

Session 13

Qualitative Approaches

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As a tool to model complex systems, system dynamics is an alternative. It can be used for wide range of applications. Mostly qualitative results can be achieved by using this method. The most valuable benefit is to understand the inner functionality of the observed system. System dynamics has been used for real applications during 50 years.

13.1 Introduction

In the previous chapters, complex systems have been introduced. Their structures have been presented, their behaviour has been introduced and different ways to model complex systems have been shown. The aim of this chapter is to show the basic ideas of system dynamics and system thinking. These are tools for modelling and understanding different kind of complex systems, from technology to biology and from economy to human behaviour. System dynamics and thinking can be seen as a general tool for modelling different kind of complex systems.

First, this chapter will give short historical perspective of system dynamics during last 50 years. It tries to connect system dynamics to other fields of research. A well-known example, the Beer distribution game is presented. Few other applications are shown. At the end, the key concepts of system dynamics are presented with a small example model. Finally, important publications, software and research institutes are listed.

As an example of a dynamic system, Naill's natural gas model [1] can be seen in the figure 13.1.

13.2 History of system dynamics

The father of System Dynamics is Jay Forrester. He graduated from Engineering Collage at the University of Nebraska. After that, he got a job from Massachusetts Institute of Technology as research assistant under supervision of Gordon Brown, a pioneer in "feedback control systems". At Servomechanism Laboratory, they built an experimental control for radar, which was used during World War II [1], [2].

After the war, Jay Forrester continued to work at MIT. He started to build a flight simulator for U.S. Navy. Soon they noticed that analog computers were not able to handle problems this large. Development of digital computers started. In 1947, the Digital Computer Laboratory of MIT was founded. It was placed under the direction of Jay Forrester [1]. They designed the Whirlwind digital computer, which later on was developed to SAGE (Semi-automatic Ground Environment) air defence system for North America [2].

At the middle of 50's Jay Forrester felt that pioneering days of digital computers were over. He was also running projects worth of several million dollars and noticed that social systems are much harder to understand and control than are physical systems [1]. A business school was found in MIT and Jay Forrester joined that school in 1956. He started to think management problems with engineering background [2].

The Jay Forrester's first dynamic system was a simple pencil and paper simulation of employment instability at General Electrics Kentucky plants. Forrester was able to show that the instability of employment was due to the internal structure of the firm, not external forces such as the business cycle [2].

Next step was a compiler SIMPLE (Simulation of Industrial Management with Lots of Equations) developed by Richard Bennett in 1958. Later, 1959, SIMPLE and other system dynamics compiler was developed to DYNAMO compiler by Jack Pugh [2]. The system dynamics became an industrial standard for over 30 years. Forrester published his classic book, *Industrial Dynamics*, in 1961 [1].

Urban dynamics by Jay Forrester was the book, the brought system dynamics to even wider knowledge. It was the very first non-corporate application of

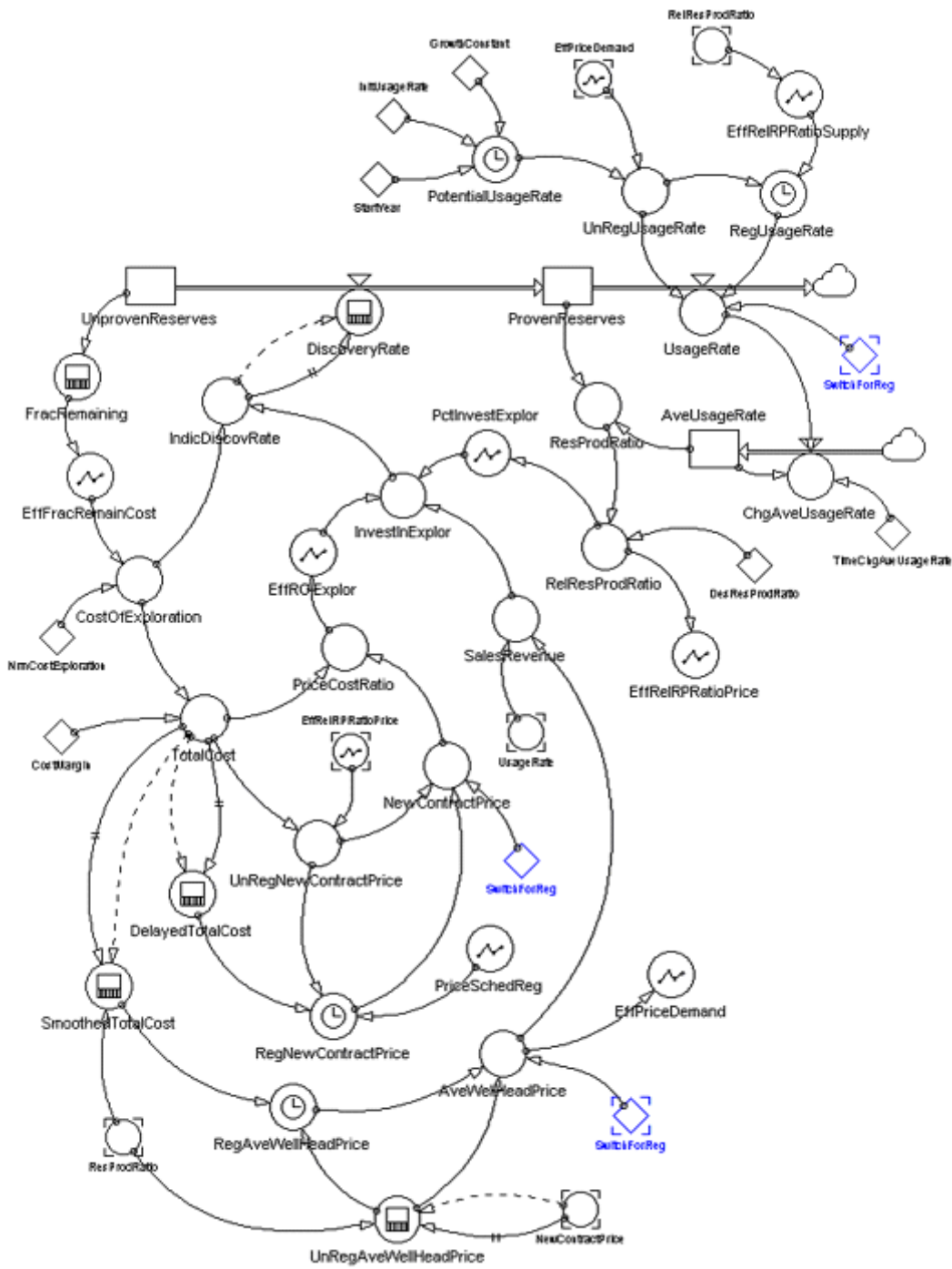


Figure 13.1: Naill's natural gas model [1].

system dynamics [1]. This model was developed with John Collins, the former mayor of Boston and his experts in 1968. The results of this study were not generally accepted, at first. They showed that many policies widely used for urban problems were in fact ineffective or even caused worse problems. Solutions, which seemed to be wrong at first glance, were, at the other hand, very effective [2].

The next turning point of system dynamics was year 1970. Jay Forrester was invited by the Club of Rome, to a meeting. He was asked if system dynamics could be used to describe the "predicament of mankind". Jay Forrester said YES and developed the first model of world's socioeconomic system, called WORLD1. Later that model was refined and the WORLD2 model was published in the Forrester's book titled *World Dynamics* [2]. This model and book showed that world's socioeconomic system would collapse sometime during 21st century if no actions were taken to lessen the demands for earth's carrying capacity. Forrester's formed Ph.D. student Dennis Meadows developed the WORLD2 model further and the Club of Rome published a book titled *the Limits of Growth* on based on the WORLD3 model [1]. Although, the *Limits of Growth* is widely criticised, it is an excellent example of usability of system dynamics.

Last years Jay Forrester has been developing National model for U.S. In addition, he has introduced system dynamics to education from kindergartens to high schools [1].

At 1990 Peter Senge, a director of the Systems Thinking and Organizational Learning Programs at MIT's Sloan School of Management published a best seller book *the Fifth Discipline – The Art & Practice of The Learning Organization*. It re-introduced the system thinking to managers worldwide. The relationship of system thinking and system dynamics is following: They look the same kind of system from the same kind of perspective. They construct the same causal loop diagrams but system thinking rarely takes additional steps for constructing or testing computational simulations [3]. In Finland Markku Perkola is using ideas of system thinking [4].

At the beginning of the new millennium, 2000, Professor John Sterman for MIT's Sloan School of Management, published a book *Business Dynamics – System Thinking and Modelling for a Complex World*. The roots of this book relates back to the publications of Jay Forrester and the Fifth Discipline by Peter Senge. The ideas of system dynamics and system thinking are combined into this book. There are wide range of examples for using system dynamics and thinking for different kind of applications, mostly economical. In addition, the wide range of graphically attractive computer programs for

system dynamics modelling has brought the ideas of Jay Forrester back again. System dynamics is seen as an option for modelling the complex world.

System dynamics has almost 50 years history behind it. It is a real tool used for solving complex system problems, not a piece of ironic new science.

13.3 Beer distribution game

A classical example of dynamic systems is the Beer distribution game. The concepts of this dynamic system are shown at first. Next, the management flight simulator is presented.

13.3.1 Rules of the beer distribution game

Beer distribution game is said to be an enjoyable and effective introduction to the principles of system thinking [5]. MIT's Sloan School of Management developed it in the beginning of 60's. The game is used to teach supply chain management. It illustrates that the problems of system is caused by the system itself, not an external factor [6]. Beer distribution game shows how inventories and delays create fluctuation and overcompensation in supply chains.

The rules of the game are rather simple:

1. There are four different links in supply chain: factory, distributor, wholesaler and retail, seen in the figure 13.2.
2. Orders are sent to upstream and shipments downstream. There are delays before ordered goods arrive.
3. Orders from downstream and shipments from upstream are the only information available for supplier. The levels of other inventories are not known.
4. If supplier cannot deliver orders, they will be logged in backlog, which is expensive.
5. Keeping goods in inventory is expensive; backlogging goods is even more expensive. The goal is to minimize these fees.

Players are trying to follow those rules. They try to keep inventories as low as possible and at same time, deliver all the orders to their customer. Players

soon realise that even the rules of this game are very simple, the whole system is complex. Overcompensations and fluctuations appear soon.

The supply chain of the beer distribution game is shown in the figure 13.2 [7].

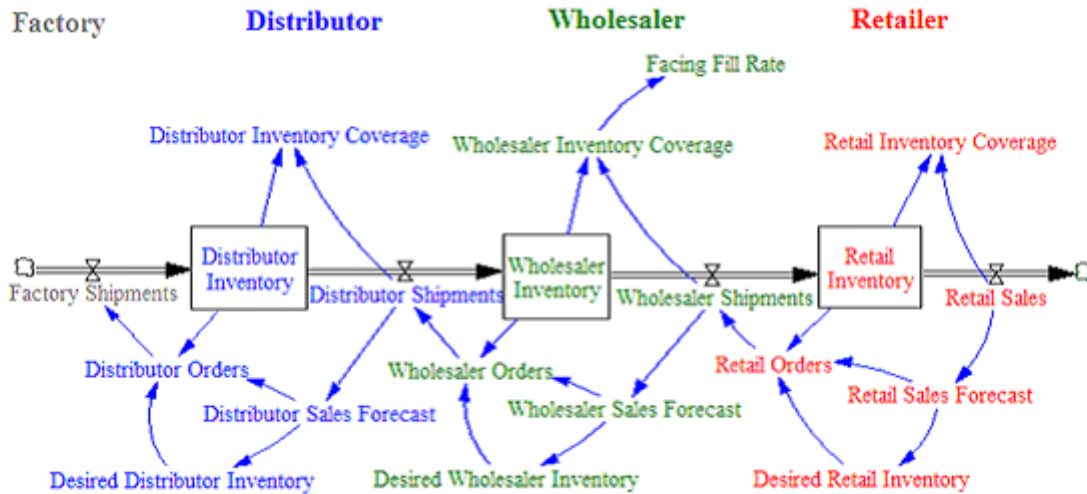


Figure 13.2: Supply chain of the beer distribution game [7].

One can also inspect the factors affecting on a supplier in the supply chain. These effects can be illustrated by using causal loop diagrams, which are the basis of the system dynamics and thinking. The figure 13.2 was an example of causal loop diagrams. In the figure 13.3 those loops are shown for a single supplier.

Customer orders define the supplied goods. There is a delay however. According to the customer orders, the sales forecast is calculated. In addition, desired inventory must be calculated. According to the level of current inventory, desired inventory and sales forecast, the orders are sent to supplier. Again, there is a shipping delay before goods arrive to supplier's inventory.

All these effects can be seen in the figure 13.3.

We have to keep in mind that system thinking is causal thinking. There is a cause and an effect. We cannot look and calculate correlations between the different things. Correlations among variables reflect the past behaviour of a system [5], not necessary the true causality between variables. Well know example is correlation with ice cream eating and drowning during a warm summer. We have to look at the true correlations between different things. Sometimes this is easy; sometimes several experts are needed in order to find

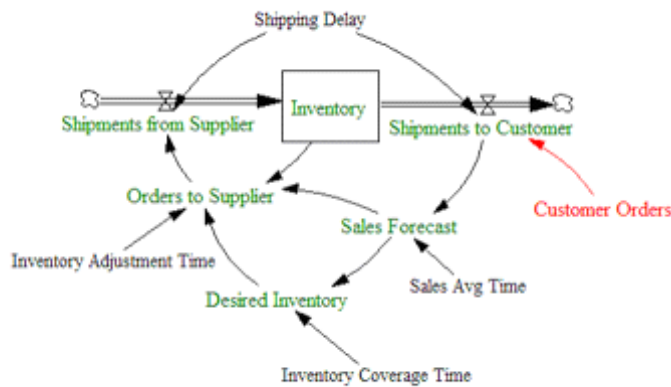


Figure 13.3: Simple, single-stage model, in the Beer distribution game [7].

right cause and effect [2]. Causal laws of distributor’s inventory can be seen in the figure 13.4.

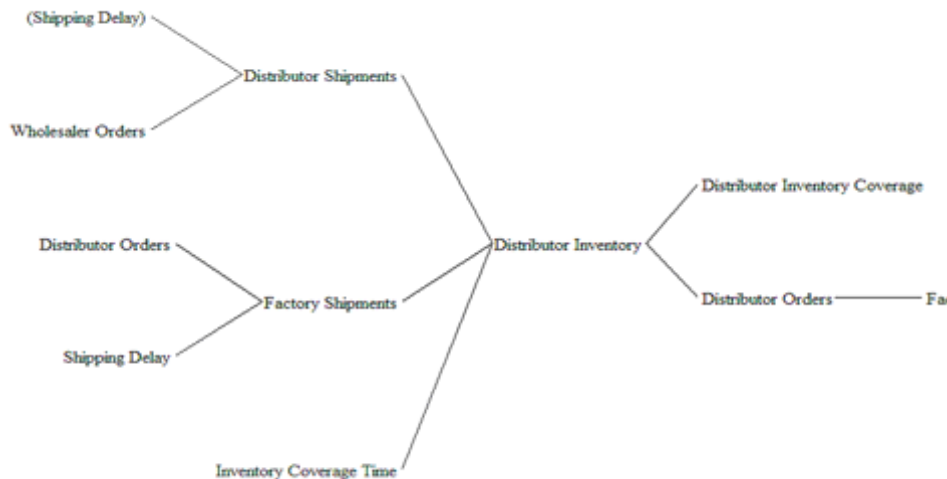


Figure 13.4: Causal tree of distributor’s inventory in the Beer distribution game [7].

After playing the beer distribution game for a while, the players noticed the overcompensations and fluctuations are caused by the system itself. An example of these can be seen in the figure 13.5.

One way to compensate these overcompensations and fluctuations is to increase the available information. Vendor Managed Inventory (VMI) is discussed here [7]. Every supplier in the supply chain knows the average retails



Figure 13.5: Multi-stage response to changes in retailer level. Picture from the Beer distribution game [7].

sales (retails sales forecast). In addition, every supplier knows the levels of all inventories in the supply chain. Each stage ships goods using these values: the average retails sales plus the balance of inventories downstream.

After applying this simple method the overcompensations and fluctuations seen in the figure 13.5 are almost removed, which can be seen in the figure 13.6.

More information and an example game can be found in the Internet [7].

13.3.2 Management flight simulators

A management flight simulator is the visually attractive front end to the underlying system dynamic model. The aim is to invite decision makers to train in the simulator just as an aircraft pilot does. The decision maker runs the dynamic system through the flight simulator. He or she makes decisions; runs model further, sees the response of the system and makes another decision. After the simulation is run through, the decision maker is invited to examine why the system behaved as it did. The same simulation can be run repeatedly with different decision policies. After certain amount of runs, the decision maker hopefully understands the underlying system and will apply the learned lessons to the reality [1].

Peter Senge used the management flight simulators as a principal tool used by learning organization. He focused to the idea that employees should learn the underlying system. Employees of learning organization have shared, holistic,



Figure 13.6: Multi-stage response to changes in retailer level after implementing Vendor Managed Inventory (VMI). Picture from the Beer distribution game [7].

and system vision, and have capacity and commitment to continually learn. They just do not execute a master plan put forth by the “grand strategist” at top of the hierarchy [6]. Peter Senge’s ideas are somehow contradictory to the hierarchical structure. They are similar to the ideas of networked structure. Hierarchical and network structures are presented in the previous chapters as an examples of complex systems.

13.4 Applications

The supply chain game, the Beer distribution game, is not the only applications of system dynamics and system thinking. Few other applications were already presented in the beginning of this chapter. As earlier mentioned the system dynamics is a real tool used for solve real life problem. Here are some additional applications presented.

World models showed that the finite nature resources would be overused. The result is overshoot and collapse of world’s socioeconomic system. Models WORLD2 and WORLD3 were developed for the Club of Rome [1].

The life cycle theory of geologist M. King Hubbert is based on the idea that there is a limited amount of certain resource, e.g. oil, available. If consumption is exponential, the limited resources will lead to peak in consumption after growth and then long decline in consumption. Later Naill confirmed

this theory in his Master's thesis. The result was a three-year study of U.S. energy transition problem. This problem is currently solved by importing energy resources, which is cheaper than developing new domestic energy supplies [1].

Naill also developed a model of natural gas resources. This model was aggregate. However, the model was refined and further developed to COAL1, COAL2 and FOSSIL1. Name was FOSSIL1, since it looked at the transition of an economy that is powered by fossil fuels to one that is powered by alternative energy sources. FOSSIL1 was later developed to FOSSIL2 and it was used by the U.S. Department of Energy to analyse following things from the late 1970s to the early 1990s [1]:

- *The net effect of supply side initiatives (including price deregulation) on US oil imports.*
- *The US vulnerability to oil supply disruptions due to political unrest in the Middle East or the doubling of oil prices.*
- *Policies aimed at stimulating US synfuel production.*
- *The effects of tax initiatives (carbon, BTU, gasoline, oil import fees) on the US energy system.*
- *The effects of the Cooper-Synar CO₂ Offsets Bill on the US energy system.*

These days the FOSSIL2 model is refined to IDEAS model and it is still actively used.

John Sterman, as a PhD student, noticed that the models above, COAL-FOSSIL-IDEAS-models, are isolated models from the rest of the economy. Sterman showed that there are interactions between the energy sector and the rest of economy. He built significant energy-economy interactions in his dissertation [1].

Fiddemann's presented Economy-climate interactions in his dissertation 1997. The developed FREE (Feedback-Rich Energy Economy) –model was the first one dynamic model of energy-economy interactions [1].

Applications presented above are shown in the figure 13.7.

These were few examples of the real life problems, which has been modelled by using system dynamics. As earlier mentioned it is a good tool for understanding large complex systems.

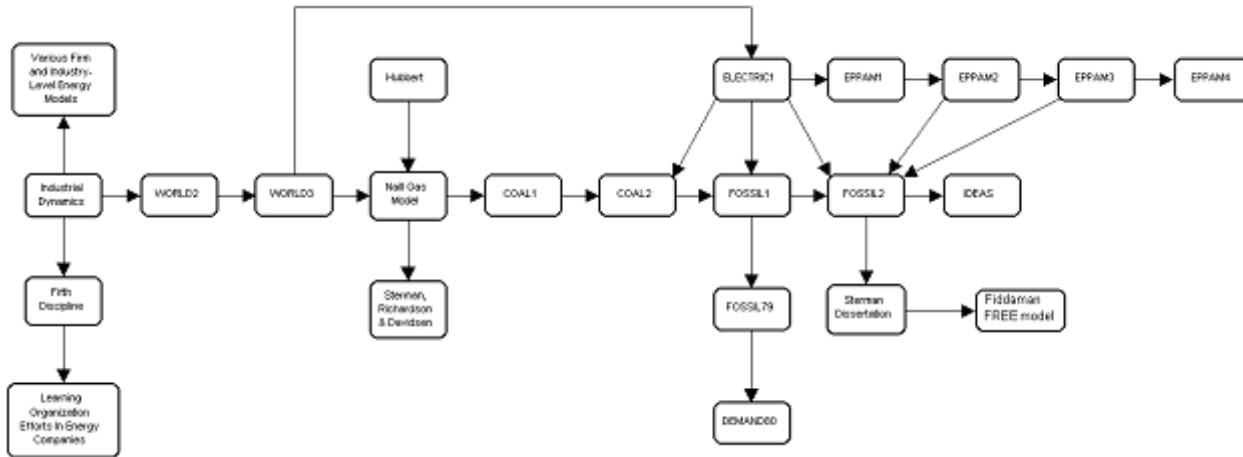


Figure 13.7: Development of system dynamic models [1].

13.5 Basic concepts of system dynamics

The basic concepts of system dynamics are presented. The stocks and flows are discussed. Causal loops are presented. In addition, a simple model of Finnish car population is built. A flight simulator is built as well. The model and flight simulator are built using a demo version of Powersim simulator. This model is by no means complete or verified. It is just a humble example.

13.5.1 Stocks and flows

At the first stock and flows are presented. We build an aging chain, which describes the aging of Finnish cars [5]. Finnish cars are divided into three different groups, 0-5 years old cars, 5-10 years old cars and over 10 years old cars. Inflows to model are brand new cars and old cars from Germany. Outflows are very old cars sold to Russia and wrecked cars. Stock and flows are shown in the figure 13.8.

Correspondences between stock and flows and tanks and valves can be easily seen.

13.5.2 Causal loops

The causality is another basic concept of system dynamic. It is presented next. When we are dealing with stocks, the delays between the different storages must be defined. The first storage is for the new cars, 0-5 years

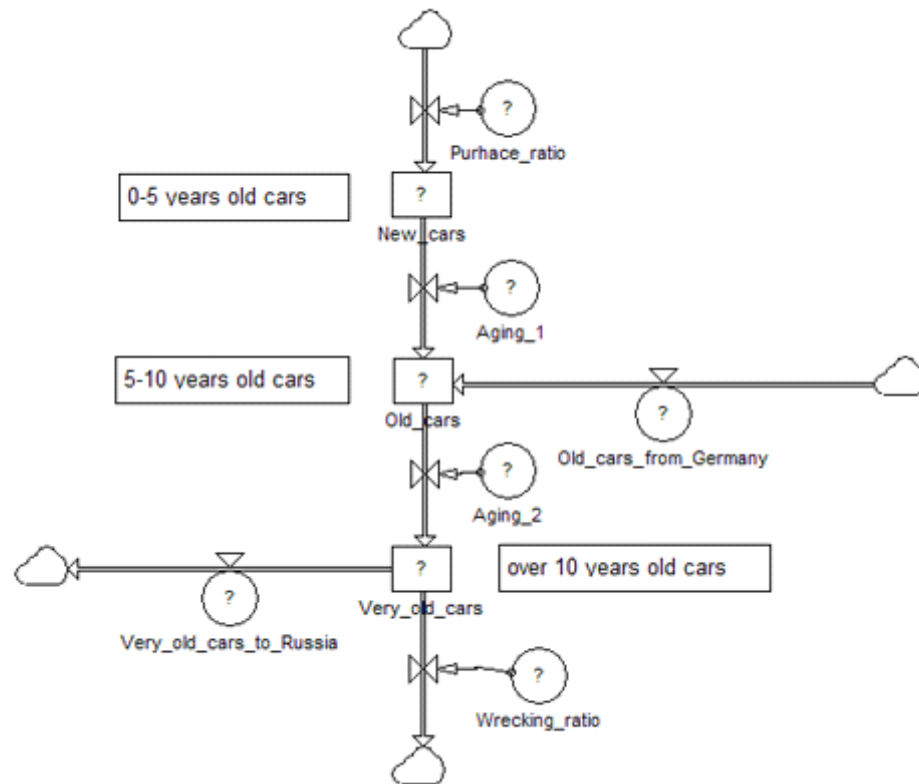


Figure 13.8: Aging chain of Finnish cars.

old cars. The only inflow is newly purchased cars. After 5 years these cars are moved to the next storage, 5-10 years old cars. To this storage, there is another inflow, old cars from Germany. The originally new cars are moved from the old car storage to the very old car storage after 5 years. The old cars from Germany are staying only 2 years in the old car storage (Old cars from Germany are 8 years old).

The final storage, very old cars, has all the cars, which are over 10 years old. Outflow from the very old cars is wrecked cars. Very old cars are not sold to Russia in this model.

Delays are added using causal loops to the figure 13.8 and the result can be seen in the figure 13.9.

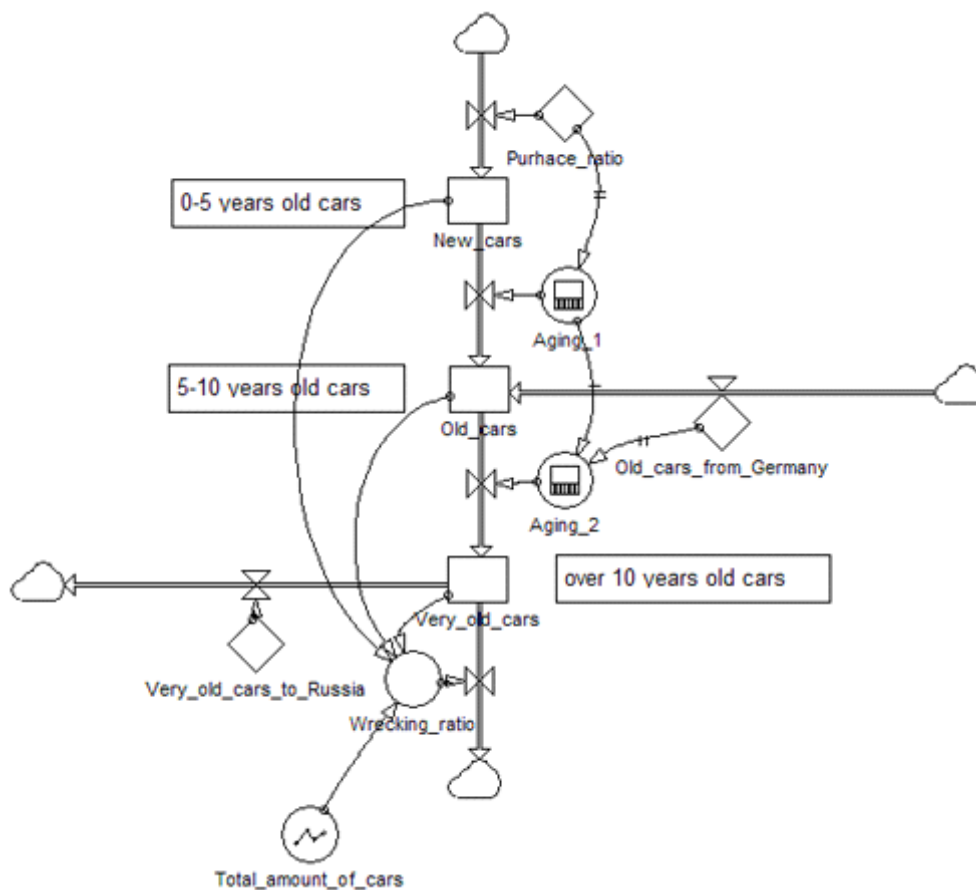


Figure 13.9: Delays of Finnish car populations.

Correspondences between causal loops and control systems can be easily seen.

13.5.3 Equations behind the model

Even the system dynamics is usually considered a qualitative tool; the numbers have to be entered to the model if simulations are wanted to be run. Next, we have to define the ratios, which control the inflows, outflows and flows between the different age groups.

$$\begin{aligned} New_cars_0 &= 250000 \\ \frac{\partial New_cars}{\partial t} &= Purchase_ratio - Aging_1 \end{aligned} \quad (13.1)$$

$$\begin{aligned} Old_cars_0 &= 250000 \\ \frac{\partial Old_cars}{\partial t} &= \\ Old_cars_from_Germany - Aging_2 + Aging_1 \end{aligned} \quad (13.2)$$

$$\begin{aligned} Very_old_cars_0 &= 500000 \\ \frac{\partial Very_old_cars}{\partial t} &= \\ -Wrecking_ratio - Very_old_cars_to_Russia + Aging_2 \end{aligned} \quad (13.3)$$

$$\begin{aligned} Aging_1_{0,1,2,3,4} &= 50000 \\ Aging_1_t &= Purchase_ratio_{t-5} \end{aligned} \quad (13.4)$$

$$\begin{aligned} Aging_2_{0,1,2} &= 50000 + 0 \\ Aging_2_{3,4,5} &= 50000 + Old_cars_from_Germany_{t-2} \\ Aging_2_t &= Aging_1_{t-5} + Old_cars_from_Germany_{t-2} \end{aligned} \quad (13.5)$$

$$\begin{aligned} Wrecking_ratio &= \\ (New_cars + Old_cars + Very_old_cars) \\ - Total_amount_of_cars \\ Wrecking_ratio &\geq 0 \end{aligned} \quad (13.6)$$

$$Old_cars_from_Germany_0 = 0 \quad (13.7)$$

$$Purchase_ratio_0 = 50000 \quad (13.8)$$

$$Very_old_cars_to_Russia = 0 \quad (13.9)$$

Total amount of cars is defined as a curve, seen in the figure 13.10. The amount of cars is predicted to increase. We can adjust the curve if forecasts

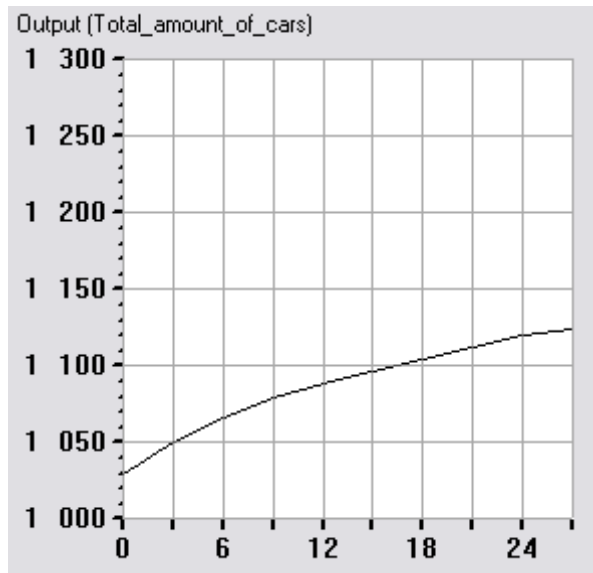


Figure 13.10: Total amount of cars (*1000) as function of time.

that are more precise are available. In addition, different scenarios can be tested. The amount of cars is considered independent to the amount of new cars. If more new cars are bought, more old cars are wrecked. If less new cars are bought, people use old cars longer and there will be less wrecked cars. This is of course an assumption.

The model defined here describes the age distribution of Finnish cars. Model is rather simple but the qualifiedly correct. If tax revenue is added to this model, it will result to a much more interested and realistic model.

13.5.4 Flight simulator

Third basic concept of system dynamics is a flight simulator. An example is built here. Jay Forrester tried to build a real flight simulator in the 50's before he moved to the system dynamics. The flight simulators are still here, although they are commonly called management flight simulators.

A management flight simulator is a front end to dynamic model, which is easy to use and can illustrate system behind the flight simulator. It might have graphs and sliders. User can run and test different combinations. The idea is to learn behaviour of the system and make decisions according this new knowledge.

We try to build a simple flight simulator for our model of Finnish car popula-

tion. The most important thing is to watch the total amount of cars as well as the amounts of different age groups. In Finland, we have the oldest cars in the Europe. Those cars are unsafe and the pollution is huge. The goal of politicians should be to lower the average age of Finnish cars. Politicians can do this by lowering the taxes of imported cars from Germany or the taxes of new cars in Finland.

With this flight simulator, it is possible to test how the average age of cars behaves, if a great amount of cars is imported from Germany or if a great amount of new cars is bought.

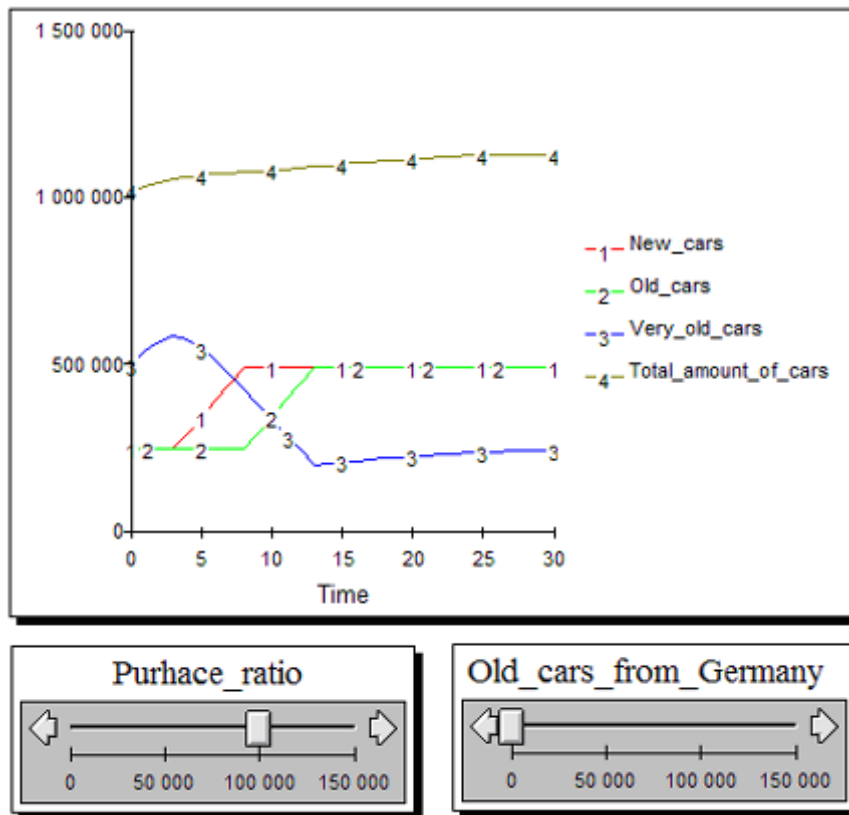


Figure 13.11: Flight simulator of Finnish car population.

After testing different combinations, it can be seen that the only way to lower the average age of Finnish cars is to lower the taxes of new cars. Later on the model can be further developed and taxes and prices of cars can be added to the model.

13.6 Literature and research institutes

At the end of this chapter, current literature of the system dynamics and system thinking is presented. The related software is discussed. The research institutes studying system dynamics and thinking are listed.

13.6.1 System dynamics literature

Jay Forrester invented system dynamics in the late 50's. His work has been referred earlier when the history of system dynamics was presented. At 90's after the book *The Fifth Discipline* by Peter Senge, the system dynamic and thinking seemed to gain popularity. Most likely visually attractive software has brought system dynamics to wider knowledge. In addition, the ideas of complex systems at the beginning of new millennium are new ground for system dynamics.

The following books are published between 1990-2000. These are related to Sterman's Business Dynamics. The list is from Amazon.com [8]:

- Jamshid Gharaajedaghi, *Systems Thinking: Managing Chaos and Complexity: A Platform for Designing Business Architecture*, Butterworth-Heinemann (Trd); (May 1999)
- Barry Richmond, *The "Thinking" in Systems Thinking: Seven Essential Skills*, Pegasus Communications; (January 5, 2000)
- Stephen G. Haines, *The Manager's Pocket Guide to Systems Thinking*, Human Resource Development Pr; Pocket edition (February 1999)
- Joseph O'Connor and Ian McDermott, *The Art of Systems Thinking: Essential Skills for Creativity and Problem Solving*, Thorsons Pub; (April 1997)
- Peter Checkland, *Systems Thinking, Systems Practice: Includes a 30-Year Retrospective*, John Wiley & Sons; (September 16, 1999)
- Stephen G. Haines, *The Systems Thinking Approach to Strategic Planning and Management*, Saint Lucie Press; (June 13, 2000)
- Gerald M. Weinberg, *An Introduction to General Systems Thinking*, Dorset House; (April 15, 2001)

- Virginia Anderson and Lauren Johnson, Systems Thinking Basics: From Concepts to Causal Loops, Pegasus Communications; (March 1997)
- John D. W. Morecroft. Peter Senge and Jay Forrester, Modeling for Learning Organizations, Productivity Press; (August 2000)

Most of the literature discusses the business and management issues. It can be seen that the ideas of system dynamic can motivate those who control complex systems.

13.6.2 Research institutes

- MIT System Dynamics Group is the home of system dynamics and thinking.
<http://sysdyn.mit.edu/sd-group/home.html>
- System Dynamics Society is a good source of information about system dynamics.
<http://www.systemdynamics.org>
- The Santa Fe Institute is a private non-profit institute with multi-discipline project also focusing on the complex systems.
<http://www.santafe.edu/>

13.7 Conclusions

In this chapter, system dynamics and system thinking were presented as a qualitative tool for modelling complex system. System dynamics has almost 50 years history behind it. The most well known application is WORLD3 model which was used by the Club of Rome in its' book *The Limits of Growth*. System dynamics is actively used for solving real life problems.

History of system dynamics is heavily bound to the development of digital computers and programming languages. System thinking has similar ideas as network structures. It is almost reverse to the ideas of hierarchical structures. In addition, system dynamics and thinking has common thoughts with system theory presented in the next chapter.

System dynamics and thinking are ways to understand complex systems. They are not ironic new science.

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