MODELING STRATEGIC AND OPERATIONAL DECISION-MAKING – AN AGENT-BASED MODEL OF ELECTRICITY PRODUCERS

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ABSTRACT

Essential steps in building agent-based models is to conceptualize, quantitatively representing and implementing the behavior of agents. A formal approach is presented to model the behavior of consumers, institutions or companies as rational decision-makers. Key element is a generic ontology for socio-technical systems and a framework for conceptualizing actors as agents with strategic, tactic and operational behavior. The approach was used to represent the behavior of electricity producers who must decide on investments, day-to-day operations and deal with CO_2 emission-rights. This exercise amply demonstrates the value of using a formal conceptual framework in the development of agent-based models.

INTRODUCTION

Infrastructures for transportation, telecommunication, natural gas, electricity, etc. are essential for a modern industrial society. Infrastructure networks are technologically advanced large scale systems, which development, structure and operation is decided upon by a myriad of actors. These infrastructures are *socio-technical systems*, which are defined as systems in which physical elements are embedded in a social network of actors and institutions. The electricity infrastructure system, for example, not only consists of the physical infrastructure for electricity production, transportation and distribution, but also spans electricity producers, network operators, a variety of consumers, financial institutions, knowledge and service providers. Its evolution and operation is determined by discrete events, decisions by incompletely informed (ir)rational, agents on continuously operating, interconnected systems. As a consequence, the dynamics of this and other infrastructure systems cannot be predicted from scientific and engineering principles alone. Indeed, management science uses psychology, sociology and economy.

We believe that combining knowledge from both engineering and management science is required to successfully explore the emergent behavior of these systems by simulation. Appropriate models for socio-technical systems must represent a great many external factors, apparatus, technologies or facilities and a spectrum of actors. The latter determine government policy, develop and interpret regulations, invest under uncertainty in a global, continental or regional market, respond to consumer demand and preferences, ensure proper operation, avoid congestion and so on.

Particularly agent-based models (ABM) appear suitable to explore and gain insight in the dynamics of socio-technical, systems: in a socio-technical system, a subsystem of actors and a technical subsystem interact on different levels of aggregation. Agent-based simulation models can cope with discrete events, multi-level (disaggregate) decision-making, emergent markets (Dam *et al.*, 2007; Nikolic *et al.*, in print) More important, ABMs offer a good way to include the social and behavioral aspects. An ABM model describes the behavior of parts of the system, the system behavior emerges from the behavior of the smaller autonomous parts (Dam and Lukszo, 2006). Therefore, ABM simulations can be used for explorative research with different scenarios.

There is a wide range of application domains for ABM, since agent-based modeling originates from different research domains, such as social sciences, mathematics and from artificial intelligence (Wooldridge and Jennings, 1995; Bussmann *et al.*, 1998; Jennings, 2000). The agent paradigm in agent-based research can be very conceptual and has to be operationalised to be applicable in simulation.

A modular and flexible environment to set-up and execute ABM simulations has been developed (Nikolic *et al.*, 2004; Nikolic *et al.*, 2006). By using an ontology as its foundation (Dam *et al.*, 2006) effective representation and implementation for a range of problems in a top-down procedure has become feasible. The remising ‘simulation engine’ is suitable for doing experiments in different domains.

In this paper we focus on the conceptualization and formalization of agent behavior with respect to strategic and operational decisions. The case study presented addresses part of the electricity infrastructure, notably the electricity production sector where producers must deal with CO_2 emission-rights trading. The main objective of the case study was to obtain insight in the effect of the policy instrument CO_2 emission-trading (CET) on the types of power plants power producers prefer to build and the power generation portfolio that emerges from their decisions over time.

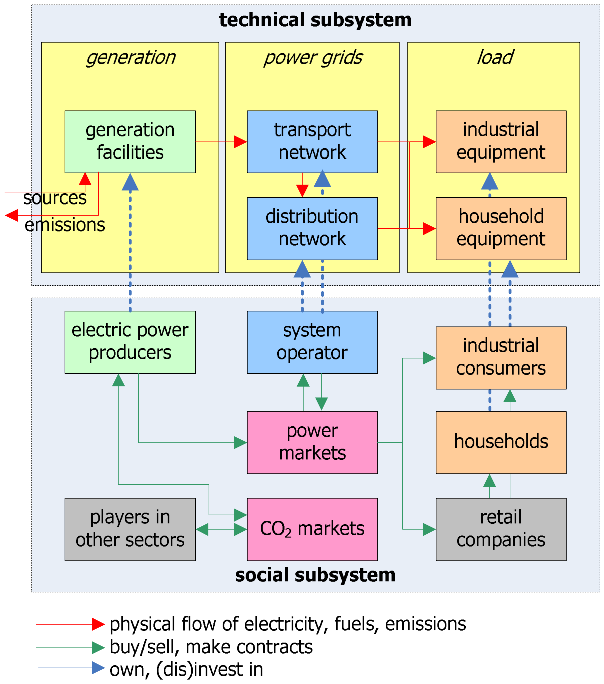

Figure 1. Socio-technical Power Production System (Chappin and Dijkema, 2007b)

The main question addressed in this paper is: **How can the decision-making process of electricity producers, investing in and in control of power plants, be modeled for use in an agent-based model?**

The remainder of the paper is structured as follows: First the system description and the background of the case are given. Second, a generic conceptual framework for socio-technical systems consisting of agents and physical installations is presented. Third, the decision-making process of electricity producers is operationalised using the presented framework. Some results are given to illustrate the advantage of the approach used. Conclusions are given and some areas for future work are identified.

SYSTEM DESCRIPTION

The system studied is that wherein electricity producers play a pivotal role: the electricity infrastructure. Today, electricity producers must effectively operate in power-exchange markets, but also in markets for fuels, capital and emission rights. The electricity infrastructure is a socio-technical system: The social network is composed of power production companies, retail companies and consumers that trade on different markets. Governments and regulatory bodies are also part of this network. Power generation facilities, power grids and consumers equipment form the technical network. Figure 1 shows the interdependencies of the social and technical networks. Electricity producers thus must operate and invest in power plants respecting current rules and regulations. Consumers invest and operate their end-user equipment. Suitable power grids operated by distribution companies and/or controlled by government connect the two. Each of these must anticipate and act upon demand, market and regulatory developments expected in interdependent social and technical subsystems.

CET affects producers decisions to invest by forcing the possession of permits for emitting CO_2 (Laurikka and Koljonen, 2006; Olsina et al., 2006). The amount of permits issued is limited and can be traded amongst parties on emission markets (Svendsen and Vesterdal, 2003; Vesterdal and Svendsen, 2004; Schleich et al., 2006). CET is implemented because it is assumed that it would lead to the most cost effective emission reduction due to the “invisible hand” (Smith, 1776; Svendsen, 1999). Because the long term impact of CET is unknown and serious experience is lacking, we conjectured that agent-based simulations could help to provide insights (Chappin and Dijkema, 2007a).

The main impact of CET on total sector CO_2 emissions would emerge from altered investment decisions of power producers (Chappin and Dijkema, 2007a). Governments implemented this instrument because it is assumed that it will lead to a less CO_2-intensive generation-portfolio. However, the producers, the agents in the electricity infrastructures, are autonomous. History shows that individual producers do not exhibit the same decision-behavior. Furthermore, investment and disinvestment decisions are discrete events about capital-intensive pieces of equipment. Agent-based models are suitable for explicitly simulating this. Our research into CET effects is of an exploratory nature, mainly because of the lack of historic data on emission-trading and its impact. Exploratory modeling for decision-support is very well possible with agent-based modeling.

CONCEPTUAL FRAMEWORK FOR SOCIO-TECHNICAL SYSTEMS CONSISTING OF AGENTS AND PHYSICAL INSTALLATIONS

The conceptual framework presented here consists of the definition of an ontology, which is a formal specification of concepts from a certain domain. Here the domain is that of socio-technical systems and the ontology aims at being generic so that different application domains can be expressed with it. The concepts defined in the ontology form the communication language of the agents as well as the framework in which the decisions of the agents is formalized. The concepts are abstract descriptions of classes.

Figure 2 shows a fragment of the ontology that describes the agents and physical installations as nodes. Agents in this model own physical apparatus that are on the level of physical assets. Physical assets do not act themselves as they are passive and controlled by agents owning them. The main concepts from Figure 2 are introduced below:

- **Agent:** Representation of an actor or institution. Can be the owner/controller of physical installations. Agents have decision-making abilities and can interact with other agents, forming a social network. Examples are the electricity production companies, the world market, the power exchange, etc.
- **Technology:** A physical installation that transforms physical flows. Technologies cannot make decisions

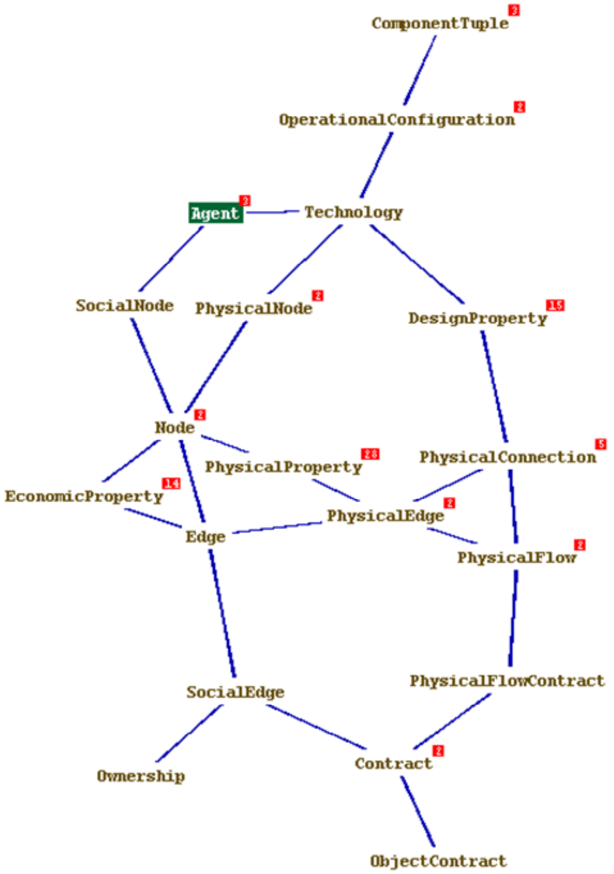

Figure 2. Fragment of the ontology, showing the main classes of the socio-technical system (social nodes and physical nodes) as well as the links and properties

themselves. They operate in a certain operational configuration, which describes which flows go in and which flows go out. Technologies are connected with other technologies forming the physical network. Examples are a coal power plant, a wind farm, uranium delivery, etc.

- **Edge:** connections between nodes (given that both agents and technologies are nodes). Social nodes (such as contracts) connect social nodes, while physical connections (such as cables or pipes) and physical flows (such as flows of electricity over time) can only occur between physical nodes.
- **Properties:** Both nodes and edges can have physical, economic and design properties. These properties, such as voltage, price, or maintenance costs, describe the elements that they are attached to.

This fragment of the ontology shows the specific classes and properties used in this model. It is only a small part of the full ontology, with other classes such as data flow, transport contract, industrial plot, an extensive hierarchy of labels for goods, and more properties such as GIS locations, phase state, voltage, composition, distance and transport modality.

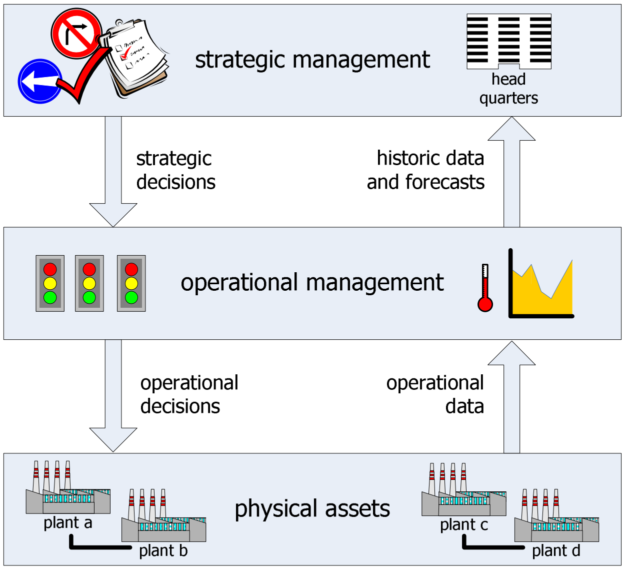

Figure 3. Three Layer Model (Chappin, 2006)

Besides this ontology structuring its concepts, a model is proposed to structure the socio-technical system itself. In the Three Layer Model, the social and technical subsystems are distinguished as well as their interaction. The Three Layer Model, shown in Figure 3, defines the interdependencies of actors and their physical assets. Actors in the real world are modeled as agents that manage on a strategic level and on an operational level. Agents thus act on these two levels.

On the strategic level agents make and plan for long term decisions that can affect their long term performance. Such decisions can be investment decisions, but also consideration of its objectives. On the level of operational management, daily procedures are followed and decisions are taken on a regular basis. This includes negotiation and contracting, buying resources and selling products, for example. Recall that actors and physical assets are in the ontology represented as social and physical nodes respectively, more specifically as agents and technologies.

Not only the distinction between agents and its physical assets are apparent in this model, but also the interaction that occurs between the three layers. The ontology concepts are merged with the three layer concept to formalize this interaction (see Figure 4). Strategic and operational management, as mentioned in the Three Layer Model, are parts of agents. Both are distinct and have decision-criteria originating from agents identity. Those criteria define the agents' management style. Interaction is translated into different types of edges (depicted as the three arrows in Figure 4).

On the top layer, the decisions of agents can lead to changes in its identity, but also to changes in the ownership of physical installations. That means that **ownerships relations** are defined at the strategic level. On the intermediate layer, agents negotiate and engage into agreements with other agents. This interaction is structured in **contracts**. On the lowest layer, interaction has a physical nature. The interaction of physical assets is by **physical exchange of materials**. Interaction on all those levels is in the ontology grasped in edges.

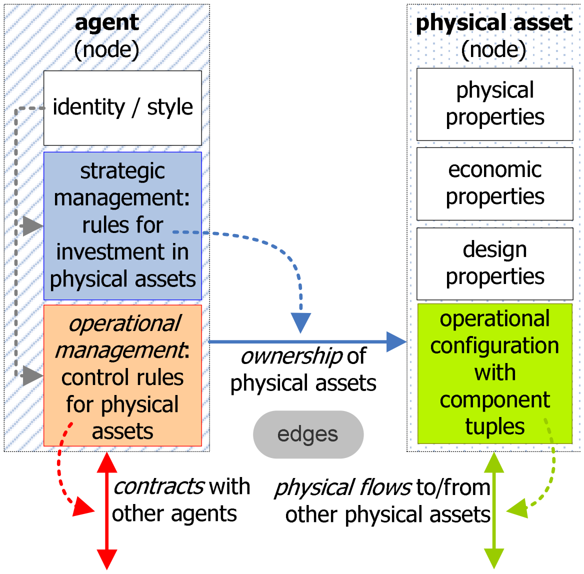

Figure 4. Interaction of agents and physical assets: extending the ontology for agents that invest in and are in control of physical assets

To summarize, social and physical nodes are distinguished. Social nodes are called agents; agents act by strategic management to change its identity and its ownership of physical nodes, also called technologies. Agents act by operational management to engage in contracts and physical installations constitute a physical network in which materials are exchanged. Actions are based on economic, physical and design properties of the agents and physical installations.

OPERATIONALISING DECISION-MAKING OF ELECTRICITY PRODUCERS

In this section, the decision-making of electricity producers is operationalised structured according to and based on the presented conceptual framework. As discussed in the previous section, agents act on two levels. This section focuses on the electricity producing agents, but some remarks are made on the other agents as well. An overview of the agents is drawn in the inner circle of Figure 5. Next to six electricity producers the government, consumer, other industry, power, fuel and emission markets and environment are modeled as agents as well. In this section, strategic management and operational management are separately discussed.

Strategic management of electricity producing agents

Electricity producing agents' strategic management is the decisions to invest or disinvest in power plants and the criteria to do so. In reality this is a process in which preferred type and timing of investments and disinvestments are made together. For practical reasons, it is chosen to split this process in three consecutive parts. The following decision scheme is constructed:

1. deciding what power plants should be dismantled
   a. because the technical lifetime is passed
   b. or because it is a cause for continuous losses;
2. deciding if investing in a new power generation facility is needed
   a. because old power plants should be replaced
   b. or because there is need for portfolio expansion (e.g., to accommodate growing demands);
3. deciding which type of electricity generation plant is preferred, only after the decision was made to invest.

The electricity producing agents all use this (dis)investment decision structure. In fact, the criteria used to base decisions on are the same for all electricity producing agents. The only unique part is the relative importance given to the different criteria. Therefore, actual decisions can be different between the electricity producing agents. We will now focus on part three of the decision scheme: *deciding on which power plant type is preferred*.

It is assumed that electricity producing companies use more than one criterion to decide on their preferred power plant type. Therefore, a multi-criteria analysis is used to model the selection of the preferred power plant type. In general, in a multi-criteria analysis a number of alternatives are evaluated to more than one criterion. By weighing the different criteria, the best scoring alternative is chosen.

The set **t** contains *k* weight factors – actual values – that rank the importance of criteria of the multi-criteria analysis. The ranking in **t** is different for every electricity producer, making the agents unique in their decisions: they have a unique management style or preference. It is important to note that *only* **t** is agent-dependent. The other parts of the decision process are the same for all agents. The set of factors for the multi-criteria analysis is represented in (1):

$$\mathbf{t} = \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_k \end{bmatrix} \tag{1}$$

Five criteria are used, namely the yearly expected profitability, nuclear friendliness, market adoption, nuclear fear and the availability of locations. The agent-based approach makes it possible to include the softer criteria, such as nuclear fear. Electricity producing agents all evaluate those five criteria, thus *k* equals five, but they assign different levels of importance to these criteria. Those levels are grasped in **t**.

Let **a** be the alternatives that are evaluated in the analysis (the technologies that represent possible power plants with their economic, physical and design properties and possible operational configurations) and assume that *m* alternatives are evaluated then **a** can be represented as (2):

$$\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} \tag{2}$$

Five alternatives are evaluated (m therefore equals 5): a coal fired power plant, a natural gas power plant, a wind farm, a biomass power plant and a nuclear power plant. All electricity producers evaluate the same set of alternatives.

Next, a score matrix **S** is build in which the score of each alternative on all criteria is listed (see (3)).

$$\mathbf{S} = \begin{bmatrix} s_{1,1} & s_{1,2} & \cdots & s_{1,k} \\ s_{2,1} & s_{2,2} & \cdots & s_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ s_{m,1} & s_{m,2} & \cdots & s_{m,k} \end{bmatrix} \tag{3}$$

Agents have the ability to calculate what the score is of all evaluated alternatives on the criteria. In other words: agents are able to calculate **S**. The ontology is used in the calculations: the data needed of the alternatives is represented in technology objects with physical, economic and design properties. For instance, the expected yearly profitability is calculated on basis of the economic properties of the different power plants, fuel consumption, fuel prices, etc. All data necessary is expressed in concepts defined in the ontology.

After filling **S** with scores, a normalization procedure is executed in order to make the criteria comparable. Per criterion, the 'best' score now equals 1 and the 'worst' score equals 0. So the most profitable alternative scores 1, the least profitable alternative scores 0. Now the scores are not related to chosen units anymore and the scores on different criteria are comparable. Matrix $\mathbf{S}^*$ contains the normalized values of matrix **S**, represented in(4).

$$\mathbf{S}^* = \begin{bmatrix} s^*_{1,1} & s^*_{1,2} & \cdots & s^*_{1,k} \\ s^*_{2,1} & s^*_{2,2} & \cdots & s^*_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ s^*_{m,1} & s^*_{m,2} & \cdots & s^*_{m,k} \end{bmatrix} \tag{4}$$

The normalization procedure is as follows. Let C be the subset of elements $\{1, 2, \ldots, k\}$ for which holds that the criteria t_C for all elements in C is positively oriented: a higher score s means a better score. For the elements $\{1, 2, \ldots, k\}$ not in C this is not the case: in other words, those criteria are negatively oriented. Given this subset c, normalization takes place by Equation (5). The normalized scores fill $\mathbf{S}^*$.

$$s^*_{i,j} = \begin{cases} \dfrac{s_{i,j} - \min\limits_{l\in\{1,2..m\}} s_{l,j}}{\max\limits_{l\in\{1,2,\ldots,m\}} s_{l,j} - \min\limits_{l\in\{1,2,\ldots,m\}} s_{l,j}} & j \in C \\ \dfrac{\max\limits_{l\in\{1,2..k\}} s_{l,j} - s_{l,j}}{\max\limits_{l\in\{1,2,\ldots,m\}} s_{l,j} - \min\limits_{l\in\{1,2,\ldots,m\}} s_{l,j}} & else \end{cases} \tag{5}$$
$$\text{with } j \in 1,2\ldots,k$$

After normalization the scores are comparable: the 'best' scoring alternative has value 1, the 'worst' scoring alternative has value 0. Note that **S*** is the same for all agents, since they evaluate the same alternatives using the same criteria. However, the scores can now be weight by multiplication with **t**, the vector containing agent-specific preference values. After weighing, the alternative a_j corresponding to the highest score r_j is selected following Equations (6).

$$\mathbf{r} = \mathbf{S}^*\mathbf{t} = \begin{bmatrix} s^*_{1,1} & s^*_{1,2} & \cdots & s^*_{1,k} \\ s^*_{2,1} & s^*_{2,2} & \cdots & s^*_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ s^*_{m,1} & s^*_{m,2} & \cdots & s^*_{m,k} \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ \vdots \\ t_k \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_m \end{bmatrix} \tag{6}$$
$$r_j = \max_{i\in\{1,2,\ldots,m\}} r_i$$

Since r_j has the highest weight score, the chosen alternative is the j^{th} element of **a** (element a_j). Although **S*** not static over time, **S*** is equal for all agents at a certain point in time. Only the weight factors **t** differ, possibly leading to different selections for the preferred alternative power plant type, a_j. If for some weight factors, 0 is chosen, the criterion does not play any role in the decision. In this case, the criteria used are agent-specific as well. One could therefore, with the same structure also opt for an agent-specific set of criteria.

Operational management of electricity producing agents

Besides strategic behavior, electricity producing agents also must exhibit operational behavior. As said in conceptual terms, by operational actions agents engage in negotiation and contracts. In general, a choice is made for demand-driven trade: negotiation always starts by the party that has demand for a good or service. Negotiation can lead to contracts and use the concepts defined in the ontology as language. For instance, if an agent needs coal, it will ask around for contracts for the delivery of the good called coal (all these concepts are defined in the ontology, recall the previous section).

Electricity producing agents perform the following consecutive steps:

1. bid on power exchange
2. acquire resources
3. acquire CO_2 emission rights

In these steps, the agents base their contracts on data of their physical assets: for coal power plants, for example, the required resource is coal. This is expressed in the operational configuration of this technology.

By interaction with the power exchange, contracts are setup to deliver electricity. More details can be found below. The amount of resources needed is based on its electricity production and contracts are setup to acquire the correct types and amounts of resources. Electricity producing agents acquire CO_2 rights in contracts as well. This is different than the other resources, since it is no physical good. Since this process is demand driven as well, the government sells rights at no cost, based on an allocation scheme. More rights can be bought on the emission rights market. Details on allocation, which can in more detail be found in (Chappin and Dijkema, 2007b).

Operational management of other agents

Non-electricity producing agents, such as the consumer, are modeled as aggregate agents: one agent represents all consumers and one agent represents government. All agents look at their physical assets to acquire resources. In other words, they also do step 2. The consumer, for example, requires the resource ‘electricity’ for its technology ‘consumer installation’ (a representation of the electricity demand) and will look for agents that have the technology to supply them with this resource.

The electricity market agent accepts bids from electricity producing agents per installation. A set of bids contain for *n* installations a reference to the installation (*i*), a bidding price (*b*) and the capacity of electricity to be sold (*c*). The agents bid marginal cost and full capacity. The electricity market also requests import price, import capacity and aggregate demand.

By a market clearing model, the market algorithm selects how much each installation (*i*) will produce (*a*) and at what price (*p*) and records that in a set of contracts. The developed market clearing model has been described in detail in (Chappin and Dijkema, 2007b). Based on these contracts, which are social edges as described in the conceptual framework, agents transfer money and operate their power plants to deliver exactly the amount of electricity contracted.

All agents are demand driven and they negotiate with other agents based on observations of their physical installations. The input-side of the operational configuration of power plants gives information on the types and amounts of resources needed. Agents retrieve that information when needed.

The agents negotiate and they select and sign their preferred contracts. Some assumptions were made to make sure the physical representation is accurate. First, the environment is modeled as an agent and is also demand driven, which means that it contracts all emissions. It also is the supplier of air. Next, all primary resources come from one agent representing the world market. Those resources are essentially unlimited and prices are exogenously determined. Third, after negotiation, contracts are signed and agents are responsible for the operational actions on their physical assets, such that the contracted amounts are sent and received. The agents themselves make sure and check that their physical flows of materials coincide with the settings in their physical installations (Nikolic *et al.*, in print).

FROM PARAMETER SETS TO AGENT BEHAVIOR

In this section, a number of agents used in the electricity case is described (Chappin and Dijkema, 2007a; 2007b). An overview of the model’s social and technical systems can be found in Figure 5. This picture is structured according to the Three Layers Model and the structure of interaction and (recall Figure 3 and Figure 4). The inner circle contains the agents and physical installations are drawn in the outer circle. The model currently contains a static number of agents. Contracts between the agents are displayed as lines between them. The establishment of contracts depends both on the physical layer (e.g. does a facility need natural gas to produce electricity?) and the style and preferences of a particular agent (will I invest in natural gas fired power plant, or is a wind farm with lower return on investment also an option). Over time, changes in the contract layer do occur and as a result the social network is adjusted. Ownership is shown as lines between the agents in the inner circle and those physical installations. Physical exchange of materials is displayed between the according physical installations.

Based on the contracts arranged via the power exchange market or by bilateral agreement, agents operate their power plants to supply electricity to the consumer and acquire resources from world markets. Their discrete and autonomous investment or disinvestment decisions lead to changes in the physical system. Long-term, the power generation portfolio, overall emission levels of power production, electricity prices and emission credit prices are also affected.

On a disaggregate level, agents decide based on their own criteria. Agents evolve based on their actions since their decisions have long-long term effects; many factors are used in decision criteria, reflecting the present and past. Because vector **t** (the set of factor values for decisions) is unique for each electricity producer, agents evolve over unique patterns, shaped by external factors.

The parameter sets **t** of electricity producing agents are defined and balanced as such that they represent typical companies as observed in reality. Each set defines the management style of a company, which is part of its identity. Three examples are now discussed. Electricity producer 1 is the *‘risk aversive market-player’*. This agent tries to spread risks by investing in different technologies and withholding investment until a good business case is certain. Electricity

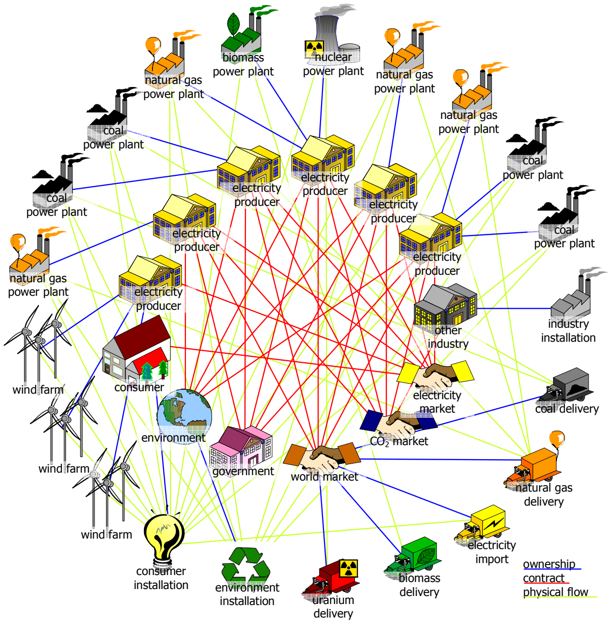

Figure 5. Simulation of the Socio-technical Network. The Inner circle consists of the agents and the outer circle of the physical installations

producer 2 is a typical *'green energy company'*. For this company, its environmental mindedness is seen as key for consumer attraction. Cost-effectiveness is less important, because of an expected volume effect of the positive, green image of the company. Since this company expects that CO_2-emissions are the long term environmental indicator, nuclear power is considered more seriously than by the other companies. Grants are exploited where possible to make a business case. Electricity producer 3 is the *'rational, profit-oriented, big player'*. This agent is careful to the fact that it will rely on known facts: power plants that have been profitable for the last decades will be sufficient in the future as well.

These three market players are characterized by their parameter set **t** and, as a consequence, the agents differ as well in their simulated behavior. That is observed from the most important emerging property: the power plant portfolio of electricity producers. The average developments of the portfolio of three electricity producers have been drawn in Figure 6. These are averages over more than 900 runs in which external developments differ. Because of differences in the investment and disinvestment decisions, over time the (relative) amounts of power plant types (forming the portfolio) develop in a way that is characteristic for the agent. It shows, for example, that the portfolio of electricity producer 2 (the green energy company) is much more sustainable than that of electricity producer 1 (the risk-aversive market player). Electricity producer 3 (the rational, profit-oriented, big player) is a cause for large emissions by using coal and natural gas as main energy sources.

Although all agents live in the same world and thus are impacted by the same external factors, their actions lead to very different power generation portfolios, because of different styles. These developments are found to be interdependent: the portfolio development of electricity producer 1 depends on the other electricity producers. As a consequence it cannot be concluded that if there existed a world with only 'green energy companies' alike that power generation would be as sustainable as shown here. The decisions are disaggregately made, but not independent of other market players. However, since on average the differences are significant (and that is also the case in reality), it is valuable to model this disaggegrately.

Strikingly, it was found that in absolute sense the portfolio of electricity producer 3 was largest – he had the largest total capacity – and therefore had the most effect on the emerging total portfolio. The result was that, although electricity producer deviated most from the rest, it was a key determiner of the total portfolio, which was found quite unsustainable. More model results and conclusions on the case can be found in (Chappin and Dijkema, 2007a; 2007b).

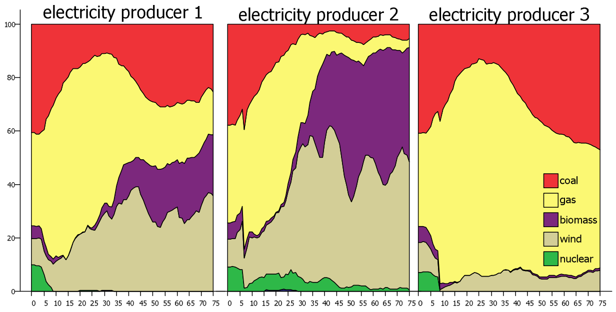

Figure 6. Evolution of Individual Agents' Portfolio.

The parameter sets **t** that weigh the criteria of power producers is part of the uncertainty in the model, since the set of investment motives selected by power producers is unknown. To deal with this fact, a wide variety of power producers' parameter sets was selected. However, since they are interdependent, as mentioned earlier, also combinations of style sets will be explored with scenario analysis in the future.

CONCLUSIONS AND FINAL REMARKS

A conceptual framework, consisting of an ontology for socio-technical systems and the interaction within it has been presented and the decision-making process was operationalised for electricity producers. Electricity producers are modeled as agents that own and operate power plants which are their physical assets in the physical layer. The system is modeled by describing the individual decision-making of the agents so that the system behavior emerges from this.

The agent-based approach is powerful because it makes it possible to model social interaction of agents as well as an adequate representation of the physical system. The model can easily be extended or adjusted, for example to the impact of policies or to include new types of power plants. The ontology is helpful to formalize the concepts used in the decision-making process of the electricity producing agents. A similar approach can and is followed in other domains and the use of a shared ontology allows re-use of building blocks and sharing source code of the simulation models.

REFERENCES

Bussmann, S., N. R. Jennings and M. Wooldridge. 1998. *Multiagent Systems for Manufacturing Control*. Berlin, Springer.

Chappin, E. J. L. 2006. *Carbon Dioxide Emission Trade Impact on Power Generation Portfolio, Agent-based Modelling to Elucidate Influences of Emission Trading on Investments in Dutch Electricity Generation*. Delft, Delft University of Technology.

Chappin, E. J. L. and G. P. J. Dijkema. 2007a. An Agent Based Model of the System of Electricity Production Systems: Exploring the Impact of CO_2 Emission-Trading. *IEEE SoSE: Systems of Systems Engineering*, San Antonio, Texas, USA, IEEE.

Chappin, E. J. L. and G. P. J. Dijkema. 2007b. On the Impact of CO_2 Emission-Trading on Power Generation Emissions. *10th International Conference on Technology Policy and Innovation*, Stavanger, Norway, ICTPI.

Dam, K. H. v. and Z. Lukszo. 2006. Modelling Energy and Transport Infrastructures as a Multi-Agent System using a Generic Ontology. *IEEE International Conference on Systems, Man, and Cybernetics*, The Grand Hotel, Taipei, Taiwan.

Dam, K. H. v., Z. Lukszo, R. Srinivasan and I. A. Karimi. 2007. Opportunities for Agent-Based Models in Computer Aided Process Engineering. *European Symposium on Computer Aided Process Engineering ESCAPE 17*, Bucharest, Romania.

Dam, K. H. v., I. Nikolic, Z. Lukszo and G. P. J. Dijkema. 2006. Towards a Generic Approach for Analyzing the Efficiency of Complex Networks. *IEEE International Conference On Networking, Sensing and Control*, Ft. Lauderdale, Florida, USA.

Jennings, N. R. 2000. "On agent-based software engineering." *Artificial Intelligence* 117(2): 277-296.

Laurikka, H. and T. Koljonen. 2006. "Emissions trading and investment decisions in the power sector - A case study in Finland." *Energy Policy* 34(9): 1063-1074.

Nikolic, I., G. P. J. Dijkema and K. H. v. Dam. in print. Understanding and Shaping the Evolution of Sustainable Large-Scale Socio-Technical Systems, Towards a Framework for Action Oriented Industrial Ecology. *Dynamics of Industrial Ecosystems*, Reviewed and accepted.

Nikolic, I., G. P. J. Dijkema, K. H. v. Dam and Z. Lukszo. 2006. General Methodology for Action-Oriented Industrial Ecology. *IEEE International Conference On Networking, Sensing and Control*, Ft. Lauderdale, Florida, USA.

Nikolic, I., G. P. J. Dijkema and M. A. Reuter. 2004. Proposed framework for the understanding of the Co-evolution of Industry and infrastructure. *Gordon Research Conference on Industrial Ecology*, Queens College, Oxford, United Kingdom.

Olsina, F., F. Garces and H. J. Haubrich. 2006. "Modeling long-term dynamics of electricity markets." *Energy Policy* 34(12): 1411-1433.

Schleich, J., K. M. Ehrhart, C. Hoppe and S. Seifert. 2006. "Banning banking in EU emissions trading?" *Energy Policy* 34(1): 112-120.

Smith, A. 1776. *An Inquiry into the Nature and Causes of the Wealth of Nations*

Svendsen, G. T. 1999. "The idea of global CO_2 trade." *European Environment* 9(6): 232-237.

Svendsen, G. T. and M. Vesterdal. 2003. "How to design greenhouse gas trading in the EU?" *Energy Policy* 31(14): 1531-1539.

Vesterdal, M. and G. T. Svendsen. 2004. "How should greenhouse gas permits be allocated in the EU?" *Energy Policy* 32(8): 961-968.

Wooldridge, M. J. and N. R. Jennings. 1995. "Intelligent agents: theory and practice." *Knowledge Engeneering Review* 10(2): 115-152.

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