Using System Dynamics-based Learning Environments to Enhance System Thinking

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Keywords: system thinking; system dynamics; learner-centered education; learning environment; microeconomic model

Abstract

System dynamics is a suitable method in education for problem-oriented learning and for improving overall system thinking skills. It is proposed that integrated learning environments consisting of system dynamics models and additional didactical material have positive learning effects. This is exemplified by the illustration and validation of a learning sequence concerning market processes.

1. Introduction

A primary task of educational systems is to prepare students for their future life. This includes the ability to act competently in complex situations which is increasingly important in a complex world. To do so, competence in system thinking, as well as *usable* knowledge is helpful.

In traditional education teachers hand objective facts to their students that are usually fragmented into academic disciplines instead of linked to other subjects and thus integrated into a larger, meaningful context. Furthermore, the relevance to the solution of specific problems is seldom explained and aspects of transfer to similar classes of problems are usually omitted. It comes as no surprise that most facts taught and learned are quickly forgotten (Bruner 1963). Even if they are remembered, they can only seldom be used to solve real problems (Organisation for Economic Co-operation and Development 2003). Such knowledge remains isolated and inert (Collins, Brown & Newman 1989; Renkl, Mandl & Gruber 1996). Educated this way, one generally fails to succeed in complex situations.

People usually reach their goals in simple systems using linear thinking, where one effect is caused only by a single factor. However, simple strategies are likely to fail in more complex systems, which are highly interconnected and dynamic, resulting in feedback-loops, oscillations and side-effects. Their behavior is often difficult to anticipate, because it is counterintuitive, nonlinear and irreversible (Senge 1990; Sterman 2000).

To improve the quality of decisions in complex environments it is important to comprehend the reasons for failure. The theoretical construct of mental models helps here. Mental models contain an individual's specific knowledge, including the structure and dynamic behavior of a domain. They are the foundation of mental simulations enabling people to come to conclusions, to deduct new ideas and anticipate future conditions. In general: to understand the world. According to Norman, mental models are incomplete, stable and unscientific (Norman 1983).
Learning can now be defined as the change of a mental model based on theoretical reflection or former experience. Such learning can be especially enhanced when decisions based on strategies derived from mental models do not lead to desired results. Put differently: If a mental model proves ineffective, it seems reasonable to adapt it. However, Norman's description of mental models and empirical observation (e.g., the pork cycle) make this assumption seem overly optimistic.
The following section shows how these problems can be addressed by creating adequate learning environments and compares different educational methods in respect to their ability to improve students' system thinking skills. In this regard, system dynamics seems promising as a central element of learning environments, which is explained in the following section. The next section exemplifies system dynamics' educational applicability with a learning environment which addresses a famous example of misbehavior in complex systems: the pork cycle. Afterwards, empirical data concerning the effectiveness of system-dynamic based learning environments for improving an understanding of complex systems are presented. Finally, an agenda for further research is suggested.

2. Educational Methods to enhance Learning in Complex Environments

By now, constructivist, learner-centered, action- and problem-orientated methods of education are widely thought to be superior to teacher-centered methods (Fosnot 1996; Harel & Papert 1991). It seems obvious, that mental models cannot be "handed" by a teacher to his students, but that students have to integrate new ideas into their existing understanding of a problem; that is, they have to actively reconstruct their own individual mental models. This changes the teacher's tasks – at least partly – from passing on objective information to creating learning environments.
The concept of learning environment describes relevant outer conditions of learning and includes learning material, tasks and all action requirements applying to a specific topic. Good learning environments should meet some of the following criteria: All learning activities should be integrated into a larger setting or a global task with sufficient complexity. Tasks should be authentic, realistic and refer to relevant contexts that enable students to identify with the task. Furthermore, students should be encouraged to think and to come to solutions independently and be given opportunities to reflect on past and future learning content and processes. However, it is important to pay attention to an adequate ratio of independent exploration and guided learning. Finally, good learning environments are longer sequences using complex methods (Duffy, Lowyck & Jonassen 1993).
When creating learning environments to enhance system thinking skills, adequate educational methods should be used. However, a well reflected choice of methods requires a clearer understanding of the somewhat fuzzy term 'system thinking'.

According to Richmond and Ossimitz (Ossimitz 2000a; Richmond 1993), 'system thinking' contains four dimensions:
1. Thinking in models which includes the ability to construct models and transfer the gained knowledge to real situations. For the latter, an awareness of a model's premises is necessary.
2. Dynamic thinking that enables anticipation of future behavior of systems with delays, oscillations and feedback loops.
3. Integrated thinking, meaning that complex linkages are considered as opposed to mere linear thinking, where one cause is thought to have only one effect.
4. Acting successfully in complex situations by choosing the right decision, well considered.

Figure 1 illustrates how learner-centered methods – which all generally have realistic and complex learning content and allow learners a high degree of independent thinking and self-regulated action – differ with regard to the dimensions of dynamic thinking and learners' degrees of freedom. The latter was added to the four dimensions of system thinking, because its consideration allows didactic fine tuning in respect to available time and students' skills in self-organization and prior knowledge. Open settings generally are more time consumptive and call for higher self-regulation and self-organization. Furthermore, open settings such as active quantitative and qualitative modeling require familiarity with the corresponding modeling tools.

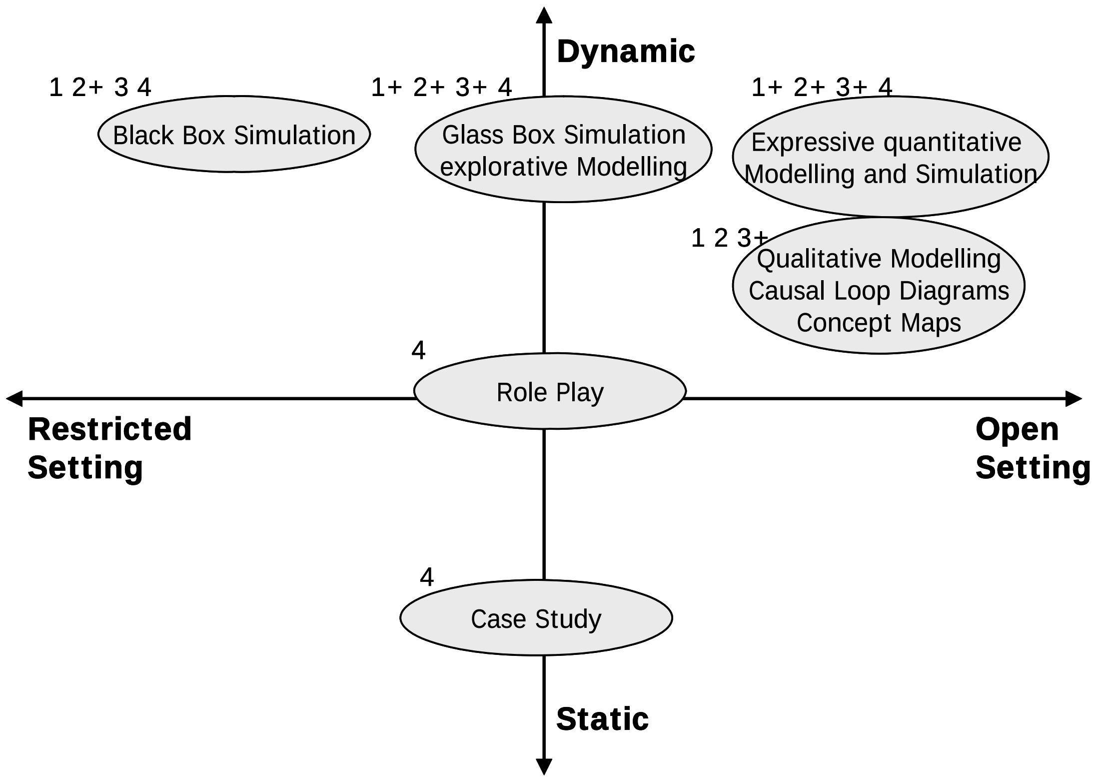

Figure 1: Typology of complex educational methods

With case studies, students are given numerous and complex data concerning a specific domain and asked to analyze it and come to a solution. They are well suited to train analyzing, communication and decision skills. Role plays make students play a specific role, which fosters empathy and tolerance to ambiguity as well as communicative and decision skills. Causal loop diagrams are an easy-to-use representational method to visualize the interconnectedness and possible feedback loops of complex systems. Students can analyze given causal loop diagrams or create them themselves. When learning with black box simulations, the underlying model's structure and premises remain unknown to the students, as opposed to glass box simulations. Expressive modeling calls for one's own creation of executable models.

These educational methods are suited differently in respect to the above described dimensions of system thinking, which is illustrated with the numbers to the top left of every method in figure 1. Each number mentioned indicates a method's strength in respect to the dimension, whereas the symbol "+" is used for higher differentiation.

Although system thinking skills can be enhanced with all the methods mentioned, glass box simulation and active modeling appear to be especially suited, because they have the potential of addressing all dimensions of system thinking effectively. Of the four major modeling approaches – system dynamics, equation-based, property-based and emergence-based modeling – system dynamics, which allows the creation of interactive simulations seems most appropriate to enhance system thinking skills: It does not require much mathematical effort and is very illustrative due to its notation. An adequate graphic representation of complex systems is beneficial to their understanding (Anglin, Vaez, & Cunningham 2004).

3. Creating Learning Environments using System Dynamics

As has been shown, when dealing with complex problems with an interconnected and/or dynamic quality, system dynamics is an advisable learner-centered method. This section discusses the relevance of adequate software, explains different methodical approaches and points out the necessity of didactic material accompanying the models.

The system dynamic notation is very easy to learn - it relies essentially only on symbols for stocks, flows and information links – yet it is sufficient to model a wide variety of complex and dynamic systems (Forrester 1961, 1975).

When creating learning environments using system dynamics, two basic approaches are available: expressive and explorative modeling (Bliss 1994).

Expressive modeling means that students build the model themselves from scratch. Starting with a problem or a case description, relevant elements and their relations are first to be identified, then modeled. To be able to do this, further research by students is usually necessary. Facts are not taught by the teacher merely because they are mentioned in a curriculum; instead students investigate topics to build simulation models and eventually come to understand a complex problem thoroughly. These facts are thus anchored in a meaningful context and are not simply learned for a test and soon forgotten. Once a model's first version is finished, simulation runs are done and the results are compared to expected results. Usually several modifications are necessary until the model seems valid. Having created a valid model, the systems behavior to specific variations of parameters can be explored. Such gained knowledge may then be

transferred to the real system, but with consideration of the model's premises and restrictions.
Using an explorative approach to explore a complex topic, students are given a simulation ready model. In addition, students are asked to do exploring tasks such as analyzing the model structure and the system behavior to parameter variations.
Hillen found out in an extensive empirical study that expressive modeling generally leads to better learning results and is good for students' cooperation and interest. The explorative approach on the other hand is of advantage in deepening existing knowledge structures (Hillen 2003). In addition, model exploration takes less time and requires fewer modeling skills. However, these two approaches are not mutually exclusive but can be combined, so that learning environments can be created that fit very well with student competence and available time. For example, they can be given a suboptimal model. By exploring it, students discover further necessities for model improvement, which can be done by expressive modeling.
Regardless of the chosen modeling approach, when simulating a model it is essential to reflect on the results. Ideally, a mental simulation precedes a computer simulation, the results of which are to be anticipated. Then the actual results are compared with the expected results and significant differences must be examined. Differences can be explained by false mental or computer models. The examination process of unexpected simulation results contains significant opportunities for learning, because it eventually requires an intensive reflection and adaption of the learner's mental model. This method of working with simulations is highly advisable, because psychological research shows that animated pictures and simulations can also deter learning. This is likely when computer simulations replace mental simulations: students run simulations without thinking, a kind of video-game-syndrome (Lewalter 1997; Sterman 2000).
Of course, a prerequisite to simulating a system dynamic model is its implementation in a software application, such as Powersim, Stella, Modus, Dynasis or CoLab. These software applications facilitate modeling complex systems as well as understanding them, because they allow modeling not only mathematically but also graphically, which is very intuitive and illustrative. Such attributes make software applications very suitable for educational purposes. They can be effectively used as cognitive tools that relieve learners from routine activities (such as calculating numbers) thus enabling active and fundamental cognitive processes (Jonassen 1991; Sweller 1988). The choice of adequate modeling software, however, is an important one. If it is not easy to use, software-handling might take too much time and effort, leading to poor motivation and learning results (Klieme & Maichle 1991). The learning environments described in the following section were created with the commercial software Powersim, because it is easy to use and very powerful. For example, it allows creating a wide variety of graphs and user interfaces. Furthermore, it is possible to develop multi-user-network applications and online simulation models. Last but not least, free light versions of Powersim are available, which are sufficient for most educational purposes. Especially for science education, integrated software applications such as CoLab, Modelling Space and WISE may be the best choice, because their structure supports inquiry-based learning in a broader context, where expressive system dynamics-modeling is one of several tools to explore specific phenomena (van Joolingen et. al. 2005; Avouris et. al. 2003; Linn 2005). However, if the didactic setting is not based on scientific experiments and if the students are to work with a combination of subsequent models or the combination of expressive and explorative modeling, "simple" modeling software in

combination with didactic materials offers greater flexibility. Thus, successive coordinated tasks, clear instructions and methodical variations can be better implemented, which is important in educational fields such as social science or economics, where scientific experiments seldom form the content of learning processes.
As has already been mentioned briefly, effective learning environments cannot consist exclusively of models. The entire didactic setting needs material for introduction and theoretical background information to the problem. Clear instructions for modeling, analyzing, and simulating (including tasks to anticipate simulation results) are especially important for students with poorer metacognitive abilities. Furthermore, it is important to exchange work-results from time to time, so problems can be discussed and solved. The ending of an extended learning unit should contain a summary, possibilities of transferring the acquired insights to similar problems, and a reflection of the entire learning process.

4. Example: Market and Price

One of the most fundamental economic models is that of supply, demand, and market equilibrium. The supply curve aggregates market behavior of producers and has a positive slope: the higher the price, the more products will be produced or offered. On the other hand, the demand curve has a negative slope, because customer demand is high when prices are low and vice versa. The basic model states that in markets with free prices there will be equilibrium between supply and demand. When there is less supply than demand the market price will rise and vice versa. This mechanism is generally illustrated as seen in figure 2.

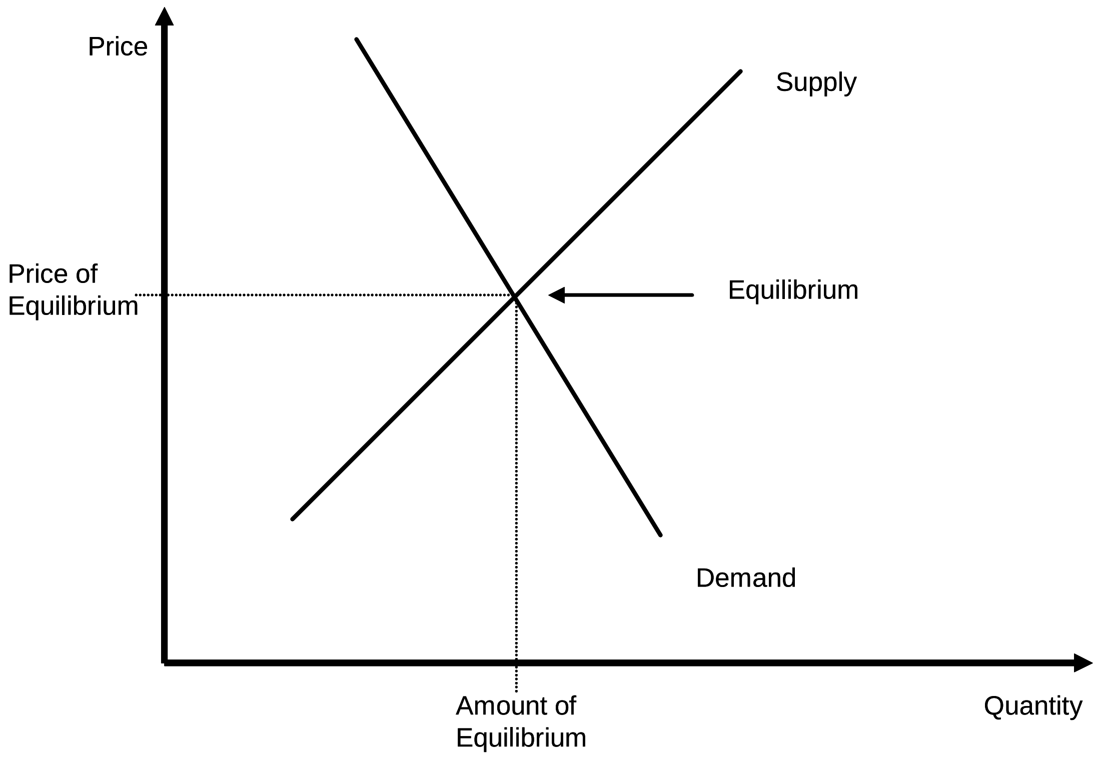

Figure 2: Static Market Model of Supply and Demand

However, largely due to time delays on the supply side, many markets fail to reach an equilibrium. A famous example of periodically oscillating prices is the pork cycle (figure 3). The phenomenon of periodic oscillations of pork prices results from agriculturalists' strategies that make them breed more pigs when prices are high due to a momentary shortage of pigs and vice versa. Since most breeders follow this strategy, a period of oversupply and falling prices is bound to come when the newly bred pigs reach slaughtering age. Low prices, however, lead to low breeding and cause a later shortage, etc. Similar cycles can be observed even today in many fields with significant time delays in such different areas as demand for and supply of raw materials, office space, teachers and engineers.

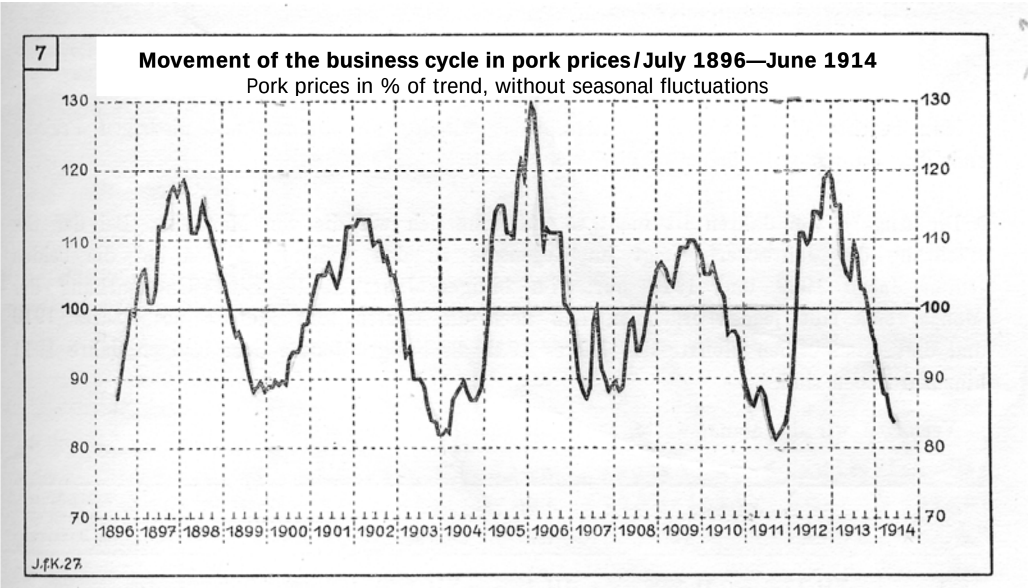

Figure 3: The Historical Pork Cycle - Oscillating Prices (Hanau 1927)

Acknowledging that markets sometimes don't reach equilibrium (immediately), the basic model is enhanced by trying to consider dynamics based on the so called cobweb-theorem which is illustrated in figure 4.

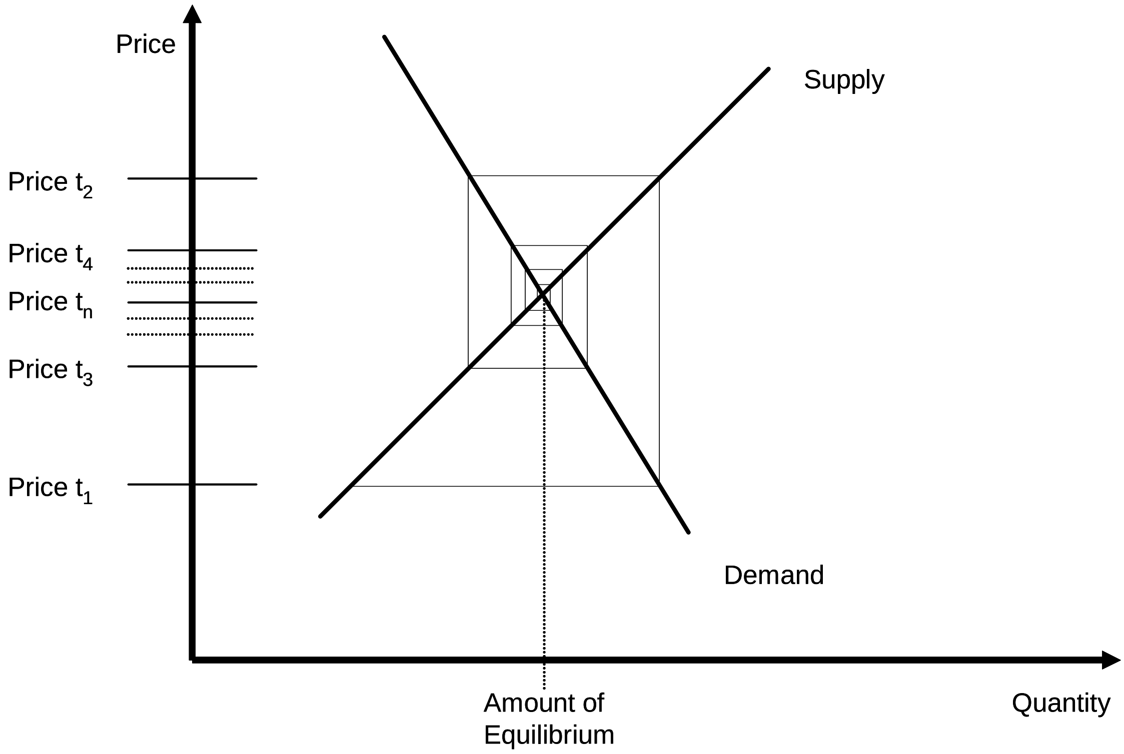

Figure 4: Dynamic Market Model of Supply and Demand

In this model, the dynamic development of prices in this model is exclusively dependent on the slopes of the demand and supply curves. However, by neglecting time delays, which are an essential cause for oscillating prices, the model is too simple. Simultaneously, it is hard to understand because this way of illustrating oscillating prices is not as intuitive as time graphs.
Using a system dynamics-based learning environment, a better understanding of the dynamics of market processes can be developed. The sequence uses the explorative modeling approach, in order to enable a fast learning process for students without much modeling skills. However, given enough time and experience in modeling, students could also build the models themselves if they are supported by their teacher or adequate worksheets.

Exogenous Price

The learning sequence starts with tasks (appendix 1) to explore a basic model of market processes where supply is a given constant and only demand is dependent on price, with price still being an exogenous element (figure 5). This simple model allows students to familiarize themselves with the software and to analyze single elements of the model and their connections. By changing the price, students notice that low prices result in excess demand. It becomes obvious that suppliers would adjust their prices. In case of excess demand, they raise the prices. In case of excess supply the prices would fall in order to increase demand.

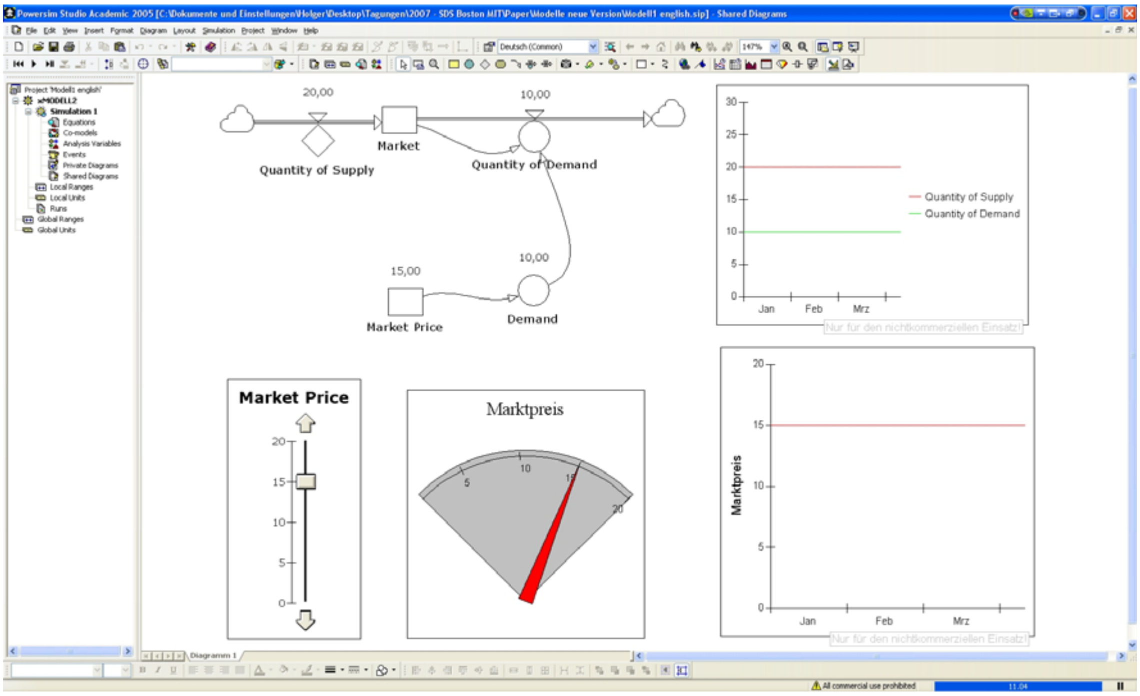

Figure 5: Basic Powersim-Model

Endogenous Price

Based on the prior realization that prices depend on the ratio of supply and demand, price is an endogenous variable in the next two models (figure 6). Here the price is found in an iterative process with suppliers adjusting their price gradually to market conditions. The magnitude of a change of price depends on the difference of supply and demand. This can be calculated by the formula: change of price = (demand – supply quantity) / price adjustment factor.

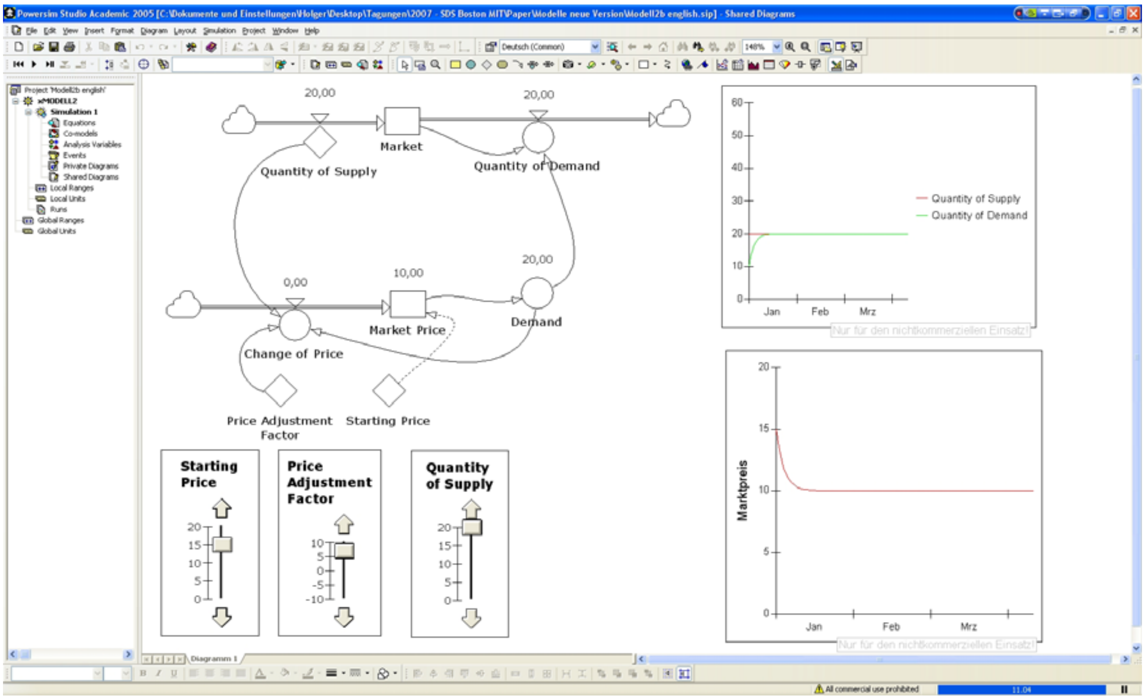

Figure 6: Powersim-Model with Endogenous Price

The price adjustment factor expresses the speed or strength of price adjustments per time step and thus reflects a products' price volatility. By reflectively changing the parameters starting price, supply quantity and price adjustment factor, students come to understand the pricing mechanism.
The last question of the corresponding worksheet - which prepares students for the next model - deals with the fact that variations of supply quantity result in changes of market price. For example, if there is only little supply, the price will have to be quite high so that there is also little demand. The exact price to reach equilibrium depends on the demand curve, which was explored by the students in the previous model.

Endogenous Supply and Time Delays

In the models of the last learning sequence the supply curve is added. Now supply is not a given exogenous variable but dependent on market price. High prices generally lead to high supply; companies invest in additional production plants and new players are likely to join an attractive market. However, it takes time to build up production capacity. These time delays primarily concerning the supply side of the market cause a more complex pricing pattern. Generally the equilibrium price is only reached after a longer period of oscillations in price. At certain values of time delay – depending on the starting price, the price adjustment factor and the slopes of supply and demand curves – no stable equilibrium is found at all.

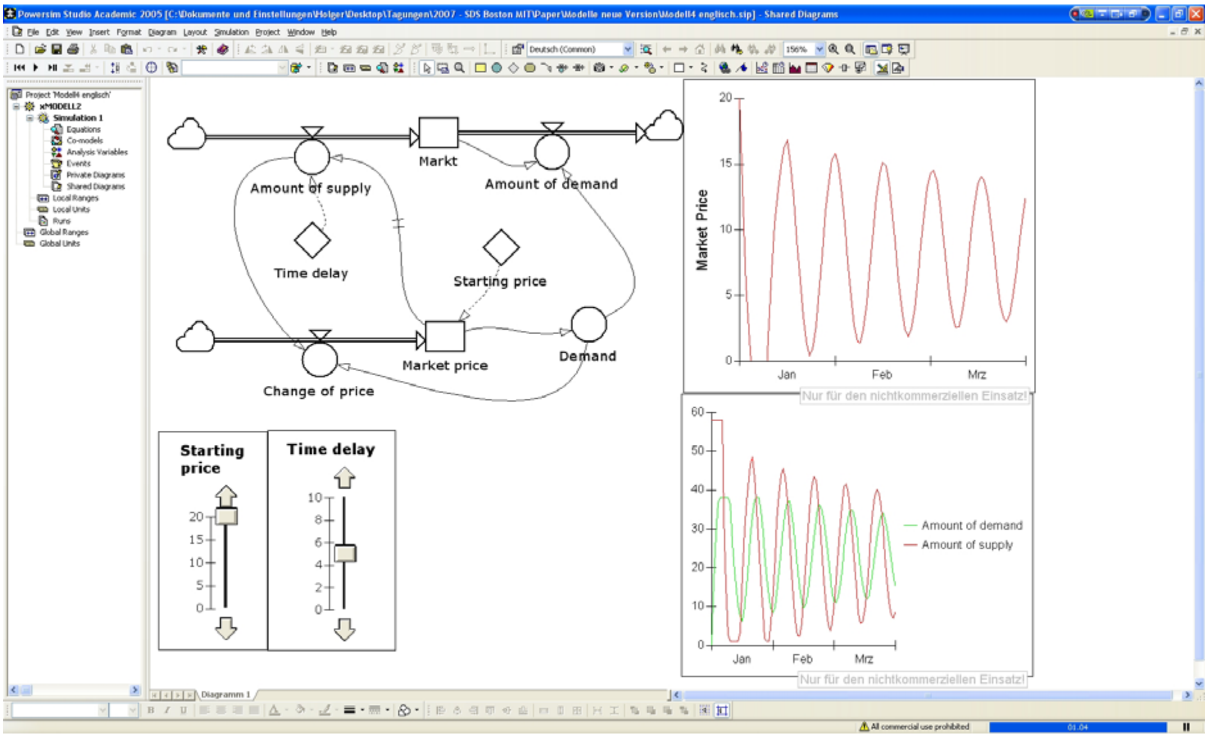

Figure 7: Final Powersim-Model of Supply and Demand – Oscillating Market Price due to Time Delays

5. Validation

The described learning environment was evaluated in an empirical study to test its ability of improving educational processes, which will be briefly described in this section. A more detailed account will be available in Arndt (2007). Research variables in focus were students' motivation, activity and social learning. Furthermore, the knowledge gained has been evaluated as well as the ability to use it in different contexts. Additional measurements concerned improvements in system thinking with subcategories such as considering dynamics, side-effects and variables' interconnections. Also, the teachers were asked about their motivation, their preferred modeling method (explorative vs. expressive modeling), the relationship of free and guided learning, and the learning environment' time consumption. The corresponding data were gathered using a combination of tools such as interviews, questionnaires and tests. The latter verbally described complex systems including time delays. Students were asked to describe and anticipate system behavior, and choose from a set of given strategies to reach a given goal. In addition, the students' answers to the worksheets and group-presentations were evaluated.

The two teachers participating in the project received the same two day introduction to system dynamics, to its applicability for educational tasks, the software Powersim and available learning environments.

The "market and price"-unit was evaluated in two classes with students aged 16 to 18. In one class (n=21) the teacher used the explorative approach and worked with the models and worksheets described above, which took three 45-minute units. The students were motivated, enjoyed the sequence and understood the topic, including its dynamic quality well. However, only six students were able to transfer what they learned to different situations. Overall system dynamic skill did not improve significantly. In the second class (n=28) the modeling was done expressively. The teacher had some trouble guiding the learning process efficiently. All in all, the sequence took seven 45-minute units without the students gaining noticeable advantages in any field compared to the other group. On the contrary, they felt less motivated and self-efficacy was lower. The students were new to system dynamics and felt overstrained. Most would have wished for clearer guidelines when modeling and for more exchange on provisional results. The teacher underestimated time necessary in class and out of class for preparation of the work material.

6. Conclusion

Although quantitative studies (e.g. Arndt 2007; Hillen 2003; Ossimitz 2000b) indicate the method's suitability for enhancing system thinking skills, which is generally accepted as an important educational goal, system dynamics is still hardly used by teachers. A number of reasons come to mind. A major obstacle might be teachers' lack of system dynamics skills. This could be altered by adding this topic to teacher-training curricula and by devising teacher-oriented system dynamics training. In addition, many more system dynamics based learning environments – not just models – need to be created and published. It would neither be time-efficient nor realistic to expect teachers to construct such environments themselves. Furthermore, if more models could be used online with just a web browser instead of requiring modeling software another barrier to system dynamics' use in education would be diminished. Finally, the effectiveness of system dynamics in education ought to be examined quantitatively in more detail, especially in comparison to different educational methods. In this context, the typology proposed in figure 1 could be checked. If research shows the suitability or even superiority of system dynamics, if more high-quality learning sequences become available, and if more teachers get to know the method during or after their professional education, then the spreading of system dynamics in education might be more dynamic in the future.

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Appendix – Student Worksheets

Model Market and Price 1
Examine Model1.sip by clicking on symbol which will advance the simulation by one time step. A click on will run through the simulation entirely, whereas resets the simulation.
During the simulation, you can change the market price with the slider. By double clicking on an element you can examine its values or programming.

1 – When examining the model, please describe these elements:
- Quantity of supply
- Quantity of demand
- Demand
- Market price

Which of these elements are constant, which are variable?

2 – Please describe and explain the causality between market price and demand. Draw the model's demand curve into the coordinate system.

3 – Let's assume the product is ice cream. How would the demand curve change if…
a) the summer is very hot
b) refreshment drinks become cheaper
c) the average income of potential customers rises
d) lots of people come to think of ice cream as unhealthy

4 – Why is actual *quantity of demand* (= the number of products bought) sometimes smaller than the potential *demand* (= the number of products people would like to buy)? When does this happen?

5 – Describe the relation between quantity of supply and quantity of demand at a market price of …
a) 3 currency units
b) 10 currency units
c) 15 currency units

Model Market and Price 2

1 – How would suppliers change their prices if
a) demand exceeds supply?
b) supply exceeds demand?

2 – Please find examples for suppliers reacting with adoptions of price to market imbalances.

3 – Open Model2a.sim. In comparison to the previous model here the market price is calculated automatically. Run a simulation and
a) describe how price and demand change over time?
b) explain how the market price is calculated

4 – Open Model2b.sip now, please. It is the same model as before but you can change starting price, price adjustment factor and quantity of supply. When working on the following tasks, just change on parameter and leave the others at their initial values.
a) Run several simulations with different starting prices. What do you notice?
b) Experiment with the price adjustment factor. What happens when you choose a negative value? What would that mean in reality?
c) Change the quantity of supply. What other element changes after that? Try to explain the causality.

Model Market and Price 3

1 – In the long run, what would be the consequences of very a) high and b) low prices in respect to the number of suppliers and the quantity of supply?

2 – Please open Model3.sip. In which way is it different from the previous model?

3 – Describe and explain the causality between market price and quantity of supply. Draw the model's supply curve into the coordinate system of the first worksheet.

4 – Anticipate the price and the quantity at which the market will be at equilibrium. Then test your assumption by simulating the model.

5 – Open Model4.sip and run a simulation. Now there is a time lag in respect to the quantity of supply.
a) Describe and explain the development of market price, quantity of supply and demand.
b) Experiment with different time lags. What effect do they have on the finding of an equilibrium market price?
c) Give some examples where companies don't react immediately to changes of prices but with a time lag.
d) Name some markets with permanently changing prices that don't reach equilibrium.