on all the issues concerning the use of M&S techniques as essential engineering tools for decision-making and optimization.

→ *http://www.ceautomatica.es/grupos/*

→ *emilio.jimenez@unirioja.es*
simulacion@cea-ifac.es

CEA-SMSG / Emilio Jiménez, Department of Electrical Engineering, University of La Rioja, San José de Calasanz 31, 26004 Logroño (La Rioja), SPAIN

CEA - SMSG Officers	
President	Emilio Jiménez, *emilio.jimenez@unirioja.es*
Vice president	Juan Ignacio Latorre *juanignacio.latorre@unavarra.es*
Repr. EUROSIM	Emilio Jiminez, *emilio.jimenez@unirioja.es*
Edit. Board SNE	Emilio Jiminez, *emilio.jimenez@unirioja.es*
Web EUROSIM	Mercedes Perez *mercedes.perez@unirioja.es*

Last data update June 2016

CROSSIM – Croatian Society for Simulation Modelling

CROSSIM-*Croatian Society for Simulation Modelling* was founded in 1992 as a non-profit society with the goal to promote knowledge and use of simulation methods and techniques and development of education. CROSSIM is a full member of **EUROSIM** since 1997.

→ *www.eurosim.info*

☏ *vdusak@foi.hr*

✉ CROSSIM / Vesna Dušak
Faculty of Organization and
Informatics Varaždin, University of Zagreb
Pavlinska 2, HR-42000 Varaždin, Croatia

CROSSIM Officers	
President	Vesna Dušak, *vdusak@foi.hr*
Vice president	Jadranka Božikov, *jbozikov@snz.hr*
Secretary	Vesna Bosilj-Vukšić, *vbosilj@efzg.hr*
Executive board members	Vlatko Čerić, *vceric@efzg.hr*
	Tarzan Legović, *legovic@irb.hr*
Repr. EuroSim	Jadranka Božikov, *jbozikov@snz.hr*
Edit. Board SNE	Vesna Dušak, *vdusak@foi.hr*
Web EuroSim	Jadranka Bozikov, *jbozikov@snz.hr*

Last data update December2012

CSSS – Czech and Slovak Simulation Society

CSSS -The *Czech and Slovak Simulation Society* has about 150 members working in Czech and Slovak national scientific and technical societies (*Czech Society for Applied Cybernetics and Informatics, Slovak Society for Applied Cybernetics and Informatics*). The main objectives of the society are: development of education and training in the field of modelling and simulation, organising professional workshops and conferences, disseminating information about modelling and simulation activities in Europe. Since 1992, CSSS is full member of **EUROSIM**.

→ *www.fit.vutbr.cz/CSSS*

☏ snorek@fel.cvut.cz

✉ CSSS / Miroslav Šnorek, CTU Prague
FEE, Dept. Computer Science and Engineering,
Karlovo nam. 13, 121 35 Praha 2, Czech Republic

CSSS Officers	
President	Miroslav Šnorek, *snorek@fel.cvut.cz*
Vice president	Mikuláš Alexík, *alexik@frtk.fri.utc.sk*
Treasurer	Evžen Kindler, *ekindler@centrum.cz*
Scientific Secr.	A. Kavička, *Antonin.Kavicka@upce.cz*
Repr. EuroSim	Miroslav Šnorek, *snorek@fel.cvut.cz*
Deputy	Mikuláš Alexík, *alexik@frtk.fri.utc.sk*
Edit. Board SNE	Mikuláš Alexík, *alexik@frtk.fri.utc.sk*
Web EuroSim	Petr Peringer, peringer@fit.vutbr.cz

Last data update December2012

DBSS – Dutch Benelux Simulation Society

The Dutch Benelux Simulation Society (DBSS) was founded in July 1986 in order to create an organisation of simulation professionals within the Dutch language area. DBSS has actively promoted creation of similar organisations in other language areas. DBSS is a member of **EUROSIM** and works in close cooperation with its members and with affiliated societies.

→ www.eurosim.info

☏ *a.w.heemink@its.tudelft.nl*

✉ DBSS / A. W. Heemink
Delft University of Technology, ITS - twi,
Mekelweg 4, 2628 CD Delft, The Netherlands

www.DutchBSS.org

DBSS Officers	
President	A. Heemink, *a.w.heemink@its.tudelft.nl*
Vice president	M. Mujica Mota, *m.mujica.mota@hva.nl*
Treasurer	M. Mujica Mota, *m.mujica.mota@hva.nl*
Secretary	P. M. Scala, p.m.scala@hva.nl
Repr. EuroSim	M. Mujica Mota, *m.mujica.mota@hva.nl*
Edit. SNE/Web	M. Mujica Mota, *m.mujica.mota@hva.nl*

Last data update June 2016

FrancoSim – Société Francophone de Simulation

FrancoSim was founded in 1991 and aims to the promotion of simulation and research, in industry and academic fields. Francosim operates two poles.

- Pole Modelling and simulation of discrete event systems. Pole Contact: *Henri Pierreval, pierreva@imfa.fr*
- Pole Modelling and simulation of continuous systems. Pole Contact: *Yskandar Hamam, y.hamam@esiee.fr*

→ *www.eurosim.info*
y.hamam@esiee.fr
✉ FRANCOSIM / Yskandar Hamam
Groupe ESIEE, Cité Descartes,
BP 99, 2 Bd. Blaise Pascal,
93162 Noisy le Grand CEDEX, France

FRANCOSIM Officers	
President	Karim Djouani, *djouani@u-pec.fr*
Treasurer	François Rocaries, *f.rocaries@esiee.fr*
Repr. EUROSIM	Karim Djouani, *djouani@u-pec.fr*
Edit. Board SNE	Karim Djouani, *djouani@u-pec.fr*

Last data update December2012

HSS – Hungarian Simulation Society

The Hungarian Member Society of EUROSIM was established in 1981 as an association promoting the exchange of information within the community of people involved in research, development, application and education of simulation in Hungary and also contributing to the enhancement of exchanging information between the Hungarian simulation community and the simulation communities abroad. HSS deals with the organization of lectures, exhibitions, demonstrations, and conferences.

→ *www.eurosim.info*
javor@eik.bme.hu
✉ HSS / András Jávor,
Budapest Univ. of Technology and Economics,
Sztoczek u. 4, 1111 Budapest, Hungary

HSS Officers	
President	András Jávor, *javor@eik.bme.hu*
Vice president	Gábor Szűcs, *szucs@itm.bme.hu*
Secretary	Ágnes Vigh, *vigh@itm.bme.hu*
Repr. EUROSIM	András Jávor, *javor@eik.bme.hu*
Deputy	Gábor Szűcs, *szucs@itm.bme.hu*
Edit. Board SNE	András Jávor, *javor@eik.bme.hu*
Web EUROSIM	Gábor Szűcs, *szucs@itm.bme.hu*

Last data update March 2008

ISCS – Italian Society for Computer Simulation

The Italian Society for Computer Simulation (ISCS) is a scientific non-profit association of members from industry, university, education and several public and research institutions with common interest in all fields of computer simulation.

→ *www.eurosim.info*
Mario.savastano@uniina.at
✉ ISCS / Mario Savastano,
c/o CNR - IRSIP,
Via Claudio 21, 80125 Napoli, Italy

ISCS Officers	
President	M. Savastano, *mario.savastano@unina.it*
Vice president	F. Maceri, *Franco.Maceri@uniroma2.it*
Repr. EUROSIM	F. Maceri, *Franco.Maceri@uniroma2.it*
Secretary	Paola Provenzano, *paola.provenzano@uniroma2.it*
Edit. Board SNE	M. Savastano, *mario.savastano@unina.it*

Last data update December2010

LIOPHANT Simulation

Liophant Simulation is a non-profit association born in order to be a trait-d'union among simulation developers and users; Liophant is devoted to promote and diffuse the simulation techniques and methodologies; the Association promotes exchange of students, sabbatical years, organization of International Conferences, courses and internships focused on M&S applications.

→ *www.liophant.org*
info@liophant.org
✉ LIOPHANT Simulation, c/o Agostino G. Bruzzone,
DIME, University of Genoa, Savona Campus
via Molinero 1, 17100 Savona (SV), Italy

LIOPHANT Officers	
President	A.G. Bruzzone, *agostino@itim.unige.it*
Director	E. Bocca, *enrico.bocca@liophant.org*
Secretary	A. Devoti, *devoti.a@iveco.com*
Treasurer	Marina Masseimassei@itim.unige.it
Repr. EUROSIM	A.G. Bruzzone, *agostino@itim.unige.it*
Deputy	F. Longo, *f.longo@unical.it*
Edit. Board SNE	F. Longo, *f.longo@unical.it*
Web EUROSIM	F. Longo, *f.longo@unical.it*

Last data update June 2016

LSS – Latvian Simulation Society

The Latvian Simulation Society (LSS) has been founded in 1990 as the first professional simulation organisation in the field of Modelling and simulation in the post-Soviet area. Its members represent the main simulation centres in Latvia, including both academic and industrial sectors.

→ *briedis.itl.rtu.lv/imb/*

✉ *merkur@itl.rtu.lv*

🖂 LSS / Yuri Merkuryev, Dept. of Modelling and Simulation Riga Technical University Kalku street 1, Riga, LV-1658, LATVIA

LSS Officers	
President	Yuri Merkuryev, *merkur@itl.rtu.lv*
Secretary	Artis Teilans, *Artis.Teilans@exigenservices.com*
Repr. EUROSIM	Yuri Merkuryev, *merkur@itl.rtu.lv*
Deputy	Artis Teilans, *Artis.Teilans@exigenservices.com*
Edit. Board SNE	Yuri Merkuryev, *merkur@itl.rtu.lv*
Web EUROSIM	Vitaly Bolshakov, *vitalijs.bolsakovs@rtu.lv*

Last data update June 2016

PSCS – Polish Society for Computer Simulation

PSCS was founded in 1993 in Warsaw. PSCS is a scientific, non-profit association of members from universities, research institutes and industry in Poland with common interests in variety of methods of computer simulations and its applications. At present PSCS counts 257 members.

→ *www.ptsk.man.bialystok.pl*

✉ *leon@ibib.waw.pl*

🖂 PSCS / Leon Bobrowski, c/o IBIB PAN, ul. Trojdena 4 (p.416), 02-109 Warszawa, Poland

PSCS Officers	
President	Leon Bobrowski, *leon@ibib.waw.pl*
Vice president	Tadeusz Nowicki, *Tadeusz.Nowicki@wat.edu.pl*
Treasurer	Z. Sosnowski, *zenon@ii.pb.bialystok.pl*
Secretary	Zdzislaw Galkowski, *Zdzislaw.Galkowski@simr.pw.edu.pl*
Repr. EUROSIM	Leon Bobrowski, *leon@ibib.waw.pl*
Deputy	Tadeusz Nowicki, *tadeusz.nowicki@wat.edu.pl*
Edit. Board SNE	Zenon Sosnowski, z.sosnowski@pb.ed.pl
Web EUROSIM	Magdalena Topczewska *m.topczewska@pb.edu.pl*

Last data update December2013

SIMS – Scandinavian Simulation Society

SIMS is the *Scandinavian Simulation Society* with members from the four Nordic countries Denmark, Finland, Norway and Sweden. The SIMS history goes back to 1959. SIMS practical matters are taken care of by the SIMS board consisting of two representatives from each Nordic country (Iceland one board member).

SIMS Structure. SIMS is organised as federation of regional societDjouaniies. There are FinSim (Finnish Simulation Forum), DKSIM (Dansk Simuleringsforening) and NFA (Norsk Forening for Automatisering).

→ *www.scansims.org*

✉ *esko.juuso@oulu.fi*

🖂 SIMS / SIMS / Erik Dahlquist, School of Business, Society and Engineering, Department of Energy, Building and Environment, Mälardalen University, P.O.Box 883, 72123 Västerås, Sweden

SIMS Officers	
President	Erik Dahlquist, *erik.dahlquist@mdh.se*
Vice president	Bernd Lie, *lie@hit.noe*
Treasurer	Vadim Engelson, *vadim.engelson@mathcore.com*
Repr. EUROSIM	Erik Dahlquist, *erik.dahlquist@mdh.se*
Edit. Board SNE	Esko Juuso, *esko.juuso@oulu.fi*
Web EUROSIM	Vadim Engelson, *vadim.engelson@mathcore.com*

Last data update June 2016

SLOSIM – Slovenian Society for Simulation and Modelling

SLOSIM - Slovenian Society for Simulation and Modelling was established in 1994 and became the full member of **EUROSIM** in 1996. Currently it has 69 members from both slovenian universities, institutes, and industry. It promotes modelling and simulation approaches to problem solving in industrial as well as in academic environments by establishing communication and cooperation among corresponding teams.

→ www.slosim.si

✉ *slosim@fe.uni-lj.si*

🖂 SLOSIM / Vito Logar, Faculty of Electrical Engineering, University of Ljubljana, Tržaška 25, 1000 Ljubljana, Slovenia

SLOSIM Officers	
President	Vito Logar, *vito.logar@fe.uni-lj.si*
Vice president	Božidar Šarler, *bozidar.sarler@ung.si*
Secretary	Aleš Belič, *ales.belic@sandoz.com*
Treasurer	Milan Simčič, *milan.simcic@fe.uni-lj.si*
Repr. EUROSIM	B. Zupančič, *borut.zupancic@fe.uni-lj.si*
Deputy	Vito Logar, *vito.logar@fe.uni-lj.si*
Edit. Board SNE	B. Zupančič, *borut.zupancic@fe.uni-lj.si* Vito Logar, *vito.logar@fe.uni-lj.si* Blaž Rodič, *blaz.rodic@fis.unm.si*
Web EUROSIM	Vito Logar, *vito.logar@fe.uni-lj.si*

Last data update June 2016

UKSIM - United Kingdom Simulation Society

The UK Simulation Society is very active in organizing conferences, meetings and workshops. UKSim holds its annual conference in the March-April period. In recent years the conference has always been held at Emmanuel College, Cambridge. The Asia Modelling and Simulation Section (AMSS) of UKSim holds 4-5 conferences per year including the EMS (European Modelling Symposium), an event mainly aimed at young researchers, organized each year by UKSim in different European cities.

Membership of the UK Simulation Society is free to participants of any of our conferences and thier co-authors.

→ *www.uksim.org.uk*

✉ *david.al-dabass@ntu.ac.uk*

✉ UKSIM / Prof. David Al-Dabass
Computing & Informatics,
Nottingham Trent University
Clifton lane, Nottingham, NG11 8NS
United Kingdom

UKSIM Officers	
President	David Al-Dabass, *david.al-dabass@ntu.ac.uk*
Secretary	A. Orsoni, *A.Orsoni@kingston.ac.uk*
Treasurer	A. Orsoni, *A.Orsoni@kingston.ac.uk*
Membership chair	G. Jenkins, *glenn.l.jenkins@smu.ac.uk*
Local/Venue chair	Richard Cant, *richard.cant@ntu.ac.uk*
Repr. EUROSIM	A. Orsoni, *A.Orsoni@kingston.ac.uk*
Deputy	G. Jenkins, *glenn.l.jenkins@smu.ac.uk*
Edit. Board SNE	A. Orsoni, *A.Orsoni@kingston.ac.uk*

Last data update March 2016

RNSS – Russian Simulation Society

NSS - The Russian National Simulation Society (Национальное Общество Имитационного Моделирования – НОИМ) was officially registered in Russian Federation on February 11, 2011. In February 2012 NSS has been accepted as an observer member of **EUROSIM**, and in 2014 RNSS has become full member.

→ *www.simulation.su*

✉ *yusupov@iias.spb.su*

✉ RNSS / R. M. Yusupov,
St. Petersburg Institute of Informatics and Automation
RAS, 199178, St. Petersburg, 14th lin. V.O, 39

RNSS Officers	
President	R. M. Yusupov, *yusupov@iias.spb.su*
Chair Man. Board	A. Plotnikov, *plotnikov@sstc.spb.ru*
Secretary	M. Dolmatov, *dolmatov@simulation.su*
Repr. EUROSIM	R.M. Yusupov, *yusupov@iias.spb.su* Y. Senichenkov, se- nyb@dcn.icc.spbstu.ru
Deputy	B. Sokolov, *sokol@iias.spb.su*
Edit. Board SNE	Y. Senichenkov, senyb@dcn.icc.spbstu.ru

Last data update June 2016

EUROSIM OBSERVER MEMBERS

KA-SIM Kosovo Simulation Society

Kosova Association for Modeling and Simulation (KA – SIM, founded in 2009), is part of Kosova Association of Control, Automation and Systems Engineering (KA – CASE). KA – CASE was registered in 2006 as non Profit Organization and since 2009 is National Member of IFAC – International Federation of Automatic Control. KA-SIM joined EUROSIM as Observer Member in 2011. In 2016, KA-SIM has applied for full membership

KA-SIM has about 50 members, and is organizing the international conference series International Conference in Business, Technology and Innovation, in November, in Durrhes, Albania, an IFAC Simulation workshops in Pristina.

→ *www.ubt-uni.net/ka-case*

✉ *ehajrizi@ubt-uni.net*

✉ MOD&SIM KA-CASE; Att. Dr. Edmond Hajrizi
Univ. for Business and Technology (UBT)
Lagjja Kalabria p.n., 10000 Prishtina, Kosovo

KA-SIM Officers	
President	Edmond Hajrizi, *ehajrizi@ubt-uni.net*
Vice president	Muzafer Shala, *info@ka-sim.com*
Secretary	Lulzim Beqiri, *info@ka-sim.com*
Treasurer	Selman Berisha, *info@ka-sim.com*
Repr. EUROSIM	Edmond Hajrizi, *ehajrizi@ubt-uni.net*
Deputy	Muzafer Shala, *info@ka-sim.com*
Edit. Board SNE	Edmond Hajrizi, *ehajrizi@ubt-uni.net*
Web EUROSIM	Betim Gashi, *info@ka-sim.com*

Last data update June 2016

ROMSIM – Romanian Modelling and Simulation Society

ROMSIM has been founded in 1990 as a non-profit society, devoted to theoretical and applied aspects of modelling and simulation of systems. ROMSIM currently has about 100 members from Romania and Moldavia.

→ *www.ici.ro/romsim/*

sflorin@ici.ro

ROMSIM / Florin Hartescu,
National Institute for Research in Informatics, Averescu
Av. 8 – 10, 71316 Bucharest, Romania

ROMSIM Officers	
President	
Vice president	Florin Hartescu, *flory@ici.ro* Marius Radulescu, *mradulescu@ici.ro*
Repr. EUROSIM	Florin Stanciulescu, *sflorin@ici.ro*
Deputy	Marius Radulescu, *mradulescu@ici.ro*
Edit. Board SNE	
Web EUROSIM	Zoe Radulescu, *radulescu@ici.ro*

Last data update partly June 2016

MIMOS – Italian Modelling and Simulation Association

MIMOS (Movimento Italiano Modellazione e Simulazione – Italian Modelling and Simulation Association) is the Italian association grouping companies, professionals, universities, and research institutions working in the field of modelling, simulation, virtual reality and 3D, with the aim of enhancing the culture of 'virtuality' in Italy, in every application area.

MIMOS has submitted application for membership in **EUROSIM** (Observer Member).

→ *www.mimos.it*

roma@mimos.it – info@mimos.it

MIMOS – Movimento Italiano Modellazione e Simulazione; via Ugo Foscolo 4, 10126 Torino – via Laurentina 760, 00143 Roma

MIMOS Officers	
President	Paolo Proietti, *roma@mimos.it*
Secretary	Davide Borra, *segreteria@mimos.it*
Treasurer	Davide Borra, *segreteria@mimos.it*
Repr. EUROSIM	Paolo Proietti, *roma@mimos.it*
Deputy	Agostino Bruzzone, *agostino@itim.unige.it*
Edit. Board SNE	Paolo Proietti, *roma@mimos.it*

Last data update June 2016

Albanian Simulation Society

At department of Statistics and Applied Informatics, Faculty of Economy, University of Tirana, Prof. Dr. Kozeta Sevrani at present is setting up an Albanian Simulation Society. Kozeta Sevrani, professor of Computer Science and Management Information Systems, and head of the Department of Mathematics, Statistics and Applied Informatic, has attended a EUROSIM board meeting in Vienna and has presented simulation activities in Albania and the new simulation society.

The society – constitution and bylaws are at work - will be involved in different international and local simulation projects, and will be engaged in the organisation of the conference series ISTI – Information Systems and Technology. The society intends to become a EUROSIM Observer Member.

kozeta.sevrani@unitir.edu.al

Albanian Simulation Goup, attn. Kozeta Sevrani
University of Tirana, Faculty of Economy
rr. Elbasanit, Tirana 355 Albania

Albanian Simulation Society- Officers (Planned)	
President	Kozeta Sevrani, *kozeta.sevrani@unitir.edu.al*
Secretary	
Treasurer	
Repr. EUROSIM	Kozeta Sevrani, *kozeta.sevrani@unitir.edu.al*
Edit. Board SNE	Albana Gorishti, *albana.gorishti@unitir.edu.al* Majlinda Godolja, majlinda.godolja@fshn.edu.al

Last data update June 2016

EUROSIM 2016

9th EUROSIM Congress on Modelling and Simulation

City of Oulu, Finland, September 12 – 16, 2016

UNIVERSITY of OULU

EUROSIM Congresses are the most important modelling and simulation events in Europe. For EUROSIM 2016, we are soliciting original submissions describing novel research and developments in the following (and related) areas of interest: Continuous, discrete (event) and hybrid modelling, simulation, identification and optimization approaches. Two basic contribution motivations are expected: M&S Methods and Technologies and M&S Applications. Contributions from both technical and non-technical areas are welcome.

Congress Topics The EUROSIM 2016 Congress will include invited talks, parallel, special and poster sessions, exhibition and versatile technical and social tours. The Congress topics of interest include, but are not limited to:

Intelligent Systems and Applications
Hybrid and Soft Computing
Data & Semantic Mining
Neural Networks, Fuzzy Systems & Evolutionary Computation
Image, Speech & Signal Processing
Systems Intelligence and Intelligence Systems
Autonomous Systems
Energy and Power Systems
Mining and Metal Industry
Forest Industry
Buildings and Construction
Communication Systems
Circuits, Sensors and Devices
Security Modelling and Simulation

Bioinformatics, Medicine, Pharmacy and Bioengineering
Water and Wastewater Treatment, Sludge Management and Biogas Production
Condition monitoring, Mechatronics and maintenance
Automotive applications
e-Science and e-Systems
Industry, Business, Management, Human Factors and Social Issues
Virtual Reality, Visualization, Computer Art and Games
Internet Modelling, Semantic Web and Ontologies
Computational Finance & Economics

Simulation Methodologies and Tools
Parallel and Distributed Architectures and Systems
Operations Research
Discrete Event Systems
Manufacturing and Workflows
Adaptive Dynamic Programming and Reinforcement Learning
Mobile/Ad hoc wireless networks, mobicast, sensor placement, target tracking
Control of Intelligent Systems
Robotics, Cybernetics, Control Engineering, & Manufacturing
Transport, Logistics, Harbour, Shipping and Marine Simulation

Congress Venue / Social Events The Congress will be held in the City of Oulu, Capital of Northern Scandinavia. The main venue and the exhibition site is the Oulu City Theatre in the city centre. Pre and Post Congress Tours include Arctic Circle, Santa Claus visits and hiking on the unique routes in Oulanka National Park.

Congress Team: The Congress is organised by SIMS - Scandinavian Simulation Society, FinSim - Finnish Simulation Forum, Finnish Society of Automation, and University of Oulu.
Esko Juuso EUROSIM President, Erik Dahlquist SIMS President, Kauko Leiviskä EUROSIM 2016 Chair

Info: eurosim2016.automaatioseura.fi, office@automaatioseura.fi