Designing Complex Systems
A Contradiction in Terms

Margot Weijnen[1], Paulien Herder[2] and Ivo Bouwmans[3]
[1] *Professor, Chair of Process and Energy Systems Engineering, TU Delft, Faculty of Technology, Policy and Management, Dept. of Infrastructure Systems & Services, Delft, The Netherlands*
[2] *Associate professor, TU Delft, Faculty of Technology, Policy and Management, Dept. of Infrastructure Systems & Services, Delft, The Netherlands*
[3] *Senior Lecturer, TU Delft, Faculty of Technology, Policy and Management, Dept. of Infrastructure Systems & Services, Delft, The Netherlands*

Abstract

Networked infrastructures are complex socio-technical systems. The complexity shows in the physical networks, in the actor networks, and in their combination. This paper addresses the question how these systems should be designed. For the physical networks as well as the actor networks, design processes exist that could be applied separately. However, for these integrated networks an integrated approach is proposed. Three cases studies of designs are discussed concerning a district heating system, a gas network and a seaport development. The studies lead to the conclusion that an integrated socio-technical complex system design process must be applied.

Keywords: complex systems, engineering design, systems engineering, infrastructures

1. Introduction

Socio-technical systems are systems that exhibit both physical and social complexity. Networked infrastructures, such as those for transport of people and goods and for provision of telecommunication, water and energy services, are prime examples of socio-technical systems. Infrastructure systems are *complex* systems in view of their combined social, economic and physical complexity.

Most of the public utility and infrastructure systems of today were not designed as integrated systems. They gradually evolved into the patchwork of physical networks, the patchwork of old and new technologies and the patchwork of actor networks and institutions they are now. They have adapted to changing economic conditions, societal demands and end-user requirements. The development of Europe's critical infrastructures is not centrally planned and coordinated but governed by many actors who optimise their management decisions and investment strategies for their own subsystem, in their own interest.

Complex adaptive systems *design* may therefore be considered a contradiction in terms: how should the future complex system be modelled, how should the design process be set up among this multitude of actors and who, if anyone, is responsible for the overall design and design process?

Nevertheless, many design engineers are involved in infrastructure development. How do they cope with the physical and social network complexity and the emergent behaviour of infrastructures? How should they be equipped to cope with complex adaptive systems and how can the designers' performance and thereby the future performance of the infrastructures be improved?

2. Complexity in infrastructure systems

2.1 Infrastructure systems as socio-technical systems

The notion of 'infrastructure' generally refers only to the physical network that connects the suppliers and end users of an infrastructure-bound service. However, in our view an infrastructure system includes – besides the transport and distribution network – the carriers, conversion and storage facilities as well as the governance, management and control systems that are needed to make the system meet its functional specifications and its social objectives.

Any infrastructure is in itself a highly complex networked system, that includes both a physical and a social network, or actor network (see figure 1). The behaviour of an infrastructure cannot be understood by merely studying the structure and behaviour of either. Both are interconnected in many ways. The physical network and the social network are complex in themselves – and their interaction, at the level of the integrated socio-technical system, presents another domain of complexity.

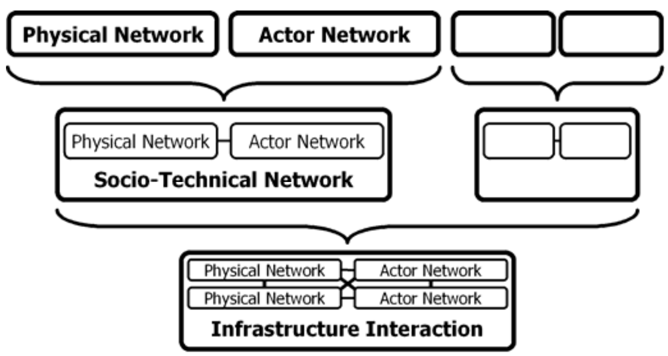

Fig. 1. Domains of complexity in infrastructures (from [1]).

2.2 Complexity in the physical network

The physical networks of infrastructure systems consist of many nodes and links. Large-scale systems, such as the European electricity infrastructure, comprise a huge number of subsystems, links and nodes, all of which are interdependent in several ways. If one subsystem is not functioning well, this may have far-reaching repercussions on the functioning of the overall system. The interdependence of the subsystems can take various forms, from simple linear dependencies to multiple, non-synchronous dependencies (see [2]).

Moreover, the nodes of the network interact with and adapt themselves to their surroundings. Their reaction to external changes is often non-linear, which can result in unpredictable behaviour of the system as a whole. Deterministic chaos is one form of such unpredictable behaviour [3]. As the number of subsystems and interrelationships increases, and as those interrelationships become more diverse, it becomes more difficult to gain an overall view of the system and to model it. Eventually, the system will become so complex that the analyst can no longer recognise or model it at all. Chaos theory shows that even if it were possible to accurately describe the changes in the nodes as they are influenced by their environment, the prediction of the state of the system could gradually diverge from its actual state, due to the exponential growth of tiny errors in the measurement of the system's initial state. Chaos theory can, however, give insight in the general behaviour of the system and the system states that can be expected.

Studies on complex systems often use the concept of agents for interacting elements in the system. In general, an agent is a model for any entity in reality that acts according to a set of rules, depending on input from the outside world. Agent Based Modelling theory uses agents that act and interact according to a given set of rules to get a better insight into system behaviour (see [4] for examples). The emergent behaviour, which is the behaviour of the system seen as a whole, follows from the behaviour of the agents at the lowest level. In many cases, emergent behaviour can be described by new rules, new formalisms, at higher levels of aggregation, disregarding the actions at the lowest level of the agents. This coincides with the notion that the value of a physical infrastructure is determined by the physical system's performance at the top level only. The end users do not care what switches or cables are used, as long as they can make a phone call, watch the television, and have a comfortably heated home.

2.3 Complexity in the social network

In a multi-actor system such as the European electric power infrastructure, many actors are involved with different, possibly conflicting, interests and hence different perceptions of 'reality'. Again, agents may be used to model the system's elements, which in this case are people and organisations. In analogy with the agents in the physical network, each actor in the social network can be described as an agent that acts according to a set of rules determined by legislation and regulation, moral and cultural codes, etc. In addition to these more explicit rules, each actor will have its own strategy. In the case of, e.g., a driver on the motorway, behavioural psychology may shed light on the determinants of individual driver behaviour. If the actor is a firm competing in an infrastructure-related market, business economics and strategy will influence the actor's behaviour. Actors, however, may also show reflection and learning: when faced with a similar situation for a second time, their behaviour will be influenced by the lessons drawn from the first time. This specific characteristic of actors makes modelling them as rule-abiding agents an extremely complicated, if not impossible, task.

The actors are interdependent: each needs the cooperation of the others. As in the case of the physical subsystem, the interdependencies can take various forms. As the number of actors involved in a problem increases, conflicts of interest grow and there is greater variation in interdependencies. Eventually, it may become impossible for any one actor to understand the situation in its entirety and the predictability of the actions undertaken by any one actor is limited.

2.4 Evolution of infrastructure systems

Part of the problem with understanding the behaviour of infrastructures is that most of the physical systems were not designed as an integrated system, but gradually evolved over time. A typical example is the way the electricity infrastructure evolved in the Netherlands [5]. Like most infrastructures, it originated in local networks, established through private initiative. City networks were established around the beginning of the 20th century. Interconnection of local networks and network expansion to rural areas was forged through intervention of the public authorities. Over time, the density of inter- and end-user connections increased. Transport and processing functions in the infrastructure were intensified to serve an increasing number of users and an increasing demand per user. Grids were interconnected across national borders to improve the stability of the network and thereby the reliability of service. Today, all national grids of mainland Europe are interconnected.

During this evolution, ownership and governance of the electricity infrastructure shifted from the private sector to the public sector. Until about a decade ago, most infrastructures were run as public monopolies. The infrastructure value chain was fully integrated vertically (figure 2, left). This was justified by the fact that the transport and distribution network have the character of a natural monopoly. Whether directly or indirectly, the government controlled the realization of the infrastructure and the universal provision of the public utility service by central planning and allocation of funds.

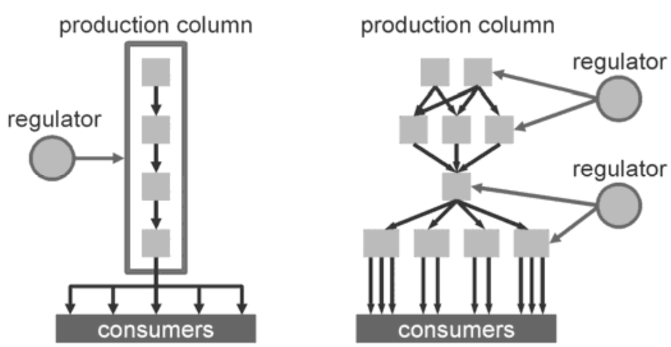

Fig. 2. Model of infrastructure market before and after liberalization: vertically integrated monopoly (left) and unbundled infrastructure value chain (right), with competitive markets in non-monopoly segments (after [6]).

This rather transparent situation has dramatically changed. Many infrastructures have gone through or are still in the midst of a transition from a vertically integrated monopoly structure to an unbundled value chain, with competitive markets being introduced in those segments of the chain that do not have a natural monopoly character. This transition does not directly impact the technical network, but mainly the social network (see figure 2, right). As a new playing field is defined, new actors enter, often in new roles. In the European electricity markets, traders and brokers have become active and new market places have emerged. National regulators have been created to ensure non-discriminatory access to the transmission and distribution networks.

It is evident that the social network has become much more complex with the larger number and variety of actors, and that the options to steer the development of the infrastructure have changed. In the old situation the government could directly interfere in the planning of the system. Nowadays, investment signals are established through market forces. Competition has been established in both the power generation market and the service provision market. Only the networks are treated as a natural monopoly, so that a precarious interface must be constructed between the competitive markets and the regulated networks.

2.5 Characterising the socio-technical system

From these analyses it is evident that there are both similarities and differences between the physical system and the social system at the conceptual level. The main difference is that the components of the physical system are technical or physical artefacts, while those of the social system are reflective actors. Reflectivity means that the actors have the ability to learn, and this has three significant implications for complex system design ([7], [8]).

- Actors display *strategic and opportunistic behaviour*. Their main motive is to realise their own objectives. Strategic behaviour (or 'game playing') refers to all actions that help the actors to do so. It can take the form of misinformation, hidden agendas, blocking decisions now in order to gain later, etc.
- Actors *learn how to neutralise interventions* by others. They learn the strategies and interventions used by other actors and, in time, may develop means to sidestep these strategies and interventions. This is known as the 'Law of Decreasing Effectiveness': every strategy is only temporarily effective because actors learn how to neutralise its effects. This enhances the dynamics of the network: actors are constantly developing new strategies to maximise their interests.
- Because actors are reflective, an *understanding of the process of interaction* that will eventually lead to a decision is crucial. In this process the actors interact, learn and display strategic behaviour. The final outcome cannot be fully understood without knowledge of the process itself. This represents a major difference compared to the physical system approach, in which the 'white box' of a system's functioning does not always have to be known in detail.

2.6 Design challenges for complex infrastructure systems

The overall demand for infrastructure services is increasing. At the same time, society demands an ever higher reliability of service as we grow more dependent on infrastructure-bound services. As the performance of the infrastructure system is determined by the interplay of the physical and social networks, ensuring high service reliability has become much more challenging.

Highly reliable services are more and more the outcome of networks of organizations, many with competing goals and interests. This creates new challenges for network design and for effective market and network regulation, and new needs for communication and information sharing. The California crisis, for example, could have been much worse than it was if the operators of the various subsystems had communicated less intensively [9].

In the design of new infrastructures, or in the redesign or expansion of existing infrastructures, the main challenge is how to deal with the many uncertainties that the system will face during its projected lifetime. Since infrastructures are deeply embedded in society, they are not only subject to rapid technological changes, but they also have to keep up with institutional and economic developments, such as deregulation, liberalisation, or increasing oil prices. The challenge is to provide technical flexibility and budget flexibility to ensure the adaptivity of the initial design to these changing requirements.

The market has a tendency towards capacity scarcity, because no private investor is prepared to invest in unprofitable overcapacity for the public good. This poses new demands on infrastructure capacity management. Innovations are needed to make better use of available capacity. Where central coordination mechanisms are lacking, making way for distributed control strategies, infrastructures might be equipped with self-organizing and self-healing properties so as to deal intelligently with disturbances and recover more effectively from incidents (e.g., see [10]).

For the longer term, the tendency towards under-investment in electricity generating capacity poses a serious threat to economic growth and social development. Research has shown that new mechanisms, such as a capacity market, must be brought in place to alleviate this risk [11]. Other concerns are emerging with respect to network quality on the longer term [12]. As the California power crisis has shown, excessive social cost may be incurred by a faulty market design.

Due to the limited possibilities to directly intervene in the established lay-out of the physical system, an important option is to ensure that the collective actions of players are steered towards the public interests through adequate market design, adequate network regulation (where the network has retained its monopoly character) and additional legislation and regulation for safety, health, environment, etc. Also, in view of private actors' interests, a better insight is needed into how individual investment decisions will perform as a subsystem of the complex infrastructure system.

3. Complex systems – addressing the design challenge

3.1 Designing complex physical systems

The system design of complex systems differs from that of a simpler system in the majority of the general design process components ([13], [14]):

- *Functional requirements*: For a simple system design, this will be a straightforward description, e.g. 'the system must store data.' In a complex system design, the function will often be compound, possibly with different functions for different actors. The system may also be 'distorted' upon implementation, i.e. it will not be used in exactly the manner that the designers intended. The more complex the system, and the greater the number of actors in the 'implementation field', the more likely it is that distortion will occur.

- *Objectives and constraints*: The degree of complexity results in a massive number of objectives and constraints that the client and other actors can impose on the design. If the designer wishes to incorporate all these requirements, the system is very likely to suffer from over-specification, which precludes any real solutions, i.e. a realistic design. Moreover, the system designer will have to contend with conflicting objectives. The more complex the problem, the more difficult it will be to determine the 'solution space', let alone select the best design from the various options.
- *Design space*: Even in simple designs the design space can quickly take on enormous proportions. For large, complex systems, the design space is practically unbounded. Other actors may also attempt to incorporate subsystems into the design space, or to ensure that they are excluded. It then falls to the designer to define and delineate the design space as best as possible.
- *Starting points*: In complex system design it is very difficult to find starting points for a design. The transplantation of models and design options is not simple and will indeed often be impossible precisely because these are systems embedded in a (dynamic) multi-actor field in a specific institutional context. Given the high degree of context sensitivity, the designer of a complex system will often have very few starting points.
- *Models and modelling*: The models map the design space into the functions, objectives and constraints. The system models that play a role in this part of the process can vary from simple, mathematical linear system models to complex probabilistic models or game theory models. The designer may also use agent-based models in order to model the complex adaptive system.

Real Options theory and exploratory modelling are examples of methods that are employed for modelling the infrastructure system, given the enhanced design complexity described above. The former is a promising approach as it treats future uncertainty as a business opportunity, contrary to other methods, which take a risk-aversive stance: similar to financial options, it allows the designer to build a real option into the currently implemented design. The option may be executed or exploited if and only if it becomes (economically) viable to do so at a certain moment in the future. The already implemented real option would significantly reduce the cost of redesign in the future, justifying the investment up-front.

Research so far has shown that improvements of 10 to 20% in the NPV can be achieved. For the case of designing and building infrastructures, this would imply that options could be built into, e.g., a power plant, allowing it to operate on multiple fuels. The advantage in this example of using the real-options approach is that the cost of implementing of a multiple fuel burner can be traded off financially against the associated cost of the probability that different fuels will have to be used in the future. In other words, the cost of *flexibility* can be made tangible in terms of monetary value.

When the design and operation of infrastructures is required to be adaptive, in view of the deep uncertainties, the decision-making processes in this system also need to be adapted. Preferably, the operational stages of any system are already considered in the design stage (in terms of Reliability, Availability and Maintainability (RAM) optimisation – see [15]), but also in the case of changing ownerships, or distributed responsibilities, which is often the case in infrastructure systems, the operation and maintenance must be executed as flexibly as possible. The design challenges for infrastructures should therefore also focus on maintenance and replacement strategies, as these are so intricately related to (grassroots) design. In fact, maintenance and replacement could be considered as heavily constrained design problems. Innovative construction and maintenance contracts, asset management and risk management are just a few emerging strategies that deal with integrating the design and the operation/maintenance challenges for infrastructure systems.

3.2 Designing complex social systems

For complex social systems, the process of 'design' should not be regarded as a process of modelling a desired reality. For a network of actors, a model of the desired reality would only be authoritative if it would be accepted by a 'critical mass' of the actors. Within the network, this is precisely the problem: given all the differing interests, the likelihood of a model being accepted is extremely small. How can consensus regarding a desired reality be achieved nonetheless? The characteristics of a network of actors reveal that two familiar types of intervention will not be effective [16]:

- Hierarchy, or 'command and control' will be impossible since no actor is superior to any other. An actor who nevertheless attempts to manage the process through command and control will only generate opposition. Attention will then shift from the hierarchy itself to the processes of interaction between the actors.
- Management by 'expertise of management', based on a content-based analysis, is also unlikely to succeed. Knowledge and information will be contested; statements based on a content-based analysis are always open to rebuttal. There is no such thing as unambiguous information. In this situation, attention will shift from expertise and unambiguous information to the process intended to arrive at negotiated knowledge.

Attention therefore shifts to the *process* of decision-making. A set of game rules of this type is termed a 'process design'. Like the design of physical systems in the engineering design tradition, process design is based on a solid set of design principles [8]:

- In the interactive decision-making process, actors must be sufficiently open with each other.
- The core values of the actors should be protected during the process.
- The process contains incentives for progress and speed.

The risk inherent in an interaction or negotiation process is that in order to reach consensus, actual content-based expertise will not be fully taken into consideration. There can be no 'negotiated knowledge', only 'negotiated nonsense'. The fourth design principle therefore is:

- The result of the interaction process must stand up to expert scrutiny.

3.3 Designing socio-technical systems

It will be evident that any design in the context of a socio-technical system should acknowledge and respect both the physical and the social reality and their respective rationalities. The socio-technical complexity of infrastructure systems calls for a synthesis between the two design perspectives or, if not a synthesis, for a systematic confrontation or combination of the two perspectives. The diagram below provides a framework for the confrontation and combination of the physical and social system design perspectives.

Table 1. Pure and cross-over forms of design methods and tools for complex socio-technical systems design and modelling (from [2]).

Perspective / Modelled object	Systems perspective	Actor perspective
Hard, technical systems	Substantive and optimal design of desired system	Rules of the game for modelling systems
Actors	Modelling actor behaviour	Process design: negotiated rules of the game

As shown in table 1, various cross-over modelling techniques have been developed that help combine the physical system perspective and the social system perspective. Cross-over modelling approaches are conducive to a meaningful dialogue between the engineering design professionals who are the experts in physical system design, and the social scientists who engineer the decision-making processes between the actors. Cross-over modelling techniques that apply rational modelling techniques to the social system are used to model the network of actors, including the sub-actors, resources, interests, strategies and interrelationships. Even though actors are not inclined to allow themselves to be modelled, the application of rational modelling techniques to actor networks performs a number of valuable functions [16]:

- It forces the modeller to consider the problems from the actor perspective.
- It provides an insight into the known and the unknown variables. In some cases, for example, the relations maintained by certain actors will be unclear, as will be their underlying interests, etc.
- If the modelling process is undertaken by several modellers (e.g. modellers playing the role of specific actors), an understanding of the differences in perception among the actors will be gained.
- A modelled actor network can facilitate the discussion and decision making with regard to the strategies to be followed.

Conversely, the question is what contribution the process-oriented modelling of the actor approach can make to the physical system perspective. As previously stated, complex systems abound with uncertainties. A model of the system will therefore always be 'contested', with various experts holding diverse opinions regarding the way the system functions. If there is a marked divergence of views, this is likely to obstruct successful interventions. In cases where the model is contested, it is necessary to pay attention to the process in order to arrive at a negotiated model. This process requires the experts to enter into a structured form of interaction. In the ideal situation, this process will reveal exactly what the experts already agree on, and where the differences of opinion lie.

4. Infrastructure design as complex system design: applications

4.1 Introduction

For each of the design challenges described in the previous section, a design case study has been performed. The first case comprises the design of a district heating infrastructure system in which the focus was on the physical design challenge: design an infrastructure with the most appropriate network topology that can stand the test of time and that takes into account any requirements that are set on the system from an institutional or social system's perspective.

The second case study describes the results of a design performed by a group of MSc students, in which the physical and social subsystems were considered simultaneously during the design process. The resulting syngas infrastructure for the Port of Rotterdam area is a prime example of an integrated complex system design.

The third case study demonstrates the value and necessity of a good process design in order to arrive at a conceptual socio-technical system design of a bio based industrial cluster. The process allowed for strong actor commitment to the Agent Based Model that was developed for this design challenge.

4.2 District heating system

District Heating Systems (DHS) provide an efficient method for house and space heating. In such systems, heat is produced and/or thermally upgraded in a central plant and distributed to the consumers through a pipeline network. An integrated conceptual design was made of the technical, economic, and institutional subsystems for using low-level residual industrial waste heat for district or city heating [17].

The technical part of the integrated conceptual design consisted of the heat demands, the design of the heat upgrading system, equipment size, the network topology and/or spatial connectivity of the needed infrastructure as well as the economic viability of the system. For modelling purposes, thermodynamic models and life cycle costing methods were used. Figure 3 shows the resulting physical subsystem.

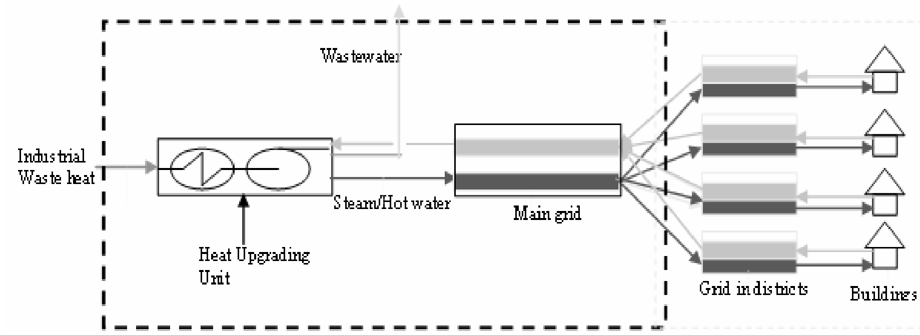

Fig. 3: System diagram of the physical subsystem (from [17])

The low-level temperature industrial waste heat is routed to the heat-upgrading unit where the temperature is raised to the required level by heat pumps before being led to the central grid. To enhance the system effectiveness and flexibility, the steam from the main grid is taken to a modular (district) grid where the possible connections to the houses and offices are made.

The social subsystem design had to take into account institutional aspects that could impact the design and realization of the heating infrastructures. Equally, the institutional design would impact the design choices made for the design of the physical subsystem. It was, therefore, crucial to design the physical and social subsystems in parallel, by frequently switching the designers' attention between both designs and confronting the designs with each other. During the design of the social subsystem, the nature and impact of (future) regulation in the heating sector was one of the most important constraints that needed to be taken into account. It is obvious that many uncertainties pervade the future of regulation, requiring a process design in addition to the institutional design. During the design process of the technical systems, such legislations were simulated and their present and future impacts on the design were assessed.

The institutional design comprised the building, operation and ownership of the infrastructure and supply of heat. Secondly, a DBFO (Design, Build, Finance and Operate) contract between public and private parties involved in a project like this was selected and designed. Due to the financial risk sharing between public and private parties in a DBFO contract, incentives are created for fulfilling requirements such as efficiency, profitability and quality of service to consumers. The assets for owning and using the grid have to be allocated ex ante by the municipality and not by the market. It was deemed most efficient that the owner and user of the grid are one actor or at least function as one. The contract and the process conditions designed helped to establish this.

4.3 Syngas infrastructure

The Port of Rotterdam has a large petrochemical cluster that processes incoming crude oil into numerous end products. In the coming decades the cluster may find itself increasingly at risk of not being supplied with enough coal and crude oil, on which it so heavily relies. Since the current cluster is quite inflexible in its need for crude oil as a feedstock, security of supply issues for crude oil threaten the operations of all cluster partners. In order to safeguard the competitiveness of the cluster as a whole, it is important to reduce the dependency on fossil fuels by increasing the feedstock flexibility.

As a solution to the feedstock inflexibility problem an industrial cluster feeding on synthesis gas has been designed [18]. Synthesis gas (or syngas in short) is a mixture of carbon monoxide and hydrogen and is widely used for methanol and ammonia synthesis as well as in the production of their derivatives. Moreover, the conventional Fischer-Tropsch process that produces liquid transport fuels from syngas has recently been modernized. The resulting designer fuels contain less sulphur and hence are relatively environmentally friendly. Carbon monoxide and hydrogen also find other applications, for example in the direct reduction of iron.

It is obvious that for the design of the cluster, a physical as well as a social subsystem had to be designed, and that both subsystems can be considered to be complex (e.g. emergent behaviour, deep uncertainty, strong interaction between physical and social subsystem). In the initial physical design space, network topologies such as ring, bus and star networks were considered. For the governance, three archetypical structure types were evaluated: hierarchy, market and network. After confining the overall design space to three combinations of the physical and social subsystem (i.e. network-bus, market-ring and hierarchy-star), the network-bus structure was chosen as the basis for further design.

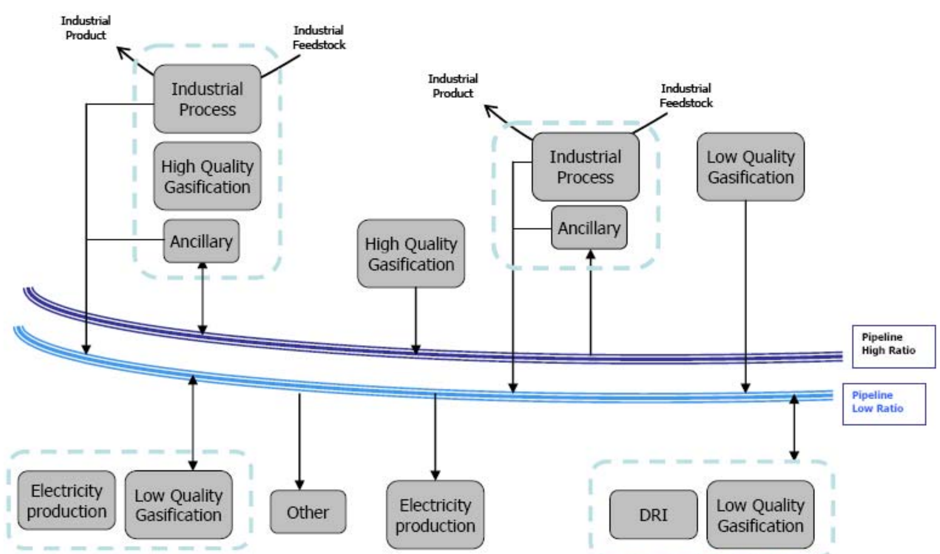

Fig. 4. The physical subsystem design: double bus network (from [18])

The final proposed design consisted of a double bus network (see figure 4): one pipeline contains pressurized ‘high-quality’ (HQ) syngas with a high H_2/CO ratio, enough to satisfy the most demanding production processes. The other bus contains syngas with a lower ratio that supplies to users with a lower demand for high-ratio syngas.

The social subsystem for this grid (i.e. local syngas market design) comprised a specially devised set of rules to play by. For suppliers and users on the HQ line two options were designed: transactions through bilateral contracts or syngas trading on a syngas spot market. For actors on the LQ pipeline bilateral deals and a syngas pool were created, from which users can buy the quantities they need. In addition, market balancing tasks were assigned to specific actors (see figure 5).

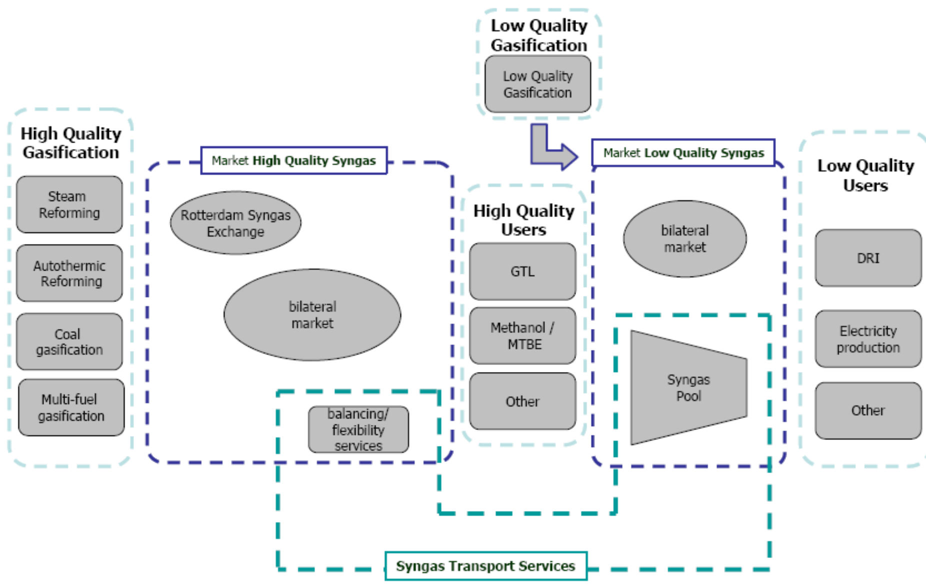

Fig. 5. The social subsystem design: institutional design (from [18])

Finally, the process design concentrated on commitment to the development process and on creating a sense of urgency by dividing the entire evolutionary process to the final cluster into a number of distinct rounds in which the conceptual technical and institutional designs would be adapted and detailed. With the inherent decrease in uncertainty with time passing by, the final design of this socio-technical complex system will evolve into one that can stand the test of time.

4.4 Seaport Groningen

Around the world, industrial areas have developed that are known for their concentration of heavy industry. Many of these industrial clusters evolved as a result of favourable geographic conditions, resource availability and infrastructure. Industrial clusters are complex socio-technical systems, being a network of physical assets controlled and maintained by an extensive social network [19]. Generally, a regional development authority has the responsibility to ensure the progress of the industrial cluster.

Groningen Seaports is the regional development authority in the Eems delta region in the north of the Netherlands. In the older of the two seaports in the region, the one around Delfzijl, a prosperous cluster has developed over time. Port, railroad, pipeline and utility infrastructures were developed to facilitate heavy industry, such as base chemicals production and alumina smelting. The available local resources, rock salt and natural gas, provided ample incentive for the development of what has become a successful chlorine-chemical cluster [20].

Following initial rapid growth and investments in heavy infrastructure in the 1970s, the economic development slowed down in the 1980s and 1990s. In 2000, the Groningen Seaports organisation was created to market the region's infrastructure pro-actively. The "Costa Due dialogue process" was then formulated in cooperation with the county, with the mission to create a sustainable bio based industrial cluster in the Eems delta. The cluster design was to comprise an initial high-level design of the technological system and the formation of a social network. To this end, the Costa Due partners approached a variety of scientists, entrepreneurs and energy companies to take part in a dialogue process, and they were all challenged to bring in innovative and feasible investment projects. The intention, of course, was to commit all these stakeholders to the project and to bring a healthily growing industrial cluster into being.

Equally important is that the Costa Due initiative also renewed the exposure of the Eems delta to potential investors. Whereas in the past both oil crises frustrated the region's development, global trends now support bio based and energy-related activities in the region. Since the Eems delta started to convey that it has a first-rate energy infrastructure and it has connections to both the national and the European gas and electricity grid, series of new investments have proved that this new tactic was successful.

It was then explored how the Costa Due partners could initiate and further the development of the cluster, building upon the success of the Costa Due dialogue process, where some 50 innovative project ideas emerged.

In the study an integrated approach was employed that comprised the physical system and the social network (with feedstock and product markets and regional and global trends as important inputs). An Agent-Based model was developed ([21], [22]) that accurately replicates the historical evolution of the cluster into the existing chlorine-cluster (see figure 6 for an example of model output structure). Inclusion of the 50 project ideas from the dialogue process indicated that the existing industry network and infrastructure are required as a nucleus for further development of the bio based cluster.

It was concluded that the Costa Due project is perfectly positioned and timed to leverage the global interest in bio based energy conversion and production. To accelerate sustainable cluster development the socio-technical system should be allowed to evolve and expand to include also bio based specialties and life sciences. The geographic conditions and the present seaport and energy infrastructure, however, are predominantly attractive to heavy large-scale industry and energy companies. To engage local players and bring more value-added, knowledge-intensive investments to the cluster, an opportunity would be to connect the existing tangible infrastructures with the intangible knowledge infrastructure available in and around the region's capital Groningen.

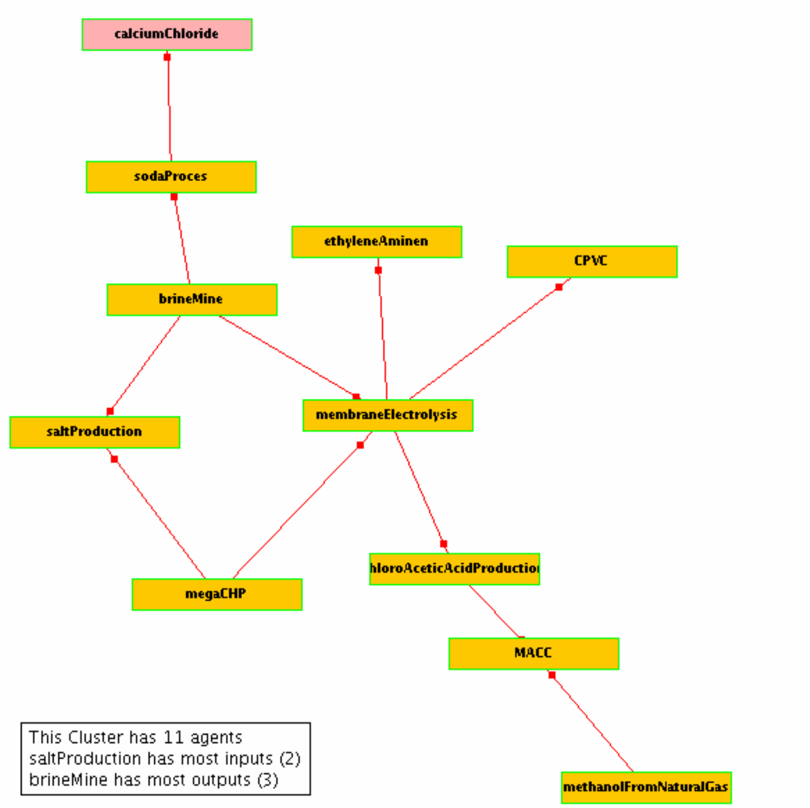

Fig. 6. The structure of an existing chlorine cluster
resulting from the Agent Based Model run (from [22]).

5. Conclusion

Can physical system design and social system design be combined to acquire a better understanding of the behaviour of socio-technical, complex systems and to effectively support better designs and design processes? The answer to this question has been addressed in this paper. The design of such socio-technical systems has been illustrated by means of three case studies, which range from a relatively simple design of a physical infrastructure (taking into account constraints from the social system), to a combined approach of process and systems design for the design and development of a large industrial cluster.

It has been be shown that a combined approach is essential, as socio-technical complex systems cannot be understood or designed without knowledge of both the physical system and the constellation of actors, i.e. the social system. It was also argued that the two designs and design processes differ in nature, and that forcing the actor perspective into a framework of system thinking would allow too little opportunity for modelling the reflectivity of the actors. Conversely, the actor perspective offers a framework which is not intended for a full description and design of the physical systems. Concluding, an integrated approach that takes into account the typical characteristics of complex system design, such as its deep uncertainty, the emergent behaviour, and the strong, unpredictable interaction between both subsystems, must be applied in the design of complex systems.

Acknowledgments

The authors would like to thank the following people for their contributions to this paper: MSc SEPAM students, Hans de Bruijn, Gerard Dijkema, Rob Stikkelman.

References

[1] Weijnen, M.P.C. & Bouwmans, I. (2006); 'Innovation in networked infrastructures: coping with complexity', Int. J. Critical Infrastructures, Vol. 2, Nos. 2/3, pp.121–132

[2] Bruijn, J.A. de, P.M. Herder, H. Priemus, Systems and Actors, Proceedings of Foundations of Engineering Systems, University Council on Engineering Systems, Georgia University of Technology, Atlanta, USA, December 14th, 2005.

[3] Holland, J., "Emergence: From Chaos to Order", Oxford University Press, Oxford, England, 1998.

[4] Netlogo (2007); http://ccl.northwestern.edu/netlogo/

[5] Hesselmans, A.N. (1995); De ware ingenieur; thesis, Delft University of Technology; Stichting Histosearch, Utrecht; ISBN 90-72105-04-4

[6] Ten Heuvelhof, E.F., M. Kuit & H.D. Stout (2004); Innovations in Infrastructures: New solutions to increase the reliability of vital infrastructures; in: Conference Papers, TTE Conference 2004, pp.6-17; www.tteconference2004.nl/pdf/TTE_A4papers.pdf

[7] De Bruijn, J.A. and E.F. ten Heuvelhof (2000), "Networks and Decision Making", Lemma, Utrecht

[8] J.A. de Bruijn, E.F.ten Heuvelhof and R.J. in 't Veld, "Process Management. Why Project Management Fails in Complex Decision-Making Processes", Boston: Kluwer 2002

[9] EPRI/PIER (2002); California's Electricity Restructuring; Technical Report prepared for EPRI & PIER by Mills College & Delft University of Technology; available online: http://www.epri.com/attachments/287226_1007388.pdf

[10] Van Mieghem, P. (2005); Robustness of Large Networks; to be published in: IEEE SMC 2005 Conference on Systems, Man and Cybernetics; Hawaii, USA, October 2005

[11] De Vries, L.J. (2004); Securing the public interest in electricity generation markets, The myths of the invisible hand and the copper plate; thesis, Delft University of Technology; available online via www.tbm.tudelft.nl/webstaf/laurensv

[12] Ajodhia, V., Regulation beyond price : integrated price-quality regulation for electricity distribution networks, PhD thesis, Delft University of Technology, The Netherlands, 2006

[13] C.L. Dym, Little, P., "Engineering Design: A Project-Based Introduction", John Wiley & Sons, Inc.USA, 2004

[14] M.W. Maier, Rechting, E.; "The Art of Systems Architecting", CRC Press, Boca Raton, 2002

[15] Goel, H.D., Integrating reliability, availability and maintainability (RAM) in conceptual process design: an optimization approach, PhD thesis, Delft University of Technology, The Netherlands, 2004

[16] Bruijn, J.A. de, P.M. Herder, H. Priemus, Systems and Actors, Proceedings of Foundations of Engineering Systems,University Council on Engineering Systems, Georgia University of Technology, Atlanta, USA, December 14th, 2005.

[17] Ajah A.N., A.C. Patil, P.M. Herder, Robust conceptual design of a residual industrial waste heat district heating system, Chemical Engineering Transactions, Vol. 7, 2005.

[18] Apotheker, D., D.J. van der Elst, M. Gaillard, M. van den Heuvel, W. van Lelyveld, SPM4910 - Sepam Design Project: The design of a syngas infrastructure in the port of Rotterdam, Faculteit TBM, TU Delft, January 2007.

[19] Nikolic, I., G.P.J. Dijkema, et al. (2007). Understanding and Shaping the Evolution of Sustainable Large-Scale Socio-Technical Systems. Towards a Framework for Action-Oriented Industrial Ecology. Dynamics of Industrial Ecosystems. M. Ruth and B. Davidsdottir. In press.

[20] Dijkema, G.P.J. and R.M. Stikkelman (2006). Position paper Eemsdelta. “Perspectieven en kansen voor duurzame economische ontwikkeling van de Eemsdelta”. Een systematische verkenning. Delft, Delft University of Technology, Faculty of Technology, Policy and Management: 1-97.

[21] Blokker, S. J. (2006). Co-evolution in the Process Industry, An Agent Based Model for the Eemshaven Chemical Cluster.

[22] Nikolic, I. and G.P.J. Dijkema (2006). Shaping Regional Industry-Infrastructure Networks - An Agent Based Modelling Framework. 2006 IEEE Conference on Systems, Man, and Cybernetics. Taipei, Taiwan: 901-905.