Summary

Capturing socio-technical systems with agent-based modelling

What is a suitable modelling approach for socio-technical systems? The answer to this question is of great importance to strategic decision makers in large scale interconnected network systems. Typical examples are the regional, national, continental and global networks found in the public utility sectors and network industries which provide, for example, energy, telecommunication and transportation services. The behaviour of such systems is determined by many actors including regulators, asset owners, operators, service providers and users. Each decision making entity is situated in a dynamic, multi-actor, multi-objective and multi-level jungle: it is part of a bigger system which is constantly changing, it has to cope with the actions of other actors who may have conflicting interests and values, and who operate on different levels of hierarchy. Which models could support such an actor to explore different scenarios and to learn about the possible consequences of different actions through simulations? Successful models should be able to capture both the physical and social reality of the system, their interactions with one another and the external dynamic environment, and they must allow users to experiment with *changes* in both the physical and the social network configuration. In other words, socio-technical systems pose a formidable challenge for modellers.

Existing tools to deal with either the physical (e.g. models of industrial processes) or the social network (e.g. economic market models) are available, but these worlds have yet to be brought together in an integrated modelling approach for socio-technical systems. That is the ambition of this thesis. The additional challenge is to meet this objective not just for one specific domain, such as energy or industry, but to set up a modelling infrastructure that is able to deal with today's reality of socio-technical network systems that are interconnected across domains. This thesis aims at contributing to an integrated framework for socio-technical systems to help modellers build better models and ultimately provide better decision support to actors involved in regulating, operating or otherwise using these systems.

This thesis covers two different story lines, which will be addressed below. The first starts with an illustration of the problems and challenges in socio-technical systems and the need for a flexible bottom-up approach to modelling, resulting in a modelling framework that fulfils these criteria. The framework can then be applied to a number of case studies, with each subsequent case study contributing to the generic framework. For this purpose the *agent-based* paradigm turned out as most promising. This story line could be

denoted as the 'framework for agent-based models of socio-technical systems'.

The second story line starts with the need of modellers to justify the choice of the selected modelling paradigm, as well as with the scientific challenge to objectively analyse the framework developed in this thesis. After a methodology for systematically performing such a comparison is given, a benchmarking exercise of modelling paradigms is done on a number of case studies. The evaluation of the framework results in rules of thumb for the applicability and its usefulness. Two models developed with the framework are then deployed to support a problem owner, demonstrating how real-life decision problems can be solved with agent-based models. This second story line could be labelled the 'critical evaluation of agent-based models of socio-technical systems'.

Framework for agent-based models of socio-technical systems

To deal with the challenges that arise from socio-technical complexity a generic agent-based modelling framework has been developed (Chapter 3). This framework aims at supporting the modeller in quickly setting up new applications by re-using building blocks and allowing the connection of existing models to one another. The framework consists of the following three types of elements:

- **Interface** definition between components, between models, between developers and between developers and problem-owners.
- **Library** of source code that can be re-used.
- **Procedures** on how to use the library and interface to build models.

In an agent-based model the system is described in terms of agents and their behaviour, where an agent is a model of a decision making entity at various levels of aggregation, from an individual to a collective. Agents are considered as software entities that are autonomous, re-active, pro-active and capable of social behaviour. The agent-based paradigm is particularly suitable to model socio-technical systems because it allows the modeller to describe the social elements of the system through algorithms. Furthermore, it offers a flexible bottom-up approach which is needed for performing experiments with changing elements (leading to different configurations of the system) to study the effect on overall system behaviour.

The cornerstone of the framework is a shared language formalised in an *ontology*, which is a formal specification of concepts. The ontology forms the interface needed to bring different aspects of the system (both social and physical) together and to interconnect different models. Besides interconnectivity, the ontology offers *interoperability*. The ontology provides a set of (abstract) classes and properties with which (concrete) instances can be defined. The instances are the system elements — or the facts — included in the model which are stored in a shared *knowledge base*. Furthermore, the concepts from the ontology (i.e. the words in the shared language) are also used to define the behaviour of the agents. Finally, a shared language also helps find a common ground when communicating with experts and users from different domains.

The modelling infrastructure can help to set up new models of socio-technical systems by following a sequence of modelling steps and, where possible, re-using already existing "building blocks" (e.g. facts, procedures, agents or technologies) from models developed during previous applications. When new elements are created for a specific case they can be fed back into the shared framework with the result that they are available for re-use. A basic set of class definitions for socio-technical systems was developed from a number of initial case studies and refined through subsequent applications.

The approach presented in this thesis has been applied to a number of case studies (Chapter 4). Applications include a model of an intermodal freight hub, an oil refinery supply chain and a chocolate production cluster. With a description of the development of these models, the model-building procedures were demonstrated and it was illustrated how the framework supports modellers. These procedures include the conceptualisation of the system in terms of agents and physical elements, refining the generic ontology for case-specific concepts, the creation of concrete instances and the implementation of agent behaviour. Furthermore, these procedures were demonstrated to be applicable by other modellers to various case-specific problems in a wide range of infrastructure domains.

The development of the framework over time, through application and refinement cycles and with contributions from many users, is well documented and the development trajectory itself has been studied and analysed (Chapter 5). The completeness, correctness and usability of the framework were tested. It is concluded that the ontology is complete for the scope that was defined and that it can be successfully expanded for new problems. After the initial development phase none of the key concepts have been changed or replaced which, together with their widespread use, indicates that the ontology is adequate. Finally, it was demonstrated that through re-use of instances in the shared knowledge base as well as of model source code, building new models for new cases using the framework requires less work. After the initial investment in the first generation of models for a number of initial cases, new applications can be developed more efficiently.

Critical evaluation of agent-based models of socio-technical systems

A critical evaluation of the advantages and disadvantages of the framework and a detailed comparison with other modelling paradigms is called for. Comparing modelling paradigms based only on the conceptual model specifications is not enough; rather a well-defined benchmarking process and experiments are required. By building different models and analysing how they are built and how they can be expanded, a well-founded justification for the choice of modelling paradigm can be made and recommendations and guidelines on which paradigm is more suitable for which problem can be given.

One of the main problems in comparing modelling paradigms lies in the definition of what is encompassed in each of the paradigms in the study (Chapter 2). A distinction between agent-based models and equation-based models found in literature overlooks the fact there is a fuzzy boundary and that both *labels* can be interpreted in different ways. The concept is not black-and-white, rather there is a continuous scale or a spectrum in the modelling space. There are two main axes on which models can differ: The *model elements* axis and the *system description elements* axis. The former deals with *what* is modelled and the constituents of the model, the latter with *how* their structure and behaviour are formally described. The constituents of the model range from individuals (i.e. decision making entities) to system level observables and the system description elements from strictly equations to algorithms. This nuance allows the conclusions of a benchmarking study to be generalised beyond the specific *models* that are compared, to the advantages and shortcomings of *modelling paradigms*.

A general scheme to compare modelling paradigms is proposed (Chapter 6), with special emphasis on the identification of what is to be benchmarked, the evaluation if objects of study are comparable and the description of well-structured experiments. This way fair and balanced conclusions can be drawn. The benchmarking scheme is then used to compare different models of an oil refinery supply chain, developed using different modelling paradigms; one using a numerical tool and the other using an agent-based platform. It was demonstrated that different modelling paradigms and tools can be used to successfully create a model of the *same* socio-technical system with comparable results. By analysing the efforts required to expand the models to allow new scenarios to be tested, the strengths of the paradigms were identified in the context of supply chain modelling. Ease of expressing the problem, ease of extending the models, ease of re-use and ease of explaining the results were used as performance indicators.

The results of the benchmarking study can, within the context in which the comparison was performed, be expanded from the specific models to the modelling paradigms. Production processes and technological aspects are well catered for by equations, while the decision making aspects can only be captured in algorithms. The complete system can, however, be fully expressed in both modelling paradigms that are compared. One can say that equation-based models, in general, are more suitable for representing the physical elements in the system whereas the (dynamic) interaction between the actors is best captured by the agent-based model. For extending or adjusting the models the general rule is that if something is only indirectly captured in the model it requires more effort to be changed. This means that for the agent-based model, where the configuration of the system is dynamic and not fixed in the model structure, adding new actors, new physical elements and, consequently, introducing new possible relationships was easy. However, adjustments in the way the technical system itself works were more easily done through adjusting equations. If a new model is built based on earlier work, for the equation-based model the conceptualisation could be re-used, but none of the actual equations could be copied. From the bottom-up agent-based approach, on the other hand, also specific building blocks could be re-used or extended. Finally, when explaining the model and the model results to stakeholders, the agent-paradigm offers a natural representation of the decision making processes and interactions between the entities in the system, while equations, in front of the right audience, have an edge when explaining the technical processes.

After performing the benchmarking study and learning about the advantages and disadvantages of agent-based modelling, it is demonstrated how simulation models developed with the framework presented in this thesis can support a problem-owner by solving a specific decision problem (Chapter 7). These problems can often be characterised by the fact that they are multi-actor, multi-criteria and multi-level problems. A decision model, formulated for a specific purpose and question, is built for a simulation model of the system and different search strategies can be defined to solve the problem.

To show how agent-based models can be applied as decision support tools two illustrative case studies with the agent-based simulation models of an oil refinery supply chain and an intermodal freight transport system, both inspired by real-life problems, are presented. It is demonstrated how a search strategy from the field of Operations Research, such as the Nelder-Mead optimisation method, can be applied to a decision problem with disturbances within the supply chain to choose the right response to abnormal situations in such a highly complex system. In another case study it is shown how different tax incentives can be used to encourage different stakeholders to agree on the location of a new freight hub. As such, it is demonstrated that agent-based models developed with the generic framework presented in this thesis can support decision makers to solve real-life problems.

Conclusions

The framework developed in this thesis presents a suitable generic modelling approach for socio-technical systems. Agent-based models are particularly appropriate to experiment with different scenarios and to answer *what if* questions. This gives valuable support for decision makers in dealing with, for example, disturbances in the physical system or with new regulations imposed.

The models built and used in this thesis were developed in a bottom-up fashion, making it possible to change the social configuration so new actors can be included in the system (e.g. different users of the freight hub or more suppliers with different prices and lead times in the supply chain) or to adjust the physical configuration (e.g. additional transport links in the intermodal freight network or extra storage tanks for the refinery). The framework was designed from the start to be able to deal with a variety of infrastructures and other socio-technical networks so that lessons learnt in one domain can be translated to other domains and (parts of) models of different infrastructure systems can be connected.

The framework development is an ongoing process through ongoing use; new modellers are using the approach for new cases and as such contribute to the shared framework. This is one of the key strengths of the approach: the more it is used, the more that can be re-used. Hereby the reader is invited to start thinking about challenges in the infrastructure domain from a socio-technical and agent-based perspective and to map the system's elements onto the ontology presented here, so that the modelling infrastructure can be used to effectively build better models and make the modelling process more efficient.

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