DESIGNING SOCIO-TECHNICAL SYSTEMS

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1 INTRODUCTION

A diverse body of research in engineering and the social sciences documents the working of systems that require technical artifacts and social arrangements to function. Single plants, firms, or entire industrial sectors constitute *socio-technical systems* if technological components and social arrangements are so intertwined that their design requires the *joint* optimization of technological and social variables. The concept of a socio-technical system originated in studies of coal mining in post-World War II Britain [Trist and Bamforth, 1951; Emery, 1959; Trist, 1981]. In contrast to previous studies that had often considered technology as an independent force to which labor had to adapt, the organizational and labor studies influenced by the socio-technical approach emphasized the close interdependence of the social and technical subsystems. Detailed empirical studies formed the starting point for the development of design principles for socio-technical systems, such as compatibility between design process and its objectives; minimal critical specification of tasks, roles, and objectives; and the control of variances as close to the point of origin [Cherns, 1976]. Part expression of the art of design and part normative statements of values, these principles formed an initial set of guidelines for the design of socio-technical systems.

Although an analytically precise definition is difficult to formulate, for the purposes of this chapter socio-technical systems will be operationalized as arrangements of multiple purposive actors and material artifacts interacting in ways that require analyzing the total system and not just the constituent subsystems (see [Ropohl, 1999] for a more detailed discussion). Depending on the level of analysis and the research questions asked, each subsystem can be further disintegrated to dissect its logic and internal dynamics. Each subsystem aims to meet its own objectives, by using its own means, but is also in an interdependent relation with other subsystems. For example, technology was designed and built by purposive agents, acting within specific institutional settings, who continue to directly and indirectly shape its future. Likewise, social arrangements, for example, the setting up of decentralized energy trading markets, are in part contingent upon technological advances that support and enable them. As a result of this interdependence, technology and social arrangements co-evolve, each enabling and constraining, but not fully determining, the other sub-system [Murmann, 2003]. This interdependent relation unfolds in real, irreversible time, often resulting in a unique path

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of socio-technical development with inter-temporal dependencies ("path dependence") [Arthur, 1994; David, 2000].

Infrastructure sectors can be considered as a particular class of socio-technical system [Kroes *et al.*, 2006; Ottens *et al.*, 2006]: technology is central for their operations and both organizational as well as sectoral forms of social control are established to ascertain a range of public values associated with their operation, such as ubiquitous and affordable supply. Engineering and social design issues arise at multiple levels of these socio-technical systems. Modern societies are heavily dependent on the services of multiple infrastructures (a term originally used by the military to refer to supporting transportation and logistical functions). Without reliable and sufficient supply of energy and water social and economic life would collapse quickly. Transportation and communication systems are required to coordinate the ever more differentiated tasks and the related flows of goods, services, and people that go hand in hand with increased specialization. The services of other infrastructure systems, such as sewerage, or waste removal, are similarly indispensable for a high quality of life and the overall well-being of society. The technical and social organization of infrastructure industries is strongly influenced by public values [Bozeman, 2007]. Many of these public values remained remarkably stable over time but the ways in which they are pursued have changed substantially.

Worldwide, the traditional system built around strong government intervention and monopolistic industry organization has been superseded by market-based approaches in which government assumes regulatory rather than owner-operator functions. Infrastructure liberalization (the opening of market entry for new service providers) and sector unbundling (the separation of the stages of the value chain, for instance, electricity generation, transmission and distribution) have increased the number of participants and created multi-stakeholder environments. The reasons for these changes are manifold but illustrate the interdependence of the technical and social subsystems. Without significant changes in technology, such as the deep diffusion of information and communication technologies that facilitate decentralized control and management of complicated infrastructure systems, policy changes would not have been feasible. On the other hand, without changing sector organization some of the latent innovation potential might not have been realized. These transformations have increased the social and engineering complexity of infrastructure systems and hence the criticality of their design.

Despite the new challenges for the design of infrastructure systems, appropriate comprehensive design processes and methods are still lacking. Important design decisions at the technical and social level are, consequently, often made without a clear view of the overall implications of these decisions for the development of the socio-technical system as a whole. In recent history, this is vividly illustrated by the severe problems and disruptions during the early phases of electricity reform in California during 2000-2001 [de Bruijne, forthcoming]. There is not even a consensus as to the prospects and limits of all-inclusive design in socio-technical systems. The majority of the disciplines that presently influence infrastructure design — in particular engineering, economics, management science, law, and public administration — assume, explicitly or more often tacitly, that effective solutions to infrastructure design issues can be found and implemented. At the other end of the spectrum is the view that large infrastructure systems cannot be designed in a rational manner at all. Due the overwhelming complexity and challenges of the optimization problem, it is argued, comprehensive design and control in the classical sense are beyond the reach of social planners and policy makers. In between these opposite positions are authors with a more nuanced view of the overall controllability of socio-technical systems. The desire to devise comprehensive solutions is looked at skeptically as "constructivist fallacy": neither the information to design such systems nor the capacity to systematically explore all interrelations and contingencies is available. Nonetheless, a piecemeal, more localized and incremental, approach is deemed possible with ample room for deliberate design choices both in the social and technical subsystems.

This chapter examines the state of research and knowledge on these issues. In addition to providing a broad framework, it reviews principles for the design of such systems that have been developed by a variety of disciplines during the past decades. The next section discusses the scope of economic, legal, and social design considerations that a prescriptive theory of infrastructure design will have to address. Section three reviews different theoretical frameworks that have or could be used to conceptualize infrastructure design issues. The implications of these considerations for the design of socio-technical systems are taken up in the fourth section. Conclusions and a brief outlook are presented in the final section. Two *Intermezzi*, one on Syngas and one on the Internet, illustrate the conceptual arguments with particular cases.

2 SCOPE OF DESIGN ISSUES IN SOCIO-TECHNICAL SYSTEMS

Before theoretical frameworks will be addressed in more detail in the next section, it is necessary to clarify key structural features of socio-technical systems and the scope of design issues that arise in such systems. Social and technical subsystems are intertwined and each has multiple layers that are designed and evolve on different time scales. Multi-level systems have been more widely studied by social scientists than by engineers, for example, in institutional approaches, some dating back to the late eighteenth century. Williamson [2000] offered a useful model that allows treating different types of social and institutional arrangements in an integrated fashion. The four layers in this framework are analytically defined. In multi-layer systems, top-down and bottom-up causation interact: upper levels enable and impose constraints on lower levels and vice versa. The approach can be expanded to model the technical and social sub-systems simultaneously, as depicted in Table 1.

Changes in the institutional and technical arrangements at these layers, whether the outcome of purposive design choices or emergent phenomena, follow different time patterns. At the lowest layer of the system, continuous decisions regarding resource allocation and operation are made. One layer up, the governance structure of a society (the "play of the game"), most importantly various contractual arrangements, is specified. Specific methods of regulation (e.g., cost-of-service versus price cap regulation), ownership decisions (e.g., state, private, or hybrid), and market design will be defined at this layer, ideally aligning governance structures with the nature of transactions. Markets, hierarchies, and networks are important forms of the broad range of available governance structures. Change at that level unfolds over periods of one to ten years. The next higher layer defines the institutional environment, the "formal rules of the game". Important design decisions at this layer encompass, among others, the organization of a polity, the organization of sector-specific regulation, and the general definition of property rights. Change on this layer is even slower than at the governance layer with some processes lasting up to a century. Finally, the layer of social embeddedness reflects informal institutions, customs, traditions, norms and religion. Change can take very long time periods, even hundreds or thousands of years. These arrangements are often not designed but emerge from interactions at lower levels of the system.

Table 1. Layers and time scales in socio-technical systems

Time scale	**Social subsystem**	**Technical subsystem**
Embeddedness Changes 10^2 to 10^3 years often non-calculative	Informal institutions, customs, traditions norms, religion	Informal conventions embedded in the technical artifacts
Institutional environment Changes 10 to 10^2 years, institutional setting	Formal rules of the game (property, polity, judiciary, ...)	Technical standards, design conventions technological paradigms
Governance Changes 1 to 10 years design of efficient government regime	Play of the game (cotracts, governance of transactions)	Protocols and routines governing operational decisions and (best available) technology
Operation and Management Continuous adjustments	Prices, quantities incentives	Operational choices

Note: inspired by [Williamson, 2000].

A correspondence can be established between the layers of the social system and the structure of technical artifacts (see Table 1). At the lowest layer of the technical subsystem, continuous operational decisions are made in response to its state. The nature of these decisions is dependent on the specific technical system. Managers of electricity grids need to balance load and supply; controllers of transport systems need to organize traffic flows; and control algorithms in communication systems need to route and prioritize traffic according to the quality-of-service requirements of various applications. These decisions may be taken by human agents and hence be directly linked to the social system, or they may be automated based on pre-specified routines and technical protocols. In this latter case, they are indirectly linked to the social system. At the next higher layer, decisions as to how these technical artifacts are designed are made. These include both the architecture of the physical systems as well as the control processes for these systems.

At the third layer, corresponding to the institutional environment in the social subsystem, decisions relating to the broad parameters of the technical solutions are taken. These may include arrangements such as patent laws, national and international standard-setting mechanisms, and the adoption of conventions for the design of technologies. The highest layer reflects tacit technical conventions and prior design decisions, as described by Hughes [1983] as characteristic for later stages of the development of a technology. In this socio-technical multi-layer system, bottom-up and top down enabling and constraining relations co-exist with horizontal ones between the respective social and technical layers. Moreover, "diagonal" forms of influence connect higher social and technical layers with lower layers in the respective other system and vice versa.

Design decisions are made at all layers but the scope for such choices is generally broader at the lower layers. Consequently, in higher layers of the socio-technical system, deliberate design decisions become less prevalent and emergent characteristics become more important. Continuous and specific design choices are made at the operational and management layer. These design decisions are constrained by design choices at the governance layer. Design decisions are also made at that layer although the decision-makers typically are different. Rather than individuals and managers in organizations, governance decisions are made by agents in government agencies, standards bodies, non-government organizations, business associations, and other stakeholders that legitimately make collective, multilaterally or bilaterally binding, decisions.

In turn, they are enabled and constrained by design decisions at the next-higher institutional layer. For example, the constitution of a nation or statutes may privilege certain forms of ownership of infrastructure networks or stipulate the mandate of regulatory agencies. Constitutions are typically designed so that they can only be changed with qualified majorities, adding additional inertia to change at this layer. At the highest layer, most characteristics are emergent. Emergence refers here to not explicitly intended or unexpected characteristics or behavior of the system. Although the notion of emergence is subject to much debate, see for example [Kroes, 2009] and [Mayntz, 2008a], it is helpful in contrasting the deliberate design decisions at lower levels with the non-deliberate outcomes and the resulting unpredictable behavior at higher levels. However, the source of what is labeled "emergence" may just be lack of thorough system knowledge; more complete theories and models may allow explaining these phenomena.

Table 2 documents, in an exemplary fashion, elements of the matrix of design decisions that arise at the various layers. The fact that such design choices exist

Table 2. Design decisions and emergence in socio-technical systems

Time scale	**Social subsystem**	**Technical subsystem**
Embeddedness *Mostly emergent*	Tacit conventions and prior decisions	Tacit conventions and prior decisions
Institutional environment *Emergent/deliberate*	Division of powers; assignment of jurisdiction; legal framework; general definition of property rights	Selection of standards, technology selection architecture
Governance *Deliberate/emergent*	Ownership; form, organisation, and methods of regulation; market design (entry, number of licencees, etc.	Design of specific technical artifacts, protoocls and routines to govern operational decisions
Operation and Management *Deliberate*	Regulation of prices and conditions, antitrust enforcement, social regulation	Execution of operational decisions

does not mean that they are actually made in a deliberate way, as they may also be done in routine or spontaneous fashion. Nor does it imply that they are in any form optimal. With each piecemeal choice, the conditions for subsequent decisions are being altered. These alterations may be reversible, reversible at a cost, or fully irreversible. Unless a decision is fully reversible, past choices will constrain the options for future decisions. The space of theoretically possible design options ranges from one, for instance if a chemical process works only in one particular way, to many alternatives, for example, with regard to the topology of networks or the organization of the governance of infrastructure services. Due to the constraints imposed by the components of the socio-technical system on each other, only a subset of this theoretically possible space is within the realm of feasible choice options.

From that space, specific choices are made that, taken together, constitute a specific configuration of socio-technical design choices. To make these choices, an understanding of the working of the system and normative criteria guiding the design, such as efficiency or robustness, are necessary. However, as all purposive decisions are made in social settings, the process of decision-making and the participating stakeholders will also influence the outcomes. A rich political science literature explores these effects (for an overview see [Sabatier, 2003] and for an integrative analytical treatment [Tsebelis, 2002]). In the social domain, the combination of choices forms a particular *institutional arrangement* (or institutional design). In the technical domain one could refer to a specific *technical arrangement* (or artifact design). Taken together, social and technical design realizations form a highly differentiated and complicated *socio-technical arrangement* (socio-technical design) with corresponding unique performance characteristics.

INTERMEZZO 1

The Port of Rotterdam, The Netherlands, 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. In order to safeguard the competitiveness of the cluster as a whole, it is important to reduce the dependency on fossil fuels by increasing feedstock flexibility [Herder *et al.*, 2008].

As a solution to the feedstock inflexibility problem an industrial cluster feeding on synthesis gas has been proposed and designed [Stikkelman *et al.*, 2006]. Synthesis gas (or syngas in short) is a mixture of carbon monoxide and hydrogen and is widely used for methanol and ammonia synthesis. Syngas is produced by gasifying carbon-containing feedstock such as coal, biomass, organic waste, crude oil, and natural gas.

In addition to serving as a generic feedstock to power plants, hydrogen and carbon monoxide are important building blocks and intermediates in the petrochemical industry. Moreover, syngas is the main feedstock to produce Fischer-Tropsch liquid transport fuels: in stead of refining crude oil to create petrol and diesel, these fuels are chemically synthesized from the building blocks in syngas. The designer fuels contain less to no sulphur and hence are more environmentally friendly than conventional diesel and petrol. Carbon monoxide and hydrogen also find other applications, for example in the direct reduction of iron, in which iron ore is reduced to metallic iron without using energy intensive blast furnaces.

It is obvious that for the design of this energy infrastructure, the physical as well as a social subsystem has to be designed, and that both subsystems can be considered to be complex (with emergent behaviour, deep uncertainty, strong interaction between physical and social subsystem, many actors). Referring to Table 2, only the “Operation and Management” level and the “Governance” level are addressed in this design.

In the proposed physical system’s design, which is approached from a technological determinism’s framework more than from a social shaping theory, network topologies such as ring, central bus and star networks can be considered. For the governance of this system, three archetypical structure types can be recognized: hierarchy, market or network structures. After confrontation of the physical with the social subsystem choices, a central bus system with a network governances structure was chosen as the basis for further design activities [Apotheker *et al.*, 2007]. The final proposed design consists of a *double* bus network, with two different qualities of syngas, due to technical “Operation and Management” (lowest level, Table 1) considerations.

The economic subsystem for this energy infrastructure (i.e. local syngas market design) comprises transaction systems through bilateral contracts or syngas trading on a syngas spot market. These design options are restricted by the technical design choices made, such as the double bus topology and the qualities of the syngas.

Finally, applying Hughes' theory on the development of large-scale systems and moving to larger time-scales in Table 1, it is obvious that the initial stages of the development of this energy infrastructure are shaped by engineers and entrepreneurs. Network topology, syngas qualities, decisions to design and construct large-scale gasifiers to produce syngas are among the most important decisions. Then, when the production and use of syngas takes off, the energy infrastructure may slowly expand and evolve mainly by its own momentum.

3 FRAMEWORKS FOR THE DESIGN OF SOCIO-TECHNICAL SYSTEMS

This section reviews several approaches that have been or could be used to design functional aspects of socio-technical systems (we will not discuss aesthetic design aspects). We briefly discuss, *inter alia*, constrained optimization approaches, systems approaches, and complexity theory. These approaches are not mutually exclusive but often complement each other. They differ with respect to their disciplinary foundations, their paradigmatic structure (the methods used and questions asked), their basic stance with regard to the possibility of deliberate socio-technical system design, and the specific forms in which such designs can be realized. Socio-technical design issues often pose "wicked" [Rittel and Webber, 1973; Conklin, 2006], poorly defined and evolving problems. One way to address them is to narrow the problem space until design issues can be formulated as simpler problems ("puzzles"). As this will not always be possible, reliance on dynamic adaptive approaches may be the only workable approach.

3.1 Constrained optimization approaches

A wide spectrum of methods to solve engineering and social design issues can be considered constrained optimization approaches. These methods have in common that a complicated and unwieldy problem is reduced to a manageable scale by focusing on variables that can be controlled or influenced. Other relevant factors are treated as independent, exogenous variables. Constrained optimization then maximizes or minimizes an objective function subject to possible values of the independent variables. In socio-technical systems nearly all decisions are constrained rather than unconstrained optimization problems. Constraints arise, among others, from physical features of the artifact; information constraints of the decision makers (incomplete information, asymmetrically distributed information, various forms of uncertainty); limitations of the decision-making process; constraints imposed by the multiple layers of socio-technical systems on each other; and constraints emanating from past choices that are not fully reversible. It may be possible to use the simplifying (methodological) assumption that some of these exogenous factors do not change to explore relations between limited numbers of them (*ceteris paribus* clause). Various mathematical and other tools, ranging from linear and non-linear programming to computational modeling and scenario analysis can be utilized in developing solutions to constrained optimization problems.

In this framework, a design (an engineering design, an institutional design, etc.) is effective if it is necessary and sufficient to cause a desired or prevent an undesired outcome. Sufficiency implies that, whenever a design is present, a certain outcome is also observable. Necessity means that this particular design can be observed whenever an outcome is present; however, it may also have other effects. This approach was elegantly formalized by Tinbergen [1952] and Theil [1964] for the field of economic policy. However, it can be restated to represent the essence of the constrained optimization approach to the design of socio-technical systems. Adopting the notation of Eggertsson [1998] the approach may be represented in the following way. A generic socio-technical design decision has four aspects: an objective function, a model of the system to be influenced, design variables, and factors external to the system. The objective function $W = W(x)$ expresses societal preferences and/or engineering goals. The most general interpretation is that W captures the overall valuation of different states by society, in other words, a social welfare function.

A model of the system $x = f(a, z)$ specifies theoretical and empirical relations between instrument (design) variables a, outcomes x, and variables z that can be considered external to the system. Such instruments could be policy measures under the discretion of a policy-maker. For example, a regulatory agency may set the price for use of the electricity transmission grid or for access to local telecommunication networks. These instrument variables are part of a larger set of available choice options $A (a \in A)$ that typically also include other instruments not relevant for a specific case. The external variables and parameters z are those aspects of the system that cannot, at a specific point in time, be controlled by the decision maker and are hence treated as exogenous to the design decision.

For many short-term decisions, in particular at the operational level, z will include the characteristics of the installed technology base and the existing institutional setting. In the medium and long-run, technology and institutional arrangements will be at least partially endogenous, shaped by design choices. Depending on the structure of the problem, different methods, including analytical or computational methods, will be best suited to determine the values of instruments that maximize the objective function $W(x^*)$. x^* are the desired, optimal outcomes that maximize the respective objective function. The goal of socio-technical design is to find optimal instruments a^*, which are dependent on desired outcomes x^* and given external conditions z. More formally, $a^* = g(x^*, z)$, that is, the choice of a^* generates outcomes x^* that maximize the objective function $W^* = W(x^*)$ given the external conditions z.

The constrained optimization view often tacitly assumes a division of labor between policy-makers, who determine $W(x)$ and experts, who reveal the relevant theoretical and empirical relations $f(a, z)$ and assist in the choice of the optimal policy instrument(s). In practice, this separation of roles is rarely maintained as experts are involved in setting goals and even the choice of instruments is not value-neutral (as claimed by many proponents of the means-end paradigm, which is one particular expression of the constrained optimization approach). This framework is often expressed in a mechanic and deterministic way [Morçöl, 2002] but it can also be formulated in a probabilistic fashion to reflect incomplete information and uncertainty [Morgan and Henrion, 1990]. The default assumption is that it is possible to control and steer a socio-technical system. However, in principle the approach also allows for situations in which no sufficient instrument is known or where not all the necessary conditions for successful control may be met. In this case, the design problem has no known workable solution.

More recent contributions have modified the basic model to take complications, in particular in the social subsystem, such as incomplete information, uncertainty and opportunistic behavior of agents, into account. These approaches abandon the view of policy makers and social designers as omniscient, omnipotent, and benevolent actors [Dixit, 1996]. Rather, all stakeholders are seen as motivated, at least in part, by their own self-interest. Under conditions of imperfect information, principles (e.g., policy-makers) typically have different information available than agents (e.g., managers of a regulated firm). A key challenge for design is to devise governance structures and processes that are incentive compatible (that is, truthfully reveal information only known to them). In this newer literature, in particular the research on mechanism design, the design of instruments and institutional arrangements becomes a more complicated, but not an impossible problem (e.g., [Hurwicz and Reiter, 2006; Laffont and Tirole, 1993]).

One of the potential shortcomings of the approach is the assumption that the regularities underlying the working of the socio-technical system are immutable. This may be correct with regard to fundamental physical and possibly some social laws but is at least questionable with regard to other aspects of design, as deliberate choices, in particular at the upper layers of the system, often are made with the intent to *change* the working of the system. Institutional theories in the social sciences have long recognized the problem that individual decisions or markets are embedded and enabled by complex systems of tacit and formal rules (see, for example, [North, 1990; Ostrom, 2005; Greif, 2006; Zak, 2008]). Another aspect of this debate is the notion of performativity in economic sociology, pointing out that the world represented in theories and models is itself shaped by measures based on such theories [Callon, 1998; Aspers, 2007]. Seen from this perspective, the constrained optimization view does not pay sufficient attention to the fundamental endogeneity of the workings of social systems. However, in spite of these weaknesses, the model may be a workable approximation to find improvements over the status quo ante in situations that can be dealt with in a piecemeal way.

3.2 System approaches

Since the 1940s, social scientists and engineers have looked at the effects of *large-scale technology.* Beginning with critical studies like those by Mumford [1963; 1967], the initial focus was on the uncontrollability and potentially devastating impact of large technology. Later the emphasis shifted on questions of whether social or technological forces were prime movers and the controllability of socio-technical systems. Technological determinism and social shaping theory constitute nearly opposite positions, claiming a dominant effect of either the technical or the social subsystem on the trajectory of the entire socio-technical system. Proponents of technological determinism assert that the evolution of technology, which is largely seen as a discovery of existing laws and processes, determines social structures [Chandler, 1995]. Social structures and processes can only adapt to successive generations of technology. In strict versions even the design choices in the technical subsystem are limited, as they follow from the technological principles. In less radical formulations, technology allows design choices but these technical choices, in turn, determine the evolution of the social subsystem.

Social shaping theory, on the other hand, emphasizes the decisive role of social factors in the evolution and in particular the application of technologies [MacKenzie and Wajcman, 1985; Williams and Edge, 1996]. It is argued that technologies are always socially embedded and that critical choices emanate from the social subsystem. Much of social shaping theory focuses on the role of the state and government. However, the influence of social factors is also, for example, seen in the organization of R&D, standardization, and the development of applications and services. Whereas technology is not irrelevant, it is malleable and strongly shaped by social forces. This approach was further developed in the now highly popular science and technology studies (STS) school, which considers social and technological factors as a seamless web of interrelationships [Bijker, Hughes, and Pinch, 1987].

A middle ground in these discussions is occupied by theories originating from the study of large technical systems and the factors influencing their course [Hughes, 1983; Mayntz and Hughes, 1988; Hughes, 2004; Mayntz, 2008c]. In Hughes' model, design choices by engineers and individual entrepreneurs are decisive during the early stages of the development of a large technical system. As the system expands to ever wider geographic reach it develops its own inner logic ("momentum") and design choices are less influential. The approach offers a useful metaphor and organizing framework to examine the evolution of network infrastructure industries (see the discussion in [Joerges, 1988] and [Sawhney, 2001]). Subsequent studies found that the specific historical trajectories of large technical systems do not seem to follow just one pattern but that different paths exist for different infrastructures and different contexts [Joerges, 1999]. Earlier approaches to the theory of large technical systems did acknowledge but not fully integrate the interaction between the technical and the social subsystems. For example, Hughes [1983] explores the interactions between technical artifacts and the social system. Perrow [1994] is even more explicit in his attention to the social aspects and in particular the role of interests and power. More recent approaches have explicitly integrated the role of agency and contexts in influencing outcomes (see, for example, [Sawhney, 2003; Ottens, *et al.*, 2004; Geels, 2005]).

Comprehensive system thinking dates back to writers in the eighteenth century, who compared societies to organisms (e.g., [La Mettrie, 1748/1912]). Cybernetics [Wiener, 1948] inspired Parsons' [1951] structural functionalism. Further attempts at a systematic theory were made with general systems theory [Bertalanffy, 1968] and mathematical systems theory [Mesarovic and Takahara, 1975]. In Germany, Luhmann [1995] and his collaborators developed a unique version of systems theory with a strong emphasis on communication processes within and between subsystems. All these approaches have in common that the reproduction of the system imposes certain functional requirements. Effective design is only possible in as far as it is compatible with system logic and functional requirements [Schneider and Bauer, 2007]. Systems models attempt to understand the dynamic processes generated by the interaction of component subsystems, which in turn may consist of interacting subsystems. In that sense they are a good match to the problem structure of multi-layer systems found in socio-technical systems. Whereas system theory is not predominantly a theory of design, its insights can inform the actions shaping socio-technical systems, at least at a conceptual level. For example, it points out that differently structured systems may yield similar overall performance characteristics ("functional equivalence", see [Ropohl, 1999]). This would suggest that no overall superior design of a socio-technical infrastructure system, for example, a fully deregulated market organization, may exist. Rather, alternative approaches will have different implications for system performance.

The notion of *System-of-Systems* (SoS) is another response to the need to better capture the social aspects of technical systems and to better account for actor behavior in socio-technical systems [Sage, 2001; DeLaurentis, 2004; Boardman, 2006]. The SoS concept is not just a "box-in-a-box" model. DeLaurentis [2004] argues that SoS have the following three traits that distinguish them from regular systems: (1) they are geographically distributed; (2) their overall functionality is primarily dependent on linkages between distributed systems; and (3) the systems are heterogeneous, especially because of the inclusion of sentient systems, such as thinking and evolving individuals or organizations. The SoS paradigm requires designers to consider the system that is studied or designed from a higher system level, i.e. the upper layers in Table 2, since these are the layers where impacts of changes at the lower layers of the system are most prominently observed.

An important consequence of the system's heterogeneity is that higher system levels often display unpredictable behavior. Decision making and designing in the SoS paradigm requires an approach that cuts across various domains, combining, for instance, economic decisions with engineering design and policy making without losing the strengths of either modeling domain [De Bruijn and Herder, 2009]. Currently, an important bottleneck for proper SoS design is the lack of a common framework or lexicon [DeLaurentis, 2004]. Using a common lexicon will allow designers to switch perspectives in a timely fashion instead of trying to force the paradigm of one domain into the straight jacket of another one. Agent-based modeling and "serious games" are emerging SoS modeling and design tools [De Bruijn and Herder, 2009]. As relatively new methods, the first tends to oversimplify actors' behavior in the SoS whereas serious gaming is likely to unduly downgrade the engineering complicatedness of the SoS.

3.3 Complexity theory

Complexity theory originated in the physical and biological sciences and was successively applied to social systems in an attempt to understand dynamic processes which were difficult to explain with prevailing equilibrium models [Rosser, 1999; Beinhocker, 2006]. It has only recently been applied to problems related to the governance and design of socio-technical technical systems (see [Longstaff, 2003; Mitleton-Kelly, 2003; Cherry, 2007; Schneider and Bauer, 2007; Bauer and Schneider, 2008; Duit and Galaz, 2008]). Scholars in this tradition recognize that such systems can operate in different states. For example, Kauffman [1993; 1995] distinguishes order, edge-of-chaos, and a chaotic state. Orderly regimes can be stable or oscillate between two or more positions. Whereas orderly regimes are predictable, the state of edge-of-chaos and chaotic regimes cannot be forecasted with accuracy. Nonetheless, the general position of the system may be known [Morçöl, 2002, p. 156]. Complex systems may undergo phase transitions. Orderly systems may become chaotic; conversely, chaotic systems can become orderly. Complex systems often exhibit non-linear dynamic behavior. They show a high degree of diversity and agents in the system are connected via multiple flows over networks of nodes and connectors [Holland, 1995; Colander, 2000; Axelrod, 1997]. This may lead to emergent behavior, i.e. overall complicated system behavior that transpires out of simple lower system level behaviors and rules.

In socio-technical systems, complexity is introduced predominantly in the social subsystem but it also may be found in the engineering aspects. Due to the multiplicity of links in complex adaptive systems, the limited ability of actors to influence the overall conditions of the system, the adaptation of actors to changing system conditions, and the unpredictability of the system, effective socio-technical designs are difficult if not impossible to determine. As designs and interventions are rarely based on a full understanding of all the relevant interactions and dynamic effects, specific choices often also have unanticipated effects. Only in rare circumstances ("leverage points") will it be possible to design and implement effective comprehensive designs although even in these cases the full implications of choices may only be realized in hindsight. One of these leverage points is the overhaul of the legal and regulatory framework of a sector ("constitutive moments", see [Starr, 2004]). In most other conditions, specific designs will at best "nudge" the overall system in the desired direction [Brock and Colander, 2000], with the overall effect modified by positive and negative feedbacks.

The complexity lens does not necessarily provide radically new and different answers to the problem of socio-economic design but it contributes additional insights. It has not yet developed a fully articulated prescriptive framework for the design of systems. Although the notions of unexpected outcomes and non-linear phenomena are common in traditional engineering disciplines (see [Kroes, 2009]), complexity theory broadens this perspective considerably. Like system theory, it highlights the importance of the overall rules, within which a sector evolves, on its performance, without claiming that there is one preferred set of rules (e.g., an "unregulated" market). Complexity is a matter of degree. If an industry is in static equilibrium or in a steady state expansion path, insights gained from complexity theory would converge with the results of constrained optimization models. However, if these conditions do not hold — and recently deregulated infrastructure industries are most likely not in such an equilibrium state — it points to aspects that are often overlooked by other approaches.

The emphasis on unpredictability challenges traditional notions of design. In extreme cases, purposive design will not be possible. The theory of complex adaptive systems does, however, yield insights that can be used for the design of systems even in these situations. First, it contributes to the design process, where it encourages designers to systematically model all feedback effects and tenaciously look for possibly overlooked interrelations that might cause unintended consequences. Such systematic explorations are greatly facilitated by computer-based modeling techniques (e.g., [Koza, 2000; Sherman, 2000; Sawyer, 2005; Epstein, 2006]). Second, if alternative designs are available, it encourages such choices that create more resilient systems that can rebound from "normal accidents", in particular in tightly coupled systems [Perrow, 1994] or by designing more modular organizations, processes, and products [Perrow, 2008]. One well-known example of the success of such design is the global Internet (see Intermezzo 2, p. 615).

Third, the theory of complex adaptive systems identifies several processes to improce performance ("fitness" in the terminology of [Kauffman, 1983; 1995]). An "adaptive walk" strategy varies single features of the design and observes its effects on system performance. Only changes in design that improve performance are retained. Such strategies will gradually approximate a local optimum but may be insufficient to reach an alternative, possibly superior optimum if it would require incurring temporary efficiency losses. For example, realizing a more efficient overall energy supply system may require short-term inefficiencies during the reorganization of the system. In such cases, "patching", the assignment of tasks to distributed units combined with some overarching coordination mechanism, might be a feasible strategy. For example, federalism can be considered a form of a patching mechanism: individual states may serve as laboratories for new policies from which a federal government can then pick successful approaches that are applied to the whole system [Cherry, 2008]. Such an approach may have desirable properties and enable the system to reach higher than just local optima.

INTERMEZZO 2: DESIGN AND EMERGENCE IN THE INTERNET

The Internet is a multi-layered global network of networks. Its physical base is a heterogeneous and diverse set of specialized and general purpose communications networks. These comprise, for example, global, regional, and national backbone networks as well as local access networks. Whereas the backbone networks are fast digital electronic and/or optical networks, a larger variety of technologies is used in the access networks. Such access platforms can range from traditional twisted pair telephone lines (limited to fairly low access speeds) to various forms of wired and wireless broadband technologies allowing much higher data rates. Important wireline access technologies include digital subscriber line (DSL), cable modems, and fiber optical networks. Wireless access technologies comprise mobile, nomadic, and stationary platforms. This multitude of technical means of communications is integrated into a seamless, end-to-end, web by logical protocols — most importantly the TCP/IP suite of protocols — that reside on these technical artifacts.

During its initial stages, although funded from government sources, the conventions at the heart of the logical Internet infrastructure emerged from voluntary forms of coordination among the pioneers of computing and data communications. Design choices, such as the end-to-end principle (resulting in a network that is essentially a dumb information transport infrastructure allowing the "intelligence" and applications to reside on the fringe of that network) or the numbering conventions of nodes on the network, were pragmatic responses to specific problems. As the network grew beyond a limited number of nodes, these early design principles were retained and shaped the rapidly expanding network. When the initial government operated network in the U.S. was privatized and increasingly operated by commercial enterprises in the 1990s, the informal governance mechanisms of the Internet were augmented by a more formal structure [Mueller, 2003].

Initially, this was achieved with the creation of the non-profit, U.S.-based Internet Corporation for Assigned Names and Numbers (ICANN). ICANN is assisted in its tasks, which include technical and operational aspects of the Internet as well as numbering and domain name conventions, by two supporting organizations, the Address Supporting Organization (ASO) and the Domain Name Supporting Organization (DNSO). Domain name administration is accomplished at the operational level by many private sector registrars. These are coordinated by five Regional Internet Registries (RIRs) such as RIPE for the European region or AfriNIC for Africa, which, in turn, cooperate in the Internet Assigned Numbers Authority (IANA). In the two U.N. sponsored World Summits on the Information Society (WSIS) in 2003 and 2005, a new global governance structure was added, assigning policy development to the Internet Governance Forum (IGF), which is organized as a multi-stakeholder policy dialogue.

The Internet is also affected by design choices at the level of the supporting access networks. Operational choices are made by a large number of commercial firms, non-profit organizations, and government operators. These are in varying degrees regulated by national regulatory agencies, regional bodies, such as the European Commission, and international agencies such as the International Telecommunication Union (ITU) or the World Intellectual Property Organization (WIPO). These organizations cooperate with national organizations directly in working groups that define standards and operational principles as well as in policy-setting regional and global conferences, whose results are adopted with modifications into national laws and regulations. Content traveling on the Internet is furthermore heavily influenced by national political systems and laws governing the freedom of speech. Moreover, it is shaped by increasing concerns about information security [Zittrain, 2008].

The resulting socio-technical system was and is thus shaped by many decentralized decisions, coordinated and integrated at different layers of the system. Decisions at higher levels initially resulted from bottom-up forms of coordination. As the Internet grew in complexity, increasingly higher levels of governance were added adding a top-down direction of governance. In this process, past choices created many forms of path dependency, influencing subsequent choice options. The overall system emerges from these sequences of decisions but no single actor or group of actors controls the overall evolutionary path.

3.4 A comparative assessment

These theories have widely differing consequences for the design of socio-technical systems. The dominant constrained optimization approach tacitly assumes that socio-technical systems can be controlled and that sufficient solutions to a design problem can be found and implemented. Depending on the diagnosis of the primary problem different solutions or mixes of solutions will be devised. Systems and complexity approaches are more cautious as to whether socio-technical systems can be fully controlled. Design of such systems is seen as an adaptive, incremental process, plagued by unanticipated events. Nevertheless, even these approaches see considerable room for deliberate design of social and technical aspects and the improvement of designs in physical and virtual (simulated) trial and error processes. With few exceptions it is typically recognized that design decisions are made under limited information and will have to be adapted as effects become visible and/or external conditions change. To realize overarching public values, SoS and in particular complexity approaches tend to see a larger and more effective role in designing the meta-conditions, the “order” of a sector rather than specific interventions at the operational level of socio-technical systems as manifested in the institutional and governance layers of the system as described in Tables 1 and 2. All approaches see ample room for artifact design.

The constrained optimization approach may have been a reasonable simplification while infrastructure systems were organized as (state) monopolies. This setup gave social planners and designers broad control over the course of the industry. Even if planning and design mistakes were made, it was usually possible to come up with consistent approaches (if at the price of lower efficiency and higher cost). The reforms that started in the 1960s in the U.S. and in the 1980s in other parts of the world have replaced the historical monopoly approach with a more open and competitive market environment. These measures have also complicated the coordination requirements and, for various reasons, reduced the effective control span of any of the players, including policy-makers. Socio-economic design decisions in the new environment will be made in a sequence of more partial and limited decisions. Only if the overall design problem can be segmented in a way such that every incremental local improvement will also contribute to improvements in the global performance of the system will the constrained optimization approach yield reliable outcomes. In general, the new reality of socio-technical infrastructure design is better reflected in multi-stakeholder system models and complexity theory. In practice it is also reflected in a shift from outcome-oriented forms of design to process-oriented forms of designing both institutional and technical system aspects.

4 NORMATIVE FOUNDATIONS, DESIGN GOALS, AND IMPLEMENTATION

The previous section has identified overarching frameworks and explored whether and to what extent socio-technical systems can be designed and controlled. None of the reviewed approaches rejects the notion that deliberate choices can be made to design aspects of socio-technical systems although they diverge with respect to the ability of agents to influence the overall system and its dynamics. As purposive acts, design decisions are necessarily based on visions of the goals that should be realized [Bromley, 2006], even if that vision may not be articulated fully, and how it should be realized. This section reviews selected design goals and associated design/decision variables for socio-technical systems as formulated by engineers, economists, lawyers, and social planners. We also briefly discuss the relations between these goals and how possible tensions may be reconciled, if at all.

4.1 Overarching objectives

Design goals area formulated in multiple ways and amalgamated into more or less coherent systems of objectives. In infrastructure industries, important overarching and specific goals are settled in a political and social discourse, typically by players with different information and power to influence the outcomes. Such "public values" reflect a "normative consensus about (a) the rights, benefits, and prerogatives to which citizens should and should not be entitled; (b) the obligations of citizens to society, the state, and one another; and (c) the principles on which governments and policies should be based" [Bozeman, 2007, p. 17]. In that sense, public values rather than the more ambitious and vague notion of the "public interest" reflect the guiding visions of a social entity, such as local communities, regions, nations or a super-national regimes. Public values are not stable but change over time in response to general societal values, technological change, and stakeholder interests.

Public values have a dual nature: they provide orientation but they may also be invoked opportunistically to justify actions that are motivated by private and special rather than public goals. Infrastructure industries, like other social and economic activities, abound with such opportunistic behavior of all private and public stakeholders (see [ten Heuvelhof *et al.*, forthcoming] for a more extensive discussion). Because of opportunistic behavior and the limitations and challenges of socio-technical design, the practical implementation of public values and their specific operationalization may deviate from the intended effects. In that sense, socio-technical designers may fail to achieve stated and consented public values. This should predominantly be judged based on the outcomes of specific design choices rather than expressed motivations.

Table 3 summarizes important specific design goals. Some of these goals are derived from public values and the associated public discourse. Part of this discourse draws on the findings of disciplines relevant for socio-technical design, such as engineering, economics, and law. Contributions from these disciplines are particularly important when broader goals (such as equitable supply) are operationalized as more specific objectives (for example, a specific universal service funding model). Economics enjoys a unique position among these disciplines. Many social and engineering decisions can be framed in terms of the benefits and costs associated with a specific course of action. Therefore, the economic approach offers a generic framework capable of dealing with engineering and social design issues in a unified framework.

At least in principle, as long as a problem can be expressed in benefit-cost terms, economic analysis can deal with quantitative and qualitative aspects of socio-technical decisions in a commensurable way. Each engineering optimization problem has a dual economic optimization problem. Likewise, each solution to a social design problem has economic consequences and can also be expressed as an economic optimization problem. With the normative concepts of efficiency and welfare optimization, economics also has broad yardsticks to access design outcomes. Consequently, economics has played a major role in the infrastructure reform debates of the past decades. However, despite its theoretical elegance, in practice economic reasoning has serious limitations due to the ubiquitous prevalence of uncertainty, incomplete information, and the intangible nature of some public values that is often too elusive to determine costs and benefits. If costs and benefits cannot be expressed in monetary terms other forms of multi-factor optimization can be employed.

4.2 Specific design goals

From an engineering perspective, multiple specific design goals have been formulated, many of them related to the fundamental importance of the services of socio-technical infrastructure systems for society. These include technical efficiency, robustness, flexibility, safety, stability/security, resilience, modularity and controllability. Technical efficiency refers to the rate of the artifact to transfer

Table 3. Typical design goals and variables for socio-technical systems

	Technical <————————————> Social		
	Engineering	**Economic**	**Legal/Politicial**
Typical design goals	• Technical efficiency • Robustness • Flexibility • Safety • Stability/ security • Resilience • Modularity • Controllability • Sustainability	• Efficiency (technical, productive, allocative, dynamic) • Adaptability/ resilience • Stability/ security • Universality • Sustainability • Control of market power	• Constitutionality • Legality • Accountability • Transparency • Justice • Equity • Universality • Control of political power
Typical design variables (examples)	• Technology • Network topology • Capacity/ throughput • Feedstock • Dimensions • Material • Standards • Operating conditions	• Market design • Product/service • Production method • Price regulation • Organization of regulation • Competition law	• Laws • Regulatory framework • Rights and obligations • Basic rights system • Universal service obligations/ fund • Divestiture of assets

inputs into outputs, for example the processing of gas into electricity, or the transformation of voice into a digital signal. Through technology selection and the choice of the right operating conditions, this efficiency is typically maximized, whereby other design goals are often treated as constraints. The productively efficient (lowest cost) solution can be found among the technically efficient solutions, by assessing inputs and outputs at their economic value.

Robustness and flexibility are concerned with the system's capability to respond to changes in its environment. Robust systems, realized for example by over-dimensioning an artifact, are able to continue functioning in the new environment without changing their inner layout, technology or workings. Flexible systems on the other hand respond and adapt to the changed environment, for example by changing operating conditions. Over-dimensioning may result in problems of high sunk costs (costs that cannot be recovered should a project be terminated). One way to adapt the system without being trapped by large sunk cost is by introducing and selecting the right standards, as standardization allows for modularization. Systems that are built from smaller modules can be changed and replaced and upgraded relatively easy without having to upset the entire system. In modular design, the most efficient way of interfacing is through the use of standards. Most of these goals relate to the operations and the design of the technical artifacts but some may require complementary social arrangements to be implemented effectively. For example, standardization might best be pursued if a standard, once developed, is mandated rather than adopted on a voluntary basis.

The design of socio-technical systems is also strongly influenced by goals originating in political science and jurisprudence. The most important of these goals include constitutionality, legality, accountability, transparency, justice, equity, and universality of access. These goals have process-oriented aspects as well as substantive aspects. For example, constitutionality of an arrangement may imply that it corresponds to the substantive provisions of the respective constitution (e.g., with respect to the taking of private property in pursuit of public interest goals) or it may have procedural requirements (e.g., that a measure is formulated following constitutionally prescribed processes). Legal objectives are of particular importance for the design of the organizations entrusted with developing specific policies for socio-technical systems (e.g., regulatory agencies, ministerial departments, competition authorities). Designing the overall legal and regulatory framework (the "order" or "constitution") of a market and an entire economic sector is one of the most important design tasks confronted presently in socio-technical systems. The school of constitutional economics has devoted particular emphasis to these issues (see [Vanberg, 2005] for a succinct discussion of the position) although it tends to underestimate the role of the other components of the socio-technical arrangement.

Much of the regulatory reform debate, which is predominantly directed to redesigning the social framework of infrastructure industries, is based on economic concepts. Important goals stated by economists for the design of the institutional and sectoral arrangements are technical efficiency, productive efficiency, allocative efficiency, dynamic efficiency (innovation), adaptability/resilience, stability/security, universality of access to services, and sustainability. Some of these goals overlap with engineering objectives. This is not surprising, as many economic goals will either have to be implemented using a specific engineering solution, or can be achieved by choosing from engineering and economic solutions. Unless a technically feasible and cost-effective engineering solution is available, economic policy proposals are futile. Productive efficiency refers to producing any given output with the least-cost combination of inputs. Allocative efficiency requires, intuitively stated, that the mix of goods and services produced matches their valuation by consumers. Dynamic efficiency refers to the innovation rate in a system and the associated inter-temporal resource allocation decisions.

Economists have traditionally focused on these efficiency goals and subjugated all design decisions to meeting these criteria. It is a fundamental theorem of welfare economics that under certain ideal conditions decentralized decisions by individual actors in competitive markets will optimize welfare, at least in the sense of a Pareto-optimum, a state in which nobody can be made better off without making somebody else worse off (e.g., [Friedman, 2002; Just *et al.*, 2004]). Under other conditions, for example, the prevalence of externalities, public good characteristics, the existence of natural monopoly characteristics, this result does not hold and social intervention may move the system closer to the optimum. Moreover, even if a decentralized system works in principle, forms of market deficiency may require interventions to assure certain public values, such as universality of access to infrastructure services.

Many of these policy choices will violate the relatively stringent assumptions of the Pareto criterion and have distributional impacts, hence create winners and losers compared to the status quo ante. Other welfare criteria, such as the Kaldor-Hicks compensation test have been developed (see [Just *et al.*, 2004]). The latter asks whether the beneficiaries of a decision were better off even after they were to compensate the losers of a decision (without requiring that such transfers actually take place). This is essentially the criterion underpinning cost-benefit analysis. However, as policy takes place within imperfect institutions and is implemented by imperfect actors, policy design itself may be flawed. Government or governance failure may jeopardize well-intended policy designs. Thus, under real world conditions, socio-technical design has to find an appropriate balance between imperfect markets and imperfect government.

To a large part, sector design decisions, including whether to allow competition, how to support competition in market segments with strong monopolistic tendencies, and how to define the rights and obligations of the different actors, are made based on economic rationales. These design choices should also draw on legal and other bases, including political science thinking, when devising solutions to the assignment of duties to different organizations, the organization of the processes that support decision-making on an ongoing basis, and the methods of conflict resolution to adopt. Which basic rights system should be adopted (private property, commons, or open access) and how liability rules should be defined, if any, are also fudamental decisions. In a seminal paper, Coase [1960] pointed out that the assignment and specification of rights was irrelevant in the absence of transaction costs, as negotiations would allow finding an optimal solution. However, it is now widely recognized that under real-world circumstances, where transaction costs play a role, institutional choices do matter and have direct implications for overall sector performance and evolution.

4.3 Implementation

After World War II, the predominant view was that government could control technology and social processes. However, with the failure of important programs during the 1970s, such as the fights against poverty, unemployment, and business cycles, this view was superseded by a more humble perspective, recognizing the limits to controlling socio-technical systems via government intervention. Social scientists also became more aware of the fact that, probably partially in response to government deficits, government control was increasingly complemented and in some cases replaced by other forms of social coordination, including self-regulation by stakeholders, co-regulation in which the public and the private sector collaborate, and interest group representation (e.g., in business associations and public interest groups) [Streeck and Schmitter, 1985; Latzer, *et al.*, 2002]. The focus shifted from government to governance, an umbrella term referring to these multiple forms of purposive social coordination. In these emerging arrangements distinguishing between the object and the subject of governance is more difficult [Mayntz, 2008c].

In addition to the changes in the forms of local and national governance, socio-technical design issues affecting infrastructure industries are increasingly addressed at super-national regional and global levels, although not all infrastructure industries are internationalized to the same extent. A wide range of global agreements and governance arrangements exist in information and communications infrastructures and transportation but in other areas, such as energy, more limited multilateral and regional arrangements continue to prevail. Regional organizations like the European Union have become strong players shaping infrastructure networks as have global organizations such as the International Telecommunication Union (ITU) or the World Trade Organization (WTO). At that level, it is even more complicated to identify the object and the subject of design decisions. For example, in intergovernmental organizations, the subjects and objects of decisions are identical (national governments). Many issues are discussed within the civic sector, non-governmental organizations that have no clear jurisdiction or power of enforcement [Mayntz, 2008b]. Consequently, the larger the number of players and the weaker their ability to design and control, the more likely it is that the set of policies that simultaneously meets all these requirements is small or even empty. Despite this blurring of traditional forms of government control, there is substantial evidence that large nation states remain key players [Drezner, 2007].

Against these dual backgrounds of the changing forms of social control and growing criticality of infrastructures for society, the issue of their controllability deserves revisiting. One reason for the reduced controllability is the outcome of previous deliberate design choices: in most sectors some market segments have been partially or even fully deregulated. Whereas technical and social aspects could, in principle, be collectively designed, a choice was made to curtail such planning and shift decisions to decentralized firms and users. Measures directed toward the remaining regulated parts may thus be undermined by actions in the deregulated part of the industry. This is reinforced by adaptations in technology and the market organization of infrastructure industries, as visible, among others, in the phenomenon of convergence (the provision of multiple infrastructure services by one organization and the increasing (inter)dependence between infrastructure industries). The overall trajectory of the system is hence not controlled by engineers and social planners but emerges from the interaction of multiple stakeholders.

Infrastructure industries have, therefore, evolved from a controllable monopoly system to a less controllable adaptive dynamic system [Bauer, 2004]. The explicit or implicit assumption of policy-makers was that the anticipated higher efficiencies of the more dynamic system outweigh its possible costs. Such costs include the heightened coordination requirements, the possible dynamic frictions and inconsistencies, greater difficulties of safeguarding public values, as well as the reduced ability to influence the overall evolution of the infrastructure system. The challenge for socio-technical design is to seek technical and social mechanisms that might influence the balance between benefits and costs in an advantageous way. Given the magnitude of the current reorganization, such an overall assessment is, at the time of writing, in many areas still outstanding.

Another reason for potentially decreased control is that in the new environment sustainable socio-technical designs may be more difficult to find. Sustainable policies are the subset of measures that are capable of achieving the desired goals, are politically feasible, and economically viable. In other words they must be compatible with the constraints and interests of all stakeholders [Cherry and Bauer, 2004]. In a multi-stakeholder environment it is more difficult to identify policies that simultaneously satisfy all relevant constraints. This does not mean that policies and other design solutions will not be adopted at all but it increases the likelihood that challenges to policies will happen continuously, forcing decision-makers to frequently modify and adapt measures to changing circumstances and interest constellations. This difficulty may also affect finding a sustainable position with regard to the trade-off between short and long term effects of infrastructure reform. In sectors with highly durable, capital-intensive technology, the fluidity introduced by the multi-stakeholder environment may have undesirable consequences and may affect the incentives for investment and risk taking negatively. Unless appropriate adjustments are made, some of the stated goals of supporting dynamic efficiency and innovation may be inadvertently undermined due to these feedback effects. Worse, the relevant trade-offs between different goals may not be known with sufficient accuracy. In such situations, design choices will become real-world experiments with outcomes known only ex post. A design challenge is to better understand these dynamic trade-offs in advance, for instance, by using computer modeling techniques that shift the experiment into virtual design space, and to devise feasible and sustainable solutions.

Several issues arise from these transformations: First, it is important to understand whether the multiplicity of stated goals can be realized at all. Goal conflicts and incompatibilities between different aspects of the socio-technical design will have to be examined with renewed vigor to find sustainable and overall consistent solutions. Second, socio-technical designers have to find out whether issues can be addressed at one level or whether changes in one area require cascading adjustments in related areas and thus can only be effectively addressed at multiple levels (as distinguished in Table 2) simultaneously. This has immediate implications for social and engineering design choices and the ability to implement them. Goals that can be realized at an individual layer call for different design approaches than those that require action at multiple layers. In some cases, for example, information security, meeting the goal at the individual firm level also implies that the goal is met at the sector level. Design can therefore focus on the individual firm level. This does not exclude that additional benefits might be realized by coordinating approaches also at a higher layer. In some cases, the most effective level to implement a design decision may be the sector level. For example standardization is best achieved at a level higher than an individual firm.

In most cases, however, goals will need to be met at the level of the individual firm or actor and at the level of the entire industry simultaneously. Take, for example, the case of technical efficiency. The operation of an individual firm is technically efficient if it uses the least amount of resources to achieve a certain output level (or achieve the highest possible output with a given amount of resources). From individual firm technical efficiency does not necessarily follow that the entire sector is technically efficient. In fact, all individual firms could be sub-optimally small, leaving economies of scale and hence improvements of technical efficiency unutilized. Similar arguments may hold in the case of positive or negative externalities, where optimal individual level decisions nonetheless aggregate to socially sub-optimal outcomes.

Third, once the structure of the problem and the principal design responses are known, the optimal socio-technical mix of measures to implement a goal or a set of goals as well as the layer on which it is best pursued need to be determined. Design methods and processes for socio-technical systems would, ideally, facilitate such a comprehensive perspective (see also the similar arguments in [Andrew and Petkov, 2007]). In our time scale model (see Table 1), engineering objectives will often be pursued at the operational and governance level. During the time of monopoly organization, many public values, such as non-discriminatory pricing across geographic regions, used to be pursued at the operational level. However, the more decentralized market organization that emerged during the past two decades does curtail many forms of effective control at that layer.

As a consequence and also in response to new political visions as to the appropriate role of government in the economy (a change that has sometimes been identified as a move from government to the regulation state) economic design decisions are now more often located at the second, governance layer. Legal goals are most often implemented at the second and third layers, the governance and institutional layers. There is increasing evidence that infrastructure systems (like many other socio-technical systems and social processes) can only be governed with a multiplexity of forms and instruments. Traditional government hierarchical control coexists with other forms of governance. Due to the multiplexity of governance, the entire system is in continuous motion, ever in need of adapting to changing circumstances and outcomes.

5 CONCLUSIONS

This chapter has reviewed issues related to the design of socio-technical systems in general and of one particular class of such systems, infrastructure networks, in particular. The socio-technical systems approach was initially developed in the context of organizational studies. One of the key insights of the approach was that social and technical aspects of such systems needed to be optimized jointly. In principle, this method can be applied to the issues raised by infrastructure networks. At present, no overarching approach to designing such systems is available and a socio-technical systems approach might assist in closing that gap. However, the issues reach beyond devising a method of joint planning and design and might be rooted in inherent limits of designing large complex systems. The chapter first reviewed the multiplicity of design decisions that need to be made in such systems. Our review of alternative conceptual frameworks that might inform such choices revealed a bifurcation between theories that do not principally question the ability of planners and designers to shape socio-technical systems and theories that question full controllability.

In the first group are models of constrained maximization, which currently dominate public policy formation. However, a very influential group of scholars argues that such deliberate design is not possible, that is it a constructivist fallacy. This stance does not deny that deliberate design choices can be made and need to be made but it questions the possibility of a comprehensive, outcome-oriented planning process. Instead, it emphasizes that technical and social design is much more limited in its overall impacts. It may be most effective in creating a meta-framework, consisting of basic rules for standards, technologies, law, property, contract, and so forth, that allow decentralized, self-organizing forces to unfold. In this view, the overall outcomes and trajectory of the system are emergent, resulting from behavior at lower system levels, and cannot be fully planned or designed. Practical experience has generated ample evidence that design choices and planning can make a significant difference. Even if they may not be able to fully determine the overall trajectory of a socio-technical system, they matter and very often with serious consequences. Given the complexity of socio-technical arrangements, it is increasingly daunting to understand the correspondence between design choices and system responses. It would be desirable, to deepen conceptual and empirical knowledge of these correspondences. Not only should this assist in finding superior designs, it will also helps distinguishing situations in which deliberate design is possible and effective from those situations in which it may not be. Evolutionary models that allow for learning and adaptation are probably a promising step in this direction.

The dominant paradigm informing design choices continues to use static maximization methods. However, socio-technical systems are dynamic, evolving systems and static maximization may be dynamically suboptimal or have ambiguous short and long term consequences. Rational designers of aspects of socio-technical systems would address these dynamic trade-offs explicitly. However, due to a lack of dynamic analyses this is rarely the case. Socio-technical designers can rely on a variety of available and emerging dynamic simulation and optimization models. Presently, their use is more widespread in transportation and energy but they are more broadly applicable. Given the complex nature of socio-technical infrastructure systems, these models will often not produce *one* right answer, but may support them in better grasping the correspondences between socio-technical design choices and a range of possible outcomes. Such an approach would allow to help avoid inconsistent socio-technical designs that have plagued infrastructure reform. Moreover, it should allow identifying the range of consistent socio-technical arrangements. If these are in the set of feasible options, the approach will facilitate selection of the most appropriate designs, including robust, resilient or “no regret” courses of action.

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