System and Actor Perspectives on Sociotechnical Systems

Hans de Bruijn and Paulien M. Herder, Member, IEEE

Abstract—This paper addresses the complexity of analyzing and designing sociotechnical systems: systems that involve both complex physical-technical systems and networks of interdependent actors. It is shown that, although a hard system perspective and an actor perspective differ greatly in terms of terminology, methods, and applicability, they also show surprisingly many similarities. By building upon the similarities and differences of the two dominant perspectives, this paper then goes on to show that the modeling and intervention possibilities in both perspectives differ to a great extent. The emerging systems-of-systems discipline generally calls for an "integration" of both perspectives in order to model and design these complex sociotechnical systems, but in this paper, it is argued and shown that full integration is not the preferred way to go. Instead, the emerging discipline should strive to facilitate the use of both perspectives alongside each other in a sensible way and, thereby, not discard the strengths of either perspective.

Index Terms—Actor networks, complex systems, design, engineering systems, systems engineering, systems of systems.

I. INTRODUCTION

HIS PAPER examines the process of analyzing and designing complex sociotechnical systems which involve 1) physical-technical elements and 2) networks of interdependent actors. We set out the main characteristics of such complex systems and present a comparison of the main similarities between the hard systems and the actor networks, using two different perspectives. One perspective is rooted in the engineering sciences, and mainly, in the hard systems engineering discipline or, in other words, a technical-rational perspective on complex systems, we will therefore refer to it, for reasons of readability in brief, as the "system" perspective. The other perspective is rooted in social sciences and regards actors as intentional agents; we will call that, in brief, the "actor" perspective. We then consider the implications of these sociotechnical systems' features with regard to the modeling of them, as well as for the design of such systems. Finally, we will present our conclusions in the last section.

By way of introduction, we first present two examples of problems which can only be understood and resolved with knowledge of both perspectives.

H. de Bruijn is with the Faculty of Technology, Policy and Management, Delft University of Technology, 2600 GA Delft, The Netherlands (e-mail: j.a.debruijn@tudelft.nl).

P. M. Herder is with the Delft University of Technology, 2600 GA Delft, The Netherlands (e-mail: p.m.herder@tudelft.nl).

Digital Object Identifier 10.1109/TSMCA.2009.2025452

A. Example 1: Supply of Residual Heat

The first example which illustrates the issues concerns the supply of residual heat from an industrial site to a residential area [1], [2]. Residual heat is often a by-product of industrial processes and is usually "thrown away," i.e., dispersed into the atmosphere or into cooling water. If this energy is not merely wasted in this way, but used to heat homes, a reduction in the use of fossil fuels can be achieved. However, the physical transport of the heat into homes calls for the design and construction of an extensive infrastructure.

Systems: Many industrial processes create heat. Often, the heat, which is not required by the process itself, is dispersed in the cooling water or by some other cooling installation. The amount of heat produced and the exact moment at which it is produced will depend on operational considerations, e.g., the product being manufactured, the quantity of the product, and the raw materials used.

Let us suppose that the heat produced by the process can be used to heat residential property. Aside from information regarding the supply side, i.e., the quantity of available heat, we will require information concerning demand: How much heat do the households actually require? After all, the residents are the end users of the heat. While this quantitative information is clearly required, it is equally important to know when the heat is needed: During the winter months, demand will be higher than in the summer. Demand also shows dynamic variations on a smaller time scale: The heating requirement will be lower at night than during the day.

In addition to devising the system of heat supply and heat demand, it will be necessary to address questions relating to the physical infrastructure: How is the heat to be transported from the industrial process to the residents' homes? Here, the heat carrier (steam and water) is relevant: Which heat carrier should be chosen? There are also decisions to be made with regard to the dimensions of the pipelines, the number of pipelines, and the number and size of the pumping stations. How far can the heat actually be transported? How much heat loss will occur within the infrastructure?

Actors: A description of the technical or physical heat supply system is not enough. It is also important to identify and understand the parties—or "actors"—responsible for the design, implementation, and operationalization of that system. The industrial organization producing the heat will not be interested in a heat supply system which dictates when it is to conduct its processes or at what capacity. However, the local authority and the end users wish to be assured of an adequate supply of heat at those times at which it is needed. If the network is

1083-4427/\$26.00 © 2009 IEEE

Manuscript received December 22, 2006; revised July 23, 2007 and December 17, 2007. First published August 7, 2009; current version published August 21, 2009. This paper was recommended by Associate Editor K. W. Hipel.

to be realized, this conflict of interests must be addressed and contractual terms agreed.

Other actors must also be considered: Those companies whose core business is the supply of energy, and who will suddenly experience competition from an industrial process, may well involve themselves in the process, perhaps calling on the legislation which regulates the energy market. Finally, consumers are likely to invoke their right to freedom of choice with regard to energy supplier, whereby the actions within the field of actors will greatly influence whether the system can function or not.

B. Example 2: Environmental Chains

Our second example relates to an environmental issue. Suppose that a government is experiencing the problem of rapidly increasing waste flows in a particular region. The increase is so great that there is no longer sufficient processing capacity. Accordingly, the government wishes to restrict the production of domestic refuse. One of the proposals is to replace singleuse "disposable" consumer packaging with reusable packaging forms. For example, a refillable polycarbonate bottle for milk would replace the carton package; jams and conserves would be supplied in refillable jars in stead of disposable glass jars, while fruit juices would be supplied in glass bottles rather than cartons. This example focuses on the jam jars.

Systems: The packaging of a consumer product is part of a system of production and consumption. An assessment of the environmental impact caused by glass jam jars requires information concerning the raw materials used in their production, where those raw materials are obtained, how they are transported to the producer, how the packaging is produced, how it is filled, and how the filled product is then transported to the consumer. Between all these components of the production system—raw materials, transport, production, filling, transport, and consumption—there are certain interrelationships.

The behavior of a system is subject to many uncertainties. For example, what emissions are caused by the transport of raw materials from Brazil to Europe? That will depend on a large number of variables, e.g., the type of ship, the manner of loading, the weather and route, innovations, etc., which will be different on each occasion. Moreover, the introduction of reusable jam jars may result in lower demand for the existing glass recycling systems, the "bottle banks." Perhaps such systems will then no longer be cost effective, and the network of bottle banks will no longer be so finely meshed. As a result, the consumer will return fewer glass containers to the bottle banks, and the environmental performance of a region will decline.

Actors: Alongside an analysis of the technical system, it is necessary to identify the actors involved: the private and public organizations active in each of the links in the chain. Some companies are likely to resist the government's proposals and may attempt to gain support for their attempts to block this policy. They could retain research institutes to prove that the conventional glass jam jar has a good environmental performance or could appeal to a court on the grounds that the new environmental policy hinders the free traffic of goods and services. Other companies may benefit from the new policy and would then adopt strategies to promote it. Environmental organizations would also attempt to exert their influence. The "game" between all these actors has its own dynamic. The final outcome of the policy will therefore not only depend on the operation of the physical system but also on the interaction between the various actors.

C. Challenge

In both examples aforementioned, the system and actor perspectives are of great importance to fully understand the intricacies of the problems and to design appropriate solutions to the problems. Without suggesting that these two perspectives are orthogonal and should be applied entirely separately (from an analytical point of view), we have seen that doing so does offer opportunities that will help clarify and resolve the complex problems involved. The traditions in each "discipline" seem to be different, as do the terminology and approaches adopted.

The two examples also showed that the two sides are intertwined and interact with each other. Therefore, if we want to solve the problems and design solutions that work in practice, we must consider both approaches, and we must find ways to reconcile the differences between the approaches and their outcomes. The lion's share of current scientific research, however, focuses on either of the two perspectives: The emphasis in the engineering disciplines is on the hard technical systems, whereas the social sciences tend to take the technical subsystems for granted. The questions addressed in this paper therefore are the following.

- 1) What are the main characteristics of both the system and actor approaches, and what are their similarities and differences?
- 2) What are the main characteristics of modeling systems and actors?
- 3) How do we use the two paradigms of modeling in parallel, thereby using the strengths of both worlds without damaging the strengths of either by full integration?

The next section sets out the contribution that can be made by the system perspective in addressing this type of complex problems. In Section III, we shall likewise examine the actor perspective's contributions. As said, there are striking similarities between the two perspectives, but there are also important differences. In Section IV, the two perspectives will be compared, leading up to modeling and intervention issues in Section V. We will also address ways and possibilities for crossover and hybrid models. Finally, we will revisit our example, and Section VI will offer our conclusions and a research agenda.

II. TECHNICAL-RATIONAL SYSTEM PERSPECTIVE

A. Many Subsystems, Multiple Conflicting Objectives, Dependences

When looking at a large-scale system, we will often find that it actually comprises many smaller subsystems, see, for example, [3]–[6]. The type of systems considered in this paper consists of a very large number of subsystems, all of which are interdependent in several ways. If one subsystem is not functioning well or is not functioning as originally intended, it is extremely likely that the overall system will not function as intended. If the chemical plant, from the first introductory example, would shut down for maintenance, the entire system, including the heat delivery to homes, will fail to function properly. Moreover, subsystems often have conflicting functionalities: Optimizing the performance of one subsystem may result in poorer performance by another, and optimizing the operation of the chemical plant will not necessarily lead to an optimal performance of the heat infrastructure. Even in isolation, a subsystem may be subject to conflicting performance objectives. Aside from these conflicting relationships, the interdependence of the various subsystems can take various forms.

- Simple-multiple: Subsystems can be interdependent by virtue of just one variable, e.g., "information," or can be related to each other in several respects simultaneously, e.g., information, energy, and raw materials.
- 2) No feedback-feedback: Subsystems may depend on each other in such a "circular" manner that it is impossible to identify any linear relationship between them. In such cases, events in subsystem A will always (eventually and via other subsystems) have a recursive effect on subsystem A. This feedback can result in an unstable effect, a self-strengthening effect, or a self-extinguishing effect.
- 3) Linear–nonlinear: Where the functioning of the system is the sum of the performance of all its subsystems, we speak of a "linear" relationship, whereby one subsystem will react proportionately to changes in another subsystem. In a "nonlinear" relationship, there is no proportionate reaction to another subsystem.
- 4) Sequential-parallel: Subsystems may be positioned sequentially in relation to each other, whereby one subsystem must wait for the output of its predecessor; take the packaging subsystem from our second example which has to wait for the transportation subsystem. Alternatively, subsystems may be linked in parallel. This is the case where subsystem B is used as a backup to subsystem A. If one packaging machine fails, a second packaging machine can then assume its task. Many other reasons for parallel configuration may exist, such as augmentation and stability.
- 5) Synchronous–asynchronous: Subsystems may respond to each other in a synchronous or asynchronous way. Commonly, if asynchronicity poses a problem to the overall system behavior, this should be solved by proper coordination or control mechanisms.

B. Complex Systems

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 as a whole and to model that system. Eventually, the system will become so complicated that the analyst can no longer recognize or model it at all. Certainly, when many relationships between the subsystems are nonlinear and asynchronous and where there are many feedback and feedforward loops, the system will become particularly chaotic and unpredictable. The literature applies the term "complex system" to such cases [7], [8]. A typical characteristic of those systems is that they show emergent behavior. Emergence refers here to unexpected or not explicitly intended behavior and characteristics of complex systems. Although the notion of emergence is subject to much debate, see, for example [8], [10], it facilitates discussions concerning the analysis and design of complex systems.

Recursion: "systems of systems": The strength of system theory is to be found in the recursion of the system concept [11]. To understand, model, or design a system, the modeler will apply a specific decomposition into subsystems. However, it is perfectly possible that the system will itself be part of a greater whole: The system is then a subsystem [12]–[14]. On higher system levels, however, the characteristics of the system may be more complex in nature, i.e., chaotic, emergent, and unpredictable, thereby rendering the "simple" concept of recursiveness a more complicated one. As a result, a system of systems may display other or new behavior that is not a sum of subsystem behaviors.

The chosen granularity of the decomposition may depend on the objectives of the model, on data availability, and on practical issues such as time or budget constraints.

C. Dynamics and Time Scales

The example of the heat supply system demonstrates that systems must contend with a dynamic which takes place on various time scales. The dynamic, representing deliberate or nondeliberate changes in the state of (sub)systems over time or in its external influences, has an impact on the overall performance of the system. When it is desirable to have a highly dynamic performance of the system, for example, in order to respond to a highly dynamic environment, this can be achieved by activating or deactivating one or more of the subsystems within it [15].

Where various subsystems or external factors each have their own dynamic on various time scales, ways must be incorporated into the system to mitigate or strengthen their effects. For the case of the residual heat supply, the dynamics of consumption and supply of heat differ greatly: A continuous chemical production facility generally produces heat at a fairly constant rate. The consumption of heat, however, is characterized by at least two time-dependent dynamic patterns: one defined by the day–night pattern and another one determined by a seasonal pattern, as more heat is generally consumed in the winter time.

D. Rational Approach

The system perspective is largely technical-rational in nature. The underlying disciplines (mainly engineering disciplines: systems engineering/architecture and operations research [3], [8]) apply a phased and structured approach of problem solving. In the case of system design, this will involve problem analysis, conceptual design, basic design, detail design, and implementation [16]. Such an approach assumes that problems can be identified and that the information required to model and understand the system is available. Furthermore, it presupposes the existence of a globally optimal solution.

Modelers may base their work entirely on hard facts and incontestable data. To a certain extent, the rational modeler can also make use of uncertainties in the model and some disputable data. He may, for example, choose to make use of probabilistic models and exploratory modeling, apply a scenario approach, or model the system using game theory to provide a description of the underlying mechanisms.

E. Black Box Approach

As stated previously, it may not be possible or desirable (for fundamental or practical reasons) to gain a complete understanding of a complex system. Complex systems therefore may display behavior that cannot be predicted by using rational system models. The system shows behavior which was not necessarily planned or intended beforehand and not included in the "design." The system is so complex that it can no longer be understood based on fundamental principles, and it becomes a black box [7].

Nevertheless, the black box approach is not entirely futile, even though it may appear to be so at first glance. It is again a matter of desired granularity. If we are considering the performance of the system or a subsystem but do not have to know exactly how the (sub)system does what it does, the black box approach can be just as useful. It is a matter of choosing the right level of granularity for the problem at hand. In case of low granularity, the system is not defined in detail in terms of its constituent subsystems, but only in terms of its current or intended performance.

III. ACTOR PERSPECTIVE

The problems outlined in Section I cannot be understood without considering the role of the relevant actors. This section describes the main characteristics of the constellation of actors [17], [18].

A. Many Actors, Conflicting Interests, Interdependent Relationships

A decision-making process will involve many actors. In almost every case, they will have different, perhaps conflicting, interests and, hence, different perceptions of the "reality." Because the actors have differing interests and perceptions, cooperation between them cannot be taken for granted. However, cooperation is essential because the relationships between the actors are interdependent: Each needs the support of the others. No actor is able to solve the problem on their own. Together, these dependences are termed a network or, more specifically, a "policy network" or an "issue network" [18]–[21]. The dependences can take various forms, among others.

- Simple-multiple: Simple dependences can be expressed as one resource: a "one-on-one" relationship. Multiple dependences emerge when there are actors who depend on each other for several types of resources, e.g., knowledge, funds, goodwill, or authority.
- 2) Bilateral–multilateral: Multilateral dependence implies that actor A is dependent on actor B, B on C, and C is, in turn, dependent on actor A. Accordingly, there can be no simple bilateral negotiations.

- 3) Synchronous–asynchronous: Asynchronous dependences are those in which actors depend on each other at different moments, perhaps separated by a substantial period.
- 4) Simultaneous-sequential: Sequential dependences entail the actors being linked at several successive moments in time. For example, actor A may only be able to carry out a certain action once another action has been completed by actor B.

B. Overall Combination of Dependences Is Difficult to Recognize

As the number of actors involved in a problem increases, the conflicts of interests become greater, and there is greater variety in dependences; therefore, it becomes more difficult to gain an overall view of the pattern of dependences. Eventually, it may become impossible for any one actor to understand the situation in its entirety. If actor A is in conflict with actor B, there could well be unforeseen consequences at a later date. Perhaps actor A will then experience opposition from actor C, upon whom actor B has called for support. If actors have limited information on the pattern of dependences, the predictability of their actions will be limited, and they will be faced with unforeseen consequences [22].

C. Networks of Networks

Given the difficulty in following all the dependences, it is also possible that "networks of networks" will emerge. Suppose that there is a certain practical issue, such as the packaging example given in Section I and an "issue network" of the actors directly involved in resolving this issue. Some of the actors may well also have relationships with each other in other "arenas" regarding entirely different issues, such as the residual heat example. It is conceivable that these actors will eventually be the losers in the decision-making process for the packaging issue. It is also possible that they will be compensated for this loss by means of a more positive decision regarding residual heat. Linkages between the networks are thus formed. This implies that the outcome of the decision-making process on residual heat cannot be understood without a knowledge of that regarding packaging. Where there is a true "network of networks," the complexity increases significantly: a large number of actors, dependences, conflicting interests, and extremely limited recognizability of the overall set of dependences [4], [23]–[26], [31].

D. Contested Information, Wicked Problems

Information on which problem analyses and solutions are based is almost always contested or wicked. "Wicked problems have incomplete, contradictory, and changing requirements, and solutions to them are often difficult to recognize as such because of complex dependences. It has been stated that, while attempting to solve a wicked problem, the solution of one of its aspects may reveal or create another even more complex problem" [27], [28]. Contested problems also imply that there will often be differences of opinion regarding the data, the system boundaries, and the analytical methods used. Take a life cycle analysis of a package. Whose data will be used and how reliable are these data? What methodology should be used? What are the "right" system boundaries? There are no objective unambiguous answers to these questions. Where you stand depends on where you sit: Producers of carton packages might want to use other data than environmentalists. If many actors are involved in the decision-making process, there will be strong incentives to criticize each other's data, system boundaries, and methods. In such a situation, experts and expertise will be of limited importance. Decision making is then not only expert driven but also interest driven [18], [29].

Of course, there can be contested information and wicked problems even in monoactor decision-making processes. Conversely, a multiactor situation can include unambiguous problems and objective information. However, the point is that, as soon as there are several actors with many conflicting interests, there will be strong incentives for these actors to declare the information "contested." The first reason for this is that the actors have different interests and, hence, differing perceptions. The second explanation is more political and strategic in nature: When actors contest the objectivity of information, they create opportunities for interest-driven decision making and, thus, greater opportunity to optimize their own interests.

E. Dynamics

Multiactor settings are dynamic in at least two ways [22].

- Actors. At any time during the decision-making process, certain actors may choose to withdraw. The process is no longer relevant to them, they believe that their interests will be better served by not taking part in the decision making, or they see other issues to which they wish to devote their attention. It is also possible that new actors will join the decision-making process. The process may take such a turn that these new actors believe that their interests are under threat, and they will then make a greater effort to influence the decision making.
- 2) Issues. If there is a constant exit and entry, the logical consequence could be that there will be an ongoing redefinition of the problem and its solution. Producers who do not participate in the decision-making process on packages might learn that the actors involved pay no attention to safety issues. If it is in their interest to put safety on the agenda, they might enter the process. Because of this, the issue will be redefined: Packages are not only an environmental and economic issue but also a safety issue. This sometimes continuous redefinition of issues is a significant characteristic of decision-making processes within networks.

F. Decision-Making Models

Many decision-making models that are based on the engineering disciplines have a markedly rational character. The decision-making proceeds as a sequence of successive phases: identifying the problem, followed by formulating an objective, collecting information, arriving at a decision, implementing that decision, and evaluating the implementation. The belief is that good decision making can be enhanced by this phased structure and the successive implementation of the phases, each of which should be defined as minutely as possible: a precise problem definition, a precise objective, precise information gathering, etc.

In the network setting, this approach is of extremely limited use for two reasons. First, where the decision-making process involves many actors with many different interests and perceptions, each party will have a different standpoint regarding the exact nature of the problem, the most appropriate objective, the required information, the accuracy of that information, the decision itself, etc. Actors that nevertheless wish to pursue this rational model should have sufficient power to impose their problem definition, objectives, and schedules on the other parties. In a network, no one has this power.

Second, the rational approach can actually be counterproductive. Decision-making processes in a network are highly interactive, and actors will therefore need room to maneuver [32]–[34], [43], [52]. Rational sequential decision-making does not provide this room and might frustrate the decision making. A simple example is provided by the fact that the phases of the rational decision-making model are precisely defined and separated, with a firm deadline applied to each, e.g., "the decision must be taken before September 1." In a network, such a deadline will often be counterproductive. Once actor A knows that actor B intends to arrive at the decision by September 1, there are strong incentives for actor A to block the decision. This will create a problem for actor B and might strengthen the position of actor A in the process.

G. Decision Making Is the Result of Interaction

An important characteristic of the actors within networks is that they will develop strategies to maximize their own interests. Given the many dependences, they are obliged to negotiate with each other. Given these negotiations, it might be attractive to them to use the strategy of coupling and decoupling. If actors learn that a certain issue A is high on the agenda of the majority of other actors, it might be attractive for them to couple new issues to issue A. In addition, the decision making itself is often multi-issue in nature: Actors introduce new issues into the interaction or negotiation process, perhaps because they see opportunities to couple these with the other issues.

Because of this, decision making will often be emergent: It is not planned, but is the result of a large number of interactions. The decision-making process is not linear, but is often a case of "muddling through;" it meanders forward. It may seem chaotic to the outside observer [35]. The intentions do not become reality, and the eventual reality is largely unintentional [29]. However, anyone who can also see the underlying interaction rationality will be able to detect some order in this apparent chaos.

IV. SYSTEMS AND ACTORS COMPARED

It will be clear from the descriptions of the system and actor perspectives that there are both similarities and differences between them at the conceptual level. The similarities and differences can be summarized as shown in Table I.

Aspect	System perspective	Actor perspective
Unit	Subsystems, dependencies, multiple conflicting objectives	Actors, different types of interdependency, conflicting interests
Unit rationality	Subsystems show rational behavior	Actors are reflective: they adopt strategic behaviour and they learn; no optimality
Constellation of units	Complex systems: systems no longer recognisable or impossible to model rigorously	Overall set of dependencies is not recognisable: information is frequently contested, problems are 'wicked'
Unit aggregation and segregation	System decomposition	Networks of networks
Dynamic behaviour	Dynamics in subsystems and in the topology of a system	Dynamics in the constellation of actors and in the topology of the network
Design approach	Technical-rational, successive, phased approach is useful	Network and contested information frustrate rational, successive phased decision-making processes
Design results	Result / performance is key	Decision-making is the result of the interaction: knowledge of this process is crucial

TABLE I Perspectives Compared

Here, we will confine ourselves to an examination of the differences.

The main difference is that, in a black-and-white world, the system perspective treats it subjects as "mechanical" beings, while the actor perspective treats it subjects as reflective actors. Reflectivity means that the actors have the ability to learn, which has three significant implications.

- Actors display strategic behavior. Their main motive is to serve their own interests and realize their own objectives. Strategic behavior (or "game playing") refers to all those actions that help the actors to do so. Strategic behavior can take the form of misinformation, hidden agendas, coupling issues, blocking certain decisions now in order to gain greater compensation later, etc.
- 2) Actors learn how to neutralize the interventions of others. They learn the strategies and interventions used by other actors and, in time, will often develop means to sidestep these strategies and interventions. This is referred to as the "Law of Decreasing Effectiveness:" Every strategy is of only temporary effectiveness because other actors learn how to neutralize its effects [36]. This enhances the dynamic of the network: Actors are constantly developing new strategies designed to maximize their interests.
- 3) Because actors are reflective, an understanding of the process of interaction that will eventually lead to a decision is crucial. If, during the decision making process, issues like residual heat and packages are coupled and losers are compensated, one cannot understand this result, without knowing what happened during the process. This represents a major difference with the system approach, in which the internal workings of a system's functioning

do not always have to be known in order to understand the system's overall performance.

We will return to consider the significance of this statement in the following section.

V. MODELING AND INTERVENTIONS

A. Modeling

If we define a model as "an abstract description of reality," then modeling is the act of producing such a description. To produce a system model, the following elements must be described:

- 1) (de)composition of system and subsystems;
- 2) inputs and outputs (in the broadest sense of the terms) of the system and its subsystems;
- 3) the functions of the subsystems;
- 4) performance (indicators) of the subsystems;
- 5) interrelationships between the subsystems.

The model is not a blueprint of the reality (the actual or desired situation), but is a (by definition simplified) description of that reality. Many other descriptions of that reality can be contemplated. The influence of the modeler, his or her background, and the purpose of the model will be decisive. A thermodynamicist is likely to build a different system model to that produced by a mechanical engineer, and an economic model will not be the same as a mechanical model of the same reality of the residual heat case. However, all such models have one thing in common: They describe the reality in a scientifically responsible manner, according to the rules and conventions of the relevant scientific disciplines. The models are often "harder" than those found within the actor perspective (see the following).

The process of modeling a network of actors will usually involve the description of the following elements:

- 1) (de)composition of actors and subactors;
- 2) resources, standpoints, and interests of the actors;
- 3) the strategies of the actors;
- 4) the relationships between the actors.

In view of these characteristics of the systems of actors, modeling is now of limited importance or significance. Modeling is not an activity of a modeler who can examine the objective reality impartially. Rather, it is an activity undertaken by a modeler who is acting as a facilitator, who works in interaction with a number of participants, and who charts the reality in such a way that these participants can recognize themselves in it to the greatest extent possible. The resulting model is a "compass" for the actual situation.

However, this qualification—which applies equally to system and actor perspectives—requires some further shading. If we compare modeling from both perspectives, we find a number of important differences, as shown in Table II.

First, modeling is an analytical activity from the system perspective: The components of the system and their interrelationships are identified and described. This can lead to a better understanding of how the system functions. When applied to an actor network, the very act of identifying the actors, their interests, and relationships can prove threatening to the actors

TABLE II DIFFERENCES BETWEEN SYSTEM AND ACTOR PERSPECTIVES ON MODELING

Systems perspective	Actor perspective
Modelling is an analytical activity	Modelling is a political activity
Separation of analysis and intervention	Separation of analysis and
is possible	intervention is more difficult
The model facilitates a better	Modelling can be an incentive to
understanding of the system	further strategic behaviour on the
	part of actors
Modelling is a testable activity	Modelling is the result of
	negotiation

themselves. A better understanding of how the network functions and the position of the actors within it could undermine their position in the decision making process. Accordingly, there is a distinct likelihood that a number of actors will choose not to participate in the modeling process.

Second, when modeling from a system perspective, it is possible to distinguish between the analysis and the subsequent intervention. Once the manner in which the system works is clear, the players can decide how they can go about optimizing that system, because of the testability of the models. When modeling networks of actors, distinguishing analysis and intervention is more difficult. If it is not in the actors' own interests to reveal the position they occupy, they may be prompted to influence the analysis in such a way as to strengthen their position.

Suppose that a modeler asks the actors within an issue network to state their opinion and underlying interests. It is then very likely that the actors will deploy strategic behavior. If actor A, who happens to have access to considerable resources, is modeled as a fierce opponent of a proposal made by actor B, this will be to actor A's advantage. Actor B will then gain the impression that he must offer A substantial compensation in one form or another in order to gain his support. Although actor A may actually have a neutral stance with regard to B's proposal (or may even support it), strategic behavior—presenting yourself as an opponent—is attractive.

Third, actors may adjust their behavior to match whatever model is available. In a network of actors, it is significant to note that the model of the reality provides an immediate incentive to strategic behavior. If actor A is dependent on actor B and the model reveals that actor B is, in turn, dependent on actor C, there will be a strong incentive for actor A to foster relations with C.

Fourth, from a system perspective, the modeling activity is considered to be a testable activity, which will yield a model that stands the scrutiny of present-day science, regardless of the modeler(s). When different modelers conjecture different model structures or boundaries based upon their disciplinary background or expertise, this may still be subject to (scientific) debate. The model, however, can be tested and will remain accepted, until new or different scientific evidence requires a change in the model. From an actor perspective, however, a model comes about in negotiations (negotiated modeling), and the model retains its validity only as long as the actors accept it.

To summarize, models of reality are always social constructions, whether they relate to technical systems or to networks of actors. Models will therefore always have certain limitations. In this respect, the modeling of technical systems is similar to that of actor networks. However, the reflective character of the actors may result in their having no interest in a model that describes the reality of the network. They may also "use" the modeler in a strategic way in order to strengthen their own position or may adapt their behavior as soon as the model has been finalized. This is an additional complication.

It now becomes interesting to examine how the disciplines of systems and actors deal with the complexity shown in Table I and how the actors address their own reflective character. We do not intend to present a detailed description of models and modeling techniques, since that would be beyond the scope of this paper. Rather, we shall attempt to answer this more fundamental question.

B. System Perspective: Substantive Design

Within the system perspective, it is possible to make a distinction between analysis and intervention as the objective of the modeling process. In both cases, a model has to be made. The key difference is that one models an existing reality in case of system analysis, while one models a desired reality (the design) and an intervention to reach the desired state in the latter case. The modeling activity for a system has been set out in the foregoing sections. In this section, we shall examine the intervention, i.e., the design or redesign of the system.

The system design for complex systems differs from that for a more simple system in the majority of the design process components [38], [39]. We shall now examine each component [16], [37].

- Functional requirements: The first step in each system design process is to produce a description of the function of the desired system or artifact. The resulting "functional requirements" state what the system must do. For a simple system design, this will be an equally simple description, e.g., "the system must store data." In a more complex system design, the function will often be compound, perhaps with different (main) functions for different actors. It is also possible that the system will be "distorted" upon implementation, i.e., it will not be used in exactly the manner that the designers had intended, despite involving as many stakeholders in the design process as possible. 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.
- 2) Objectives and constraints: The objectives and constraints form a fixed set of requirements which the system must fulfil and which the designer must therefore address. The degree of complexity involved is a product of the practically infinite number of objectives and constraints that the client and other actors can impose. If the designer, now in the midst of all these actors and their interests, wishes to incorporate all these requirements, the system is very likely to suffer from overspecification, 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 design task at hand and the greater the number of subsystems, the more difficult it will be to determine the "solution space," let alone select the best design from the various options in the resulting Pareto space.

- 3) Design space: The "design space" enjoyed by the designer comprises all the alternatives which are open to him or her. Even in extremely simple designs with only two design variables, this design space can quickly take on innumerable choices. When designing large complex systems, the design space is practically unbounded. It then falls to the designer, based on the set objectives and constraints to define and delineate the design space as best as he can. Other actors may also attempt to incorporate subsystems into the design space or to ensure that they are excluded. Take, for example, the heat infrastructure example. During the pipe route planning stage, local residents will attempt to exclude their "backyards" from the designer's design space. However, the responsible public body (the regional authority) will attempt to make the design space as large as possible, since the larger the design space, the better the chance of realizing a feasible design. They will then exert pressure to ensure that all backyards remain within the design space.
- 4) Models and modeling: It is in this stage of the design process that the system models are built. Here, the models are not intended to provide an analysis of an existing system, but to describe a future system which has yet to be created. The models establish a link between the functions, objectives, and constraints of the design on the one hand and the design space on the other. In other words, the models assist the designer in determining the most appropriate values for the design variables in the design space and to do so in such a way as to result in an "optimal" design. The models themselves do not therefore intervene in the reality.

The system models which play a role in this part of the design process can vary from simple mathematical linear system models to complex probabilistic models or game theory models.

5) Starting points: At the beginning of the design process, every designer will study designs that have previously been implemented, whether successes or failures. He will then be able to draw lessons for the current design. He will also be able to make use of the models produced for the previous designs. However, in the complex system designs being considered by this paper, it is much more difficult to find these "starting points." Precisely because these are systems which are embedded in a (dynamic) multiactor field in a specific institutional context, the transplantation of models and design options is not a simple undertaking and will indeed often be impossible. Given the high degree of context sensitivity, the system designer of complex systems will often have to produce his own models, and there will be few system starting points or reference cases.

The aforementioned outlines how the task of the system designer is made more difficult by an increasing degree of

complexity within each of the various generic components of any design process. For now, the main principles of system design, however, remain unaltered. After the next section, we will show how the designer of complex systems can indeed deal with the system and actor complexity.

C. Actor Perspective: Process Design

As regards the modeling of the desired reality, there is a major difference between the system and actor perspectives. Actors are reflective and will display strategic behavior. For a network of actors, a model of the desired reality will only be authoritative if it is accepted by a "critical mass" of the actors. Within a network, this is precisely the problem: Given all the differing interests, the likelihood of a model being accepted is extremely small [30], [40]–[42]. How can consensus on a desired reality be achieved nonetheless? The characteristics of a network of actors make clear that two familiar types of intervention will not be effective [44].

- Hierarchical interventions or "command and control" will be impossible since no actor has the power to use this strategy [45]. An actor who nevertheless attempts to manage the process through command and control will only generate opposition. If no one has the power to use command and control, attention will shift to the question how to manage the process of interaction between the actors in order to arrive at negotiated knowledge.
- 2) "Modeling by expertise," based on a content-based analysis, is also unlikely to succeed. Problems are wicked, and knowledge and information will be contested; statements based on a content-based analysis are always open to discussion [46]–[48]. In this situation, attention will shift from the question what modeling expertise is needed to the question how to manage the process of interaction between the actors in order to arrive at negotiated knowledge [49].

How do we manage this process? How to involve the main actors? How to get their commitment to both the process and the results of the process? How to discourage them from leaving the process when they are not completely satisfied with the imminent results? As said before, we cannot discuss all these questions in detail. What is important here is that the actors accept that their interaction process requires a set of rules of the game, which will guide their interactions. One might call this a process design: a design of the rules of the game that prescribe how the actors involved will make their decisions in both the analysis of a problem and the required interventions. Therefore, in addition to the substantive design that is needed from a system perspective, there is process design to facilitate the interaction between the actors with their different interests.

What are the main characteristics—or design principles—of such a process design [44]? First and foremost, a process design should give actors a fair chance to realize their own interests. At the beginning of the process, the perception of each actor should be that this is an open process, that there is enough "decision-making space," and that the process design does not favor some above others. Second, the risk of such an open process is that both the course of the process and its result are difficult to predict. There is always the risk that, with the passage of time, one or more actors will find themselves in an awkward position. For this reason, a second design principle is that the core values of each actor should be protected. Take the packaging issue again. If the government, the industry, and the environmentalist movement decide to enter a process of reaching negotiated knowledge on the problem and its solution, a core value of the industry is that it wants to protect confidential and commercially sensitive information on the production of packages. Agreeing that this core value will be protected creates a safe environment for the industry and makes it easier to agree with the process design and to enter the process.

Third, if there is an open process and if the core values of each party are protected, another danger lurks: The process may develop into a sluggish and erratic process. The third principle for a good process design is therefore that it contains incentives to make sufficient progress. An example is that parties accept some decisions that require consensus, but that others can be made with a qualified or regular majority. Another risk is that the actors in the process are so focused on reaching negotiated knowledge that they forget to take content-based expertise into consideration. This brings us to the fourth criterion: The result of the interaction process must stand up to expert scrutiny. Experts should play a role in the process, not to impose their expertise-based opinions on the other actors, but to inform the other actors of their expertise. If this expertise is ambiguous, actors have degrees of freedom in accepting or neglecting it. If it is unambiguous, actors should respect it.

The next question is whether actors will accept a process design. They will not do it automatically. If a critical mass of the actors is satisfied with a situation in which there are no rules of the game and actors attempt to realize their own interests by means of a "free fight," there is no point in attempting to design a process. However, actors may learn that this free fight fails to reach any consolidated decision and that the costs of nondecision making are too high. If a critical mass of actors has gone through this learning process, a sense of urgency may emerge that decision-making requires cooperation. There will then be incentives for the actors to join each other in a process design to arrive at a decision. The process design required to do so can take several forms.

- Formalized and tailor made. A process design is tailor made for a set of actors and for a specific set of problems. In most cases, this process design will be the result of a process of negotiation, and the rules of the game are formalized. An example is international peace talks. Negotiations on procedures often precede the negotiations on the real issues. Therefore, here, the course of events might be that actors learn that consolidated decision making requires a process design to facilitate the process of interaction, and this process design itself is also the result of an interaction process.
- Formalized and standard. A "standard" process design is already available. Some countries have standard procedures to arrive at negotiated rulemaking, for example.
- 3) Informal. A process design can develop "emergently," perhaps because the actors have been involved in similar

TABLE III Pure and Crossover Forms of Methods

Perspective	Systems perspective	Actor perspective
Modelled object		
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

negotiations in the past and the rules of the game are part of their tacit knowledge.

To conclude, a process design has the main rules of the game that actors will use in order to arrive at decision making. A process design can be regarded as a model of a network, but it has a number of specific characteristics.

- 1) It is a negotiated model. It is based on consensus between the actors, who have indicated that they wish to arrive at a decision in the manner set out by the game rules of the process design. It is therefore the result of a "meeting of minds" between the actors and not the result of any analysis.
- 2) It is of temporary validity. It applies only to specific issues and actors. If the same actors have to solve other problems or if the same issues have to be solved by other actors, other process designs might be used.

D. Crossover Models

In the foregoing, for the sake of analytical clarity, we have considered systems and actors as entirely separate perspectives. Real-world problems (such as the examples given in Section I) will always require a combination of system and actor perspectives in order to solve the problem and design realistic solutions [8], [50]. We must then pose the question of what form the combination of these perspectives is to take. We address this question by looking at crossover (the use of one perspective for modeling in the opposite realm) and hybrid (an attempt at integration or combination of both perspectives) forms of modeling.

A description of what modeling actually entails from the actor perspective and from the system perspective has already been given. Two crossover forms exist: using a system perspective to model actors and using an actor perspective for modeling hard technical systems. Table III shows the four possible combinations. Both crossover models are described next.

1) System Perspective Applied to Actors: The first crossover form is created by applying rational engineering modeling techniques to the actor arena [24]. In that case, the techniques are used to objectively model the network of actors, including the subactors, resources, standpoints and interests, their strategies, and their interrelationships.

However, this will not be easy. After all, as we have already seen, reflective actors are not inclined to allow themselves to be modeled objectively. Nevertheless, the use of modeling techniques can serve a number of purposes.

1) It forces the modeler to consider the problems from the actor perspective.

- 2) It provides an insight into the known and the unknown variables. In some cases, for example, the relationships maintained by certain actors will be unclear, as will their underlying interests, etc. Such aspects are made explicit by means of modeling.
- 3) Where the modeling process is undertaken by a number of modelers (e.g., representatives of the actors themselves or modelers playing the role of a specific actor), an understanding of the differences in perception within the actor network will be gained. This is significant: Perceptions play an important role in determining the actors' actions.
- A modeled actor network can facilitate the discussion and decision making with regard to the strategies to be followed.

An example of this modeling technique is provided by the Dynamic Actor Network Analysis (DANA) methodology [54]. The aim of the DANA project is to construct a workbench to support policy analysts in their representation and analysis of information on the actors (organizations, stakeholder groups, or individuals) who play a role in some policy situation.

2) Actor Perspective Applied to Technical Systems: What contribution can the process-oriented modeling of the actor approach make to hard system design? As previously stated, complex technical systems contain many uncertainties. A model of the system will therefore always be "contested," with various experts holding diverse opinions regarding the manner in which the system functions. This can be a problem. If there is a divergence of views, this is likely to stand in the way of successful interventions [52].

If a model is contested, it is necessary to devote 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. They may, for example, be asked to explain their opinions in detail in order to facilitate a discussion of those opinions. In the ideal situation, this process will reveal exactly what the experts already agree on and where the differences of opinion lie. An example of such process can be found in the Pugh concept selection process, a well-known and established way for converging to and selecting design concepts [55], [56] among designers. Once again, such a process calls for a number of rules of the game, which can be provided by the actor perspective.

E. Hybrid Models

There are attempts at creating and using models that aim to combine the strengths of both perspectives. Two of those are discussed in this section: "serious gaming" and "agent-based modeling."

Serious gaming comprises actors playing out new situations in a controlled environment [57]. This environment can be supported by simulation models and/or other system-oriented models. Serious gaming thereby makes use of the strength of the system perspective in building the underlying simulated environment and combines this with the actor perspective's requirements by having real people play out the game, thereby allowing for strategic behavior and learning. Serious gaming is a rapidly growing research area and is used more and more for design and decision processes in the real world [58].

Agent-based models are computational models in which all system elements and actors are modeled as agents: small independent units that have defined inputs and outputs, a defined "transformation function," and defined behavioral rules. The agents are then put together in a simulation, and they will interact according to their rules, which will ultimately result in a solution of the complex problem. This is not necessarily the optimal solution. In a recent paper by Callon [59], he argues that all objects and actors have "agency" and that this agency changes over time and changes with the environment that it is exposed to. Agent-based models reflect this notion of agency: Changing some parameters in the environment will change the outcomes. Agent-based models also allow the modeler to include learning behavior into the agents so that they can behave purposeful and intelligent [60]. They will, however, not match human intelligence.

Although both hybrid modeling techniques are promising in describing and solving complex problems, both still suffer from the fact that concessions have to be made to one of the two perspectives in order to make them work, which lead us to conclude that both perspectives should not or cannot be integrated but must be used in parallel and alternating.

F. Case Study Revisited

The case of "supply of residual heat" [1] at the beginning of this paper showed that, in order to thoroughly analyze sociotechnical systems, one needs to adopt two perspectives. This paper then continued to explain these two perspectives in more detail, and then, we compared them and introduced modeling techniques that attempt to use the strengths of both perspectives. For the design of the residual heat infrastructure, applying both perspectives in an alternating fashion results in the following design and design process. First, a process manager needs to be installed, who is charged with creating a process design according to the process design rules discussed in this paper. This means that thought should be given to who should be involved, e.g., the plant representatives, the city council, infrastructure providers, service providers, investors, etc., and to what process rules and outcomes the participants are willing to commit. In this case, the process manager will strive for commitment to a conceptual design of the technical infrastructure, to an organizational structure, and to contracting and financing issues. The process manager could benefit from using rational system approaches to model the actor network and their interests, but he may gain more insight from applying a "serious gaming" approach. In such approach, the technical heat infrastructure would be modeled according to ruling thermodynamic models, but the actor behavior such as contracting negotiations would be played out in a controlled setting. During the design process, legislations would be simulated, and their present and future impacts on the design would be assessed.

Playing such a game would give the process manager and the design team a feel for a (set of) possible outcome(s) and behavioral patterns of the participants. One should bear in mind, however, that gaming will yield only one possible outcome per game played, so that no firm conclusions can be drawn as to the final real-life outcome. It is up to our process manager to use the serious game as a tool for consensus building within the design team.

For this specific case, the final design obtained at the end of the process comprised the following elements.

- The resulting 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 modeling purposes, thermodynamic models and life cycle costing methods were used.
- 2) A Design, Build, Finance, and Operate (DBFO) contract between public and private parties was selected and designed. Due to the financial risk sharing between public and private parties in a DBFO contract, incentives were created for fulfilling requirements such as efficiency, profitability, and quality of service to consumers. The assets for owning and using the grid had to be allocated ex ante by the municipality and not by the market.

VI. CONCLUSION

Can the system approach and the actor approach be integrated? The answer to this question is subject to various opinions. The first is that integration is actually essential. Problems cannot be understood or solved without knowledge of both the technical systems and the constellation of actors. Accordingly, an approach that can deal with both perspectives must be sought. We should not leave the hard technical systems to the engineering schools and the actors to the business schools. This would always lead to completely different problem analyses and solutions, whereby "never the twain shall meet," either intellectually or institutionally.

A second standpoint is that integration is, in principle, impossible. The main difference between systems and actors is that the actors are reflective: They learn, and they display strategic behavior. The risk of integration is that the actor perspective will be forced into the rigid framework of system thinking, in which there is little opportunity for reflectivity on the part of the "components," i.e., the actors. Conversely, the actor perspective offers a framework which is not accurate enough to allow a full description of the systems.

Our conclusion is that the actor perspective and the system perspective are "competing" perspectives which must be used alongside each other. Full integration will erode this competing character, rendering both perspectives of lesser value. Using both perspectives alongside each other means that complex sociotechnical systems need to be designed by engineering systems designers who are able to switch perspectives continuously and are able to apply both perspectives in a fruitful manner. Furthermore, we should aim our research at developing both modeling techniques and design and decision-making processes that account realistically for both perspectives. Only then will sensible social-technical system designs that can stand the test of real-world implementation be realized.

REFERENCES

- A. N. Ajah, A. C. Patil, P. M. Herder, and J. Grievink, "Robust conceptual design of a residual industrial waste heat district heating system," *Chem. Eng. Trans.*, vol. 7, pp. 85–90, 2005.
- [2] P. M. Herder, I. Bouwmans, G. P. J. Dijkema, R. M. Stikkelman, and M. P. C. Weijnen, "Designing infrastructures using a complex systems perspective," *J. Des. Res.*, vol. 7, no. 1, pp. 17–34, Jun. 2008.
- [3] A. P. Sage and C. D. Cuppan, "On the systems engineering and management of systems of systems and federations of systems," *Inf., Knowl., Syst. Manage.*, vol. 2, no. 4, pp. 325–345, Dec. 2001.
- [4] B. S. Blanchard and W. J. Fabrycky, Systems Engineering and Analysis. Upper Saddle River, NJ: Prentice-Hall, 1998.
- [5] P. B. Checkland, "The origins and nature of hard systems thinking," J. Appl. Syst. Anal., vol. 5, no. 2, pp. 99–110, 1978.
- [6] A. P. Sage, Systems Engineering. London, U.K.: Wiley, 1992.
- [7] J. Holland, *Emergence: From Chaos to Order*. Oxford, U.K.: Oxford Univ. Press, 1998.
- [8] M. W. Maier and E. Rechting, *The Art of Systems Architecting*. Boca Raton, FL: CRC Press, 2002.
- [9] P. A. Kroes, *Technical Artifacts, Engineering Practice and Emergence*. Cambridge, MA: MIT Press, 2009.
- [10] C. W. Johnson, What are Emergent Properties and How Do They Affect the Engineering of Complex Systems? 2007. [Online]. Available: http://www.dcs.gla.ac.uk/~johnson/papers/emergence.pdf
- [11] M. Bjelkemyr, D. Semere, and B. Lindberg, "An engineering systems perspective on system of systems methodology," in *Proc. 1st Annu. IEEE Syst. Syst. Conf.*, 2007, pp. 1–7.
- [12] S. J. Luskasik, "Systems, systems of systems, and the education of engineers," *Artif. Intell. Eng. Des., Anal., Manuf.*, vol. 12, no. 1, pp. 55–60, Jan. 1998.
- [13] D. DeLaurentis and R. K. Callaway, "A systems of systems perspective for public policy decisions," *Rev. Policy Res.*, vol. 21, no. 6, pp. 829–837, Nov. 2004.
- [14] C. Keating, "System of systems engineering," *Eng. Manag. J.*, vol. 15, no. 3, pp. 36–43, Sep. 2003.
- [15] P. M. Herder, A. L. Turk, E. Subrahmanian, and A. W. Westerberg, "Challenges for process systems engineering in infrastructure design," *J. Comput. Chem. Eng.*, vol. 24, no. 2–7, pp. 1775–1780, Jul. 15, 2000.
- [16] C. L. Dym and P. Little, Engineering Design: A Project-Based Introduction. Hoboken, NJ: Wiley, 2004.
- [17] N. Crozier and E. Friedberg, Actors and Systems. Chicago, IL: Univ. Chicago Press, 1980.
- [18] W. J. M. Kickert, E.-H. Klijn, and J. F. M. Koppenjan, Eds., *Managing Complex Networks*. London, U.K.: Sage, 1997.
- [19] B. Marin and R. Mayntz, Eds., *Policy Networks. Empirical Evidence and Theoretical Observations.* Boulder, CO: Westview, 1991.
- [20] T. A. Börzel, "Organizing Babylon—On the different conceptions of policy networks," *Public Adm.*, vol. 76, no. 2, pp. 253–273, 1998.
- [21] R. Agranoff, Managing Within Networks. Adding Value to Public Organizations. Washington, DC: Georgetown Univ. Press, 2007.
- [22] J. Koppenjan and E. H. Klijn, *Managing Uncertainties in Networks*. London, U.K.: Routledge, 2004.
- [23] R. Axelrod, *The Evolution of Cooperation*. New York: Basic Books, 1984.
- [24] M. McGuire, "Managing networks: Propositions on what managers do and why they do it," *Public Adm. Rev.*, vol. 62, no. 5, pp. 599–609, Sep./Oct. 2002.
- [25] J. A. de Bruijn and E. F. ten Heuvelhof, *Management in Networks:* On Multi-Actor Decision Making. London, U.K.: Routledge, 2008.
- [26] L. Salter, Mandated Science. Boston, MA: Kluwer, 1998.
- [27] H. Rittel and M. Webber, "Dilemmas in a general theory of planning," in *Policy Sciences*, vol. 4. Amsterdam, The Netherlands: Elsevier, 1973, pp. 155–169.
- [28] M. T. Douglas and A. B. Wildavsky, *Risk and Culture: An Essay on the Selection of Technical and Environmental Dangers*. Berkeley, CA: Univ. California Press, 1983.
- [29] C. E. Lindblom, The Intelligence of Democracy: Decision Making Through Mutual Adjustment. Englewood Cliffs, NJ: Prentice-Hall, 1968.
- [30] R. Quinn, Beyond Rational Management. San Francisco, CA: Jossey-Bass, 1988.
- [31] L. J. O'Toole, Jr., "Treating networks seriously: Practical and researchbased agendas in public administration," *Public Adm. Rev.*, vol. 57, no. 1, pp. 45–52, 1997.
- [32] K. G. Provan and H. Brinton Milward, "Do networks really work? A framework for evaluating public-sector organizational networks," *Public Adm. Rev.*, vol. 61, no. 4, pp. 414–423, 2001.

- [33] M. Exworthy and M. Powell, "Big windows and little windows: Implementation in the 'Congested State'," J. Public Adm., vol. 82, no. 2, pp. 263–281, Jun. 2004.
- [34] G. R. Teisman, "Models for research into decision making processes; on phases, streams and decision making rounds," *J. Public Adm.*, vol. 78, no. 4, pp. 937–956, 2000.
- [35] M. D. Cohen, J. G. March, and J. P. Olsen, "A garbage can model of organizational choice," *Adm. Sci. Q.*, vol. 17, no. 1, pp. 1–25, Mar. 1972.
- [36] J. A. de Bruijn, *Managing Performance in the Public Sector*. London, U.K.: Routledge, 2007.
- [37] P. M. Herder and R. M. Stikkelman, "Methanol-based industrial cluster design. A study of design options and the design process," *J. Ind. Eng. Chem. Res.*, vol. 43, no. 14, pp. 3879–3885, Jul. 2004.
- [38] A. Sutcliffe, W. C. Chang, and R. S. Neville, "Applying evolutionary computing to complex systems design," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 37, no. 5, pp. 770–779, Sep. 2007.
- [39] K. Eason, "Local sociotechnical system development in the NHS national programme for information technology," *J. Inf. Technol.*, vol. 22, no. 3, pp. 257–264, Sep. 2007.
- [40] D. Boddy and N. Gunson, Organizations in the Network Age. London, U.K.: Routledge, 1996.
- [41] J. Bohman, Public Deliberation: Pluralism, Complexity and Democracy. Cambridge, MA: MIT Press, 1996.
- [42] A. M. Brandenburger and B. J. Nalebuff, *Coopetition*. New York: Doubleday, 1997.
- [43] L. J. O'Toole, "Strategies for Intergovernmental Management: Implementing programmes in interorganizational network," J. Public Adm., vol. 11, no. 4, pp. 417–441, 1998.
- [44] J. A. de Bruijn, E. F. ten Heuvelhof, and R. J. in 't Veld, "Process management," in Why Project Management Fails in Complex Decision-Making Processes. Boston, MA: Kluwer, 2002.
- [45] D. Chisholm, *Coordination Without Hierarchy*. Berkeley, CA: Univ. California Press, 1989.
- [46] J. G. March, "Bounded rationality, ambiguity, and the engineering of choice," *Bell J. Econ.*, vol. 9, no. 2, pp. 587–608, 1978.
- [47] I. I. Mitroff, "On systemic problem solving and the error of the third kind," *Behav. Sci.*, vol. 19, no. 6, pp. 383–393, 1974.
- [48] B. S. Frey, M. Benz, and A. Stutzer, "Introducing procedural utility: Not only what, but also how matters," *J. Inst. Theoretical Economics*, no. 160, pp. 377–401, 2004.
- [49] C. C. Jaeger, O. Renn, E. A. Rosa, and T. Webler, *Risk, Uncertainty, and Rational Action.* London, U.K.: Earthscan Publications Ltd., 2001.
- [50] M. C. Jackson, "The nature of soft systems thinking: The work of Churchman, Ackoff, and Checkland," J. Appl. Syst. Anal., vol. 9, pp. 17– 28, 1982.
- [51] P. Bennet, S. Cropper, and C. Huxman, "Modelling interactive decisions: The hypergame approach," in *Rational Analysis for a Problematic World. Problem Structuring Methods for Complexity, Uncertainty and Conflict*, J. Rosenhead, Ed. West Sussex, U.K.: Wiley, 1989.
- [52] T. Webler, S. Tuler, and R. Krueger, "What is a good public participation process?" *Environ. Manage.*, vol. 27, no. 3, pp. 435–450, Mar. 2001.
- [53] W. Bijker, T. P. Hughes, and T. Pinch, *The Social Construction of Technological Systems*. Cambridge, MA: MIT Press, 1989.
- [54] P. W. G. Bots, Dynamic Actor Network Analysis, DANA2006. [Online]. Available: http://www.dana.tudelft.nl
- [55] S. Pugh, "Concept selection: A method that works," in *Proc. ICED*, Rome, Italy, 1981.
- [56] D. D. Frey, P. M. Herder, Y. Wijnia, E. Subrahmanian, K. Katsikopoulos, and D. P. Clausing, "An evaluation of the Pugh controlled convergence method," in *Proc. ASME DETC*, Las Vegas, NV, Sep. 4–7, 2007, pp. 1–11.

- [57] I. Wenzler and I. Mayer, "Utilities deregulation and simulation," *Simul. Gaming*, vol. 36, no. 1, pp. 28–29, Mar. 2005.
- [58] B. G. Silverman, G. Bharathy, M. Johns, R. J. Eidelson, T. E. Smith, and B. Nye, "Sociocultural games for training and analysis," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 37, no. 6, pp. 1113–1130, Nov. 2007.
- [59] M. Callon, "The role of hybrid communities and socio-technical arrangements in the participatory design," J. Center Inf. Studies, no. 5, pp. 3–10, 2004.
- [60] N. Garg, D. Grosu, and V. Chaudhary, "Antisocial behavior of agents in scheduling mechanisms," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 37, no. 6, pp. 946–954, Nov. 2007.



Hans de Bruijn was born in The Netherlands in 1962. He received the M.A. degrees in law and political science from Leiden University, Leiden, The Netherlands, and the Ph.D. degree in public administration from Erasmus University Rotterdam, Rotterdam, The Netherlands.

In 1999, he was appointed as a Professor of Organization and Management at the Faculty of Technology, Policy and Management, Delft University of Technology, Delft, The Netherlands. Together with Prof. W. Thissen, he leads the Multi-Actor Systems

research program. The program comprises approximately 60 researchers, both engineers and social scientists, who do research on multiactor decision making on technical systems in areas like electricity, transport, large infrastructures, and ecology. He is the coauthor of *Management in Networks: On Multi-Actor Decision Making* (Routledge, London), which was recently published. His research interest is multiactor decision making, and his areas of application are large infrastructural projects, environmental issues, and the utility sectors.



Paulien M. Herder (M'05) was born in The Netherlands in 1971. She received the M.Sc. and Ph.D. degrees from the Delft University of Technology, Delft, The Netherlands, in 1994 and 1999, respectively.

She currently is an Associate Professor of Design of Large-Scale Systems with the Delft University of Technology, where she was the Director of Education from 2004 to 2008. She is currently Coleader of the "Flexible Infrastructures" research subprogram and Managing Director of a large international research

program on Next Generation Infrastructures, involving over 40 research organizations and companies in energy, transportation, telecommunications, and water infrastructures. Her research work focuses on flexible design and design processes of large-scale networked systems, mainly in the energy and industrial sectors.

Dr. Herder is an IEEE Systems, Man, and Cybernetics (SMC) Society Member and the Scientific Secretary to the SMC Technical Committee on Infrastructure Systems and Services.