Research agenda for an integrated approach to infrastructure planning, design and management

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Abstract: Building on broad discussions between many universities, this paper presents a research agenda based on a holistic, comprehensive view of the issues. It proposes that our infrastructure is a system of systems involving different technical manifestations and social organisations. The implication is that we need a fundamental reconsideration of how we look at system design, away from traditional disciplinary considerations and toward a multi-domain, multi-disciplinary effort. To this end, it proposes an agenda of:

- comparative analyses across infrastructures and political structures, that would identify commonalities and larger lessons
- creation of integrated socio-technical models that usefully describe the interactions between the technical infrastructure and its social context
- methodological efforts, aimed largely at capturing the network characteristics, both technical and social, of the infrastructure system of systems
- explicit testing and evaluation of the research through programs of collaboration with practitioners and governmental organisations.

Keywords: research agenda; critical infrastructures; engineering systems; system design.

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1 Introduction

Throughout 2004, faculty, research staff and students met to identify what a comprehensive approach to the design, planning, and management of infrastructure might look like. This effort also benefited broadly from extensive suggestions from partners beyond MIT. It represents an attempt to characterise a suitable research agenda in this field. It is presented here in an attempt to stimulate discussion that will refine and improve these ideas for our collective benefit.

2 A fundamental need

Our communities need to develop fundamental understanding of the planning, design, and management of national infrastructure systems, such as those providing electric power, transport and communications. Although our academic and industrial organisations have great expertise in system components (such as power plants, aircraft or networks) we lack experience in the design of the 'systems of systems' that constitute our infrastructure at the total societal level. We do not have really solid understandings of how their technical, political and economic factors interact, particularly in the context of great uncertainties. We need to develop this capability. We need to develop novel ways to extend infrastructure lifetimes and capacities, improve their functionality, and expand their desirable attributes at a relatively low cost.

Improving the effectiveness of our infrastructures is a salient issue. Our infrastructures constitute the physical framework within which our economy and society operate. As the backbone of modern society, their functionality determines the ability of our economy to satisfy our needs and to compete in the world. Their cost, reliability and robustness, investment efficiency, environmental impact and sustainability and flexibility to changing needs are critical to the future strength of our economies.

Modernisation of infrastructure systems is a significant challenge. New technologies offer promising opportunities for improvement. However, many infrastructures have been difficult to transform effectively and efficiently. This is not surprising. Nearly all aspects of infrastructure are organised around institutions that emerged and became codified during the late nineteenth and twentieth centuries. In general, these systems evolved via incremental changes in technology, markets and regulatory processes. As we enter the 21st century, however, each sector is facing (in varying degrees):

- discontinuous and rapid shifts in technology
- deregulatory pressures
- associated greater fluctuations in demand
- natural and human threats to operations
- unanticipated forms of competition
- impacts of information technology on the organisation and management of work
- changing societal needs and expectations (Hammer, 1996).

Can we continue to rely on incremental changes to our systems? A dramatic transformation of the scope, scale, and institutional architecture of these infrastructures may well be required. Over the next 50 years, over a billion more people will populate cities in the developing countries and require modern services. This challenge is also a tremendous opportunity to effect fundamental improvements.

3 A new approach

Despite the importance of infrastructure, we have no comprehensive theory for it, no best practice approaches for its design, management, and transformation. We lack rigorous methods for developing, evaluating, and evolving future infrastructure architectures that must incorporate legacy elements while also responding to new technologies, knowledge, and demands. The fact is, traditional academic disciplines neither motivate nor support this kind of multi-domain, multi-disciplinary approach.

Skeptics might say that the area is beyond research and codification. Infrastructures are a complex web of public and private assets, created and operated within layers of government that have varying jurisdiction over their locations, design, pricing, accessibility and general operation. How can anyone coherently address such real-world complexity?

We believe that progress can be made by changing the way we frame the issues. Good infrastructure design and operation is not solely a technical issue. In particular, the interface between technical and social considerations is poorly understood and inadequately managed at the overall level of the systems. The challenge for developing a transformative capability of our infrastructures is much broader than what technology and engineering alone can address. We need a fundamental reconsideration of how we look at system architectures and processes associated with societal infrastructures. This new form of research should be:

- *Broader* than those that has been traditionally undertaken. The impact of industry structure, policy, and economics combined with dispersed decision making and myriad stakeholders call for a systems approach with deep technical and social science perspectives. What was previously treated as context is now part of the design process.
- *Strengthened* by connections with practice. Such relationships should allow knowledge to flow between academia and practice, so that research would be informed by practical realities, while theory supports the effective transition and operation of infrastructures.
- *Seeking commonality* across different infrastructure domains. Looking at similar issues in different contexts stimulates thought and provides significant insights into both fundamental and domain-specific issues.

4 A research agenda

The implementation of the new form of research involves several complementary aspects. In our view, there are four main elements, explained in more detail in the later sections:

- *Comparative analyses across infrastructure domains*. Extensive comparative analysis should be conducted across infrastructure domains to create knowledge about infrastructure systems. These should involve experts in each domain. This research should include case studies of infrastructure transformation within each domain and comparative analysis of structural, technical, operational, regulatory, financial, political, demand, market, and other factors. It is expected that this effort will identify a number of common transition barriers and problems.
- *Creation of integrated socio-technical infrastructure models*. This activity should attempt to integrate existing disciplinary approaches relevant to the understanding of infrastructure evolution. It should help us recognise and comprehend the interconnections and feedback loops between technical changes, government regulations, private initiatives, and social actors. Such an understanding will be fundamental to enabling society to promote most effectively the development and evolution of our infrastructure. This activity will be particularly challenging.
- *Methodology development*. This effort would concentrate on formulating tools and approaches that support the effective transformation of infrastructure. Making use of focal example problems and transition barriers identified by comparative analyses, researchers should develop techniques to enhance the understanding of and communication between, the multiple decision makers and stakeholders involved with infrastructure transformation. Although we cannot specify what all these tools might be, one approach would consist of integrated simulations for evaluating potential infrastructure concepts in an attempt to develop a meaningful virtual ‘experimentation’ capability – a basic need of large-scale complex systems (Rouse and Boff, 2005).

- *Application testing and evaluation*. This line of work would test and evaluate the knowledge, technology, and methods developed in the other lines of research in the context of actual efforts to develop and evolve infrastructure systems. The results of such efforts should feed back into these other lines of work and redirect them as necessary.

5 Comparative analysis across infrastructure domains

5.1 Goal

The central goal here is to expand the understanding of the fundamental issues that drive infrastructure operation and evolution. The idea is to move beyond specific domains, such as that of electric power or road transport, while integrating the knowledge existing in them. This effort would extract and compare knowledge across domains in a way that is currently not or only hardly done. To date, very little has been done in this area; the tendency has been to focus on specific technologies, typically each associated with specific disciplines with their own paradigms (such as electrical engineers, transport specialists, etc.) Yet this effort has tremendous potential to increase understanding and offer new insights on the technological, economic, regulatory, institutional, and systemic aspects of each infrastructure domain.

The expectation is that identifying commonalities and differences across domains will help in eliciting:

- problems and opportunities that researchers can address
- quantitative and qualitative observation, including patterns of evolution, which will motivate the development of models and methods of analysis
- insights of direct use to infrastructure stakeholders
- educational material for the preparation of practitioners and future researchers.

5.2 Domain characterisation

A first step in the development of comparative analyses is to provide a uniform perspective. Groups proposing to initiate this work should thus begin with some form of comprehensive characterisation and documentation of their fields. This should be based on a number of sources including reviews of the literature within each domain; interviews with domain experts; analyses of existing operational data, statistics and standards; and case studies of transformation efforts within each domain.

Each characterisation should describe the existing infrastructure both functionally and physically. The physical description should document the various technical elements within the infrastructure and, where appropriate, similar characterisations at the local and service delivery level. It should also incorporate descriptions of infrastructure operations – nominal, off-nominal, and failure modes. The operational performance of the systems should also be measured along the several dimensions of interest, such as service delivery metrics, costs and reliability.

The organisational characterisation of the infrastructure should describe the industry structure including the owners, operators, service providers, users, regulators, and standards organisations. It should present the role of government, public and private ownership and regulatory and standard environments and the process by which regulation or standards become established. Significantly, it should identify the key infrastructure stakeholders, their capacity to influence the system, and their objectives.

The economic characterisation should define the mechanisms by which infrastructure capacity and demand are balanced, and describe market expectations and their evolution. To the extent possible, it should evaluate the relationships and dependencies between the infrastructure and the general economy.

As the past often is a useful guide to the future, researchers should investigate the evolutionary history of each infrastructure to identify details of key transformations. This analysis should identify both key barriers to transformation within the infrastructure and strategies that have been successfully used to transform and modernise the infrastructure. Case studies should identify key decision makers and influences, techniques used to identify and mitigate risks and uncertainties, and unintended consequences of prior private or public sector decisions.

Where appropriate, researchers should identify best practices for infrastructure transformation and operation. They should document state-of-the-art techniques for analysis and evaluation used in each domain. Care should be taken to define the standard abstractions used within that infrastructure (e.g., network representations), the constitutive relationships (such as continuity and connectivity equations), and analytical tools (e.g., control theory). This effort should, of course, cover both technical approaches and social science methods, such as stakeholder and market analyses.

Exogenous factors that affect each infrastructure should also be evaluated. These would include changing public goals and expectations, concerns about terrorism and security, energy costs, the environment, and international regulatory action. Finally, the emergent challenges and opportunities for each infrastructure domain should be identified.

This characterisation effort offers interesting opportunities for international cooperation. It is possible to imagine parallel efforts in Asia, Europe, North America and elsewhere, each covering complementarily the performance of their infrastructure systems. Experience with such forms of cooperative international comparisons, fairly common in the social sciences, can provide interesting and even provocative insights (Gilbert and Parent, 2003).

5.3 Cross-domain comparative analysis

Based on the domain characterisations, comparative analyses should be conducted to identify both commonalities between and unique aspects of various domains of infrastructure. The central hypothesis is that infrastructure systems share patterns that can be exploited for learning and innovation. This effort, thus, would seek to identify common elements and define the degree and limits of similarity, to provide a basis for attempts to clarify cross-cutting concepts and models of infrastructure. Obviously, there are limits to these commonalities; some aspects of each infrastructure are clearly unique.

Preliminary discussions have already identified many examples of commonality. For instance, many infrastructures are network systems that exhibit dynamic coupling effects, such as cascading failures or propagating delays. Such networks generally suffer from capacity limitations, which affect service quality and can lead to more significant problems. They also face great challenges in adapting to meet evolving demand for their services. This transformation difficulty is one of the factors which motivate widespread concern with infrastructure systems (Ilic and Zaborszky, 2000).

Furthermore, research should compare the dynamic behaviour of infrastructure, both at the operational and evolutionary time scales. Most infrastructures are complex adaptive systems that have evolved over time from countless and frequently independent decisions about specific technologies and subsystems, and in the face of constant uncertainties about future loads and performance. In this regard, the evolution of the important standards and their interrelationships in each infrastructure should be studied closely.

It should be noted that these uncertainties have become especially salient in recent years due to current trends in deregulation with its subsequent economic volatility, challenges in dealing with diverse stakeholder groups, the strong impact of standards, and the deployment of information technologies that improve capacity and enable more efficient operations. It will, therefore, be important to think about managing infrastructure evolution from the perspective of flexibility and adaptation (de Neufville et al., 2004).

Comparative analyses should examine how decision makers analyse and evaluate infrastructures from intellectual, operational, and investment perspectives. They should begin at fundamental levels and consider such basic issues as definitions of terms, standard abstractions and representations. From this base, similarities and differences in performance metrics, investment criteria and other evaluation and modelling approaches should be catalogued.

Identifying the limits of commonality and characterising the fundamental differences between these infrastructures will also be important. For example, systems variously distribute mass (transport), energy (electric power) and information (communication). It is important to understand when the commonality abstractions break down. For example, an information packet can be resent if it is lost in transit whereas an aircraft cannot.

An important output of the comparative analysis will be the identification of emergent generic problems and opportunities. This result can be used to focus the development of models and tools, as suggested in the next sections. While it would be premature to state what the comparative studies will find, preliminary thinking suggests some generic problems. These are the challenges of congestion and inadequate capacity; financing of facilities; opportunities for improved management due to enhanced real-time operability; institutional and standards 'lock-in' and understanding tradeoffs between optimality and robustness.

6 Creation of integrated socio-technical infrastructure models

6.1 Goal

The primary goal here is to contribute to the underlying knowledge base of analytical and theoretical methods to support effective infrastructure transformation. Recognising that this task is fundamentally broad and interdisciplinary, researchers should develop innovative methods that combine social, technical and economic factors using integrative frameworks such as network theory, feedback control theory, or agent-based models.

The intent is to develop methods that will enable broader and deeper understanding of infrastructures and infrastructure transformation. The models should include:

- drivers (congestion, decay, new technologies, efficiency and reliability, natural and human catastrophic events, flexibility, changing needs)
- constraints (costs, existing structure, environmental and social impacts, other externalities)
- context (government intervention, stakeholder actions, social factors, and economic-political opportunities including development of improved standards and protocols architectures).

It is important to note that whereas the context is sometimes fixed, it is often subject to deliberate design. For example, the modalities of government intervention may be shaped deliberately. Thus, much of the success (and failure) of efforts to privatise electric power markets depended on the way the institutions for organising and clearing these markets were properly designed (or not).

6.2 Research approach

To deal coherently with the breadth of the issues, research should incorporate social, technical, economic and operational concepts and considerations. It should integrate them into theoretical or modelling frameworks designed to capture the key factors influencing our capability to transform infrastructures. We envisage two research approaches aimed at understanding:

- infrastructure performance and operation, to enable us to evaluate the impact of potential changes – be they structural, technical, operational, regulatory, organisational, or economic
- the process and factors that enable effective infrastructure transformation.

A prime candidate as an integrative approach consists of models that combine social and technical networks. Urban transportation planning models that mesh demand and network flows have demonstrated the value of this approach. Once social and technical network models are integrated, a next logical step is to introduce dynamic effects, such as agency and feedback in order to address evolution and transformation. This should also be joined with recent generic thinking about the general structures (architecture) of networks. Finally, the increasing availability of data on infrastructure performance enabled by information technology advances (sensors, communications, and data archives) enables new abilities to calibrate and validate these network models. Real-time application of these technologies might also add another layer of complexity to the system being modelled.

Recent work in network science points towards the possibility of developing and articulating principles that could be applied in more generalised approaches to understanding the design and evolution of complex systems such as infrastructures. The important properties include robustness, communication, and flexibility, and have been articulated within an emerging approach to the architecture of complex systems (Whitney et al., 2004; Moses, 2004; Magee and de Weck, 2004). Moreover, this is being coupled with social network research and put it in the context of real-world possibilities (Watts, 1999, 2003; Watts et al., 2002; Barabasi, 2002).

6.3 Integrative network theory applied to infrastructure

As most infrastructures can be characterised as networks in some sense, network theory approaches are central to the understanding of the performance and operation of the infrastructures. Thus, it may be useful to develop a network-based theory of infrastructure. Elements of this theory could be developed through research addressing specific aspects of complex heterogeneous inter-networked systems:

- models that combine technical, economic and institutional networks in novel ways in order to study key infrastructure problems
- models of the complex dynamics at the network nodes and links, recognising the large variation in their nature, and, thus, requiring extensive development of existing network analyses
- connectivity patterns and hierarchies of the networks as reflected in their topologies
- fundamental influences of topology (architecture) on the properties of the infrastructure system
- the mechanisms by which standards and protocols affect system topology.

Mismatch between network demand and capacity, typically results in congestion. Several strategies can be used to resolve this problem. In simplest terms, either capacity can be increased through growth and increased operational efficiency, or demand can be controlled through regulatory or market-based demand management. The fact that initially localised congestion in network infrastructures can propagate non-linearly through a system, motivates the need for technical models of the network. On the other hand, the fact that market forces affect congestion requires a social perspective. Hence, there is the need to build models that combine technical, economic, and institutional aspects of each network.

Commonalities between network infrastructures suggest research on the development of a generalised infrastructure theory. For example, current network structures and control mechanisms, especially in air transport and electrical distribution, create both advantages such as flexibility and robustness, and disadvantages such as vulnerability and fragility (Barabasi, 2002). It seems necessary to understand this tension and to develop methods to determine optimal operating strategies. The fundamental trades in this problem are similar to those in other stochastic domains such as signal detection theory or the design of buffering networks.

Putting aside system failures, economies of scale exist in the construction and operation of networks. Connecting more people to a network increases its utility. However, significant costs – those of managing, protecting, and making the system reliable – may increase more than linearly with network size and scope. Thus, networks may have an optimal scale, although the penalty of being some distance from the optimum might not be great. For example, landline telephone networks derive and deliver huge value by increasing their connections to virtually everyone. The reliability problems and other diseconomies of scale are small and so we enjoy a system, where virtually everyone is connected. In contrast, there are major penalties for enlarging the electricity grid. Many people concluded after 11th September (as after the US blackout in 2003) that the North American power grid should be configured as several loosely connected regions. An important research question is to determine the impact of scale on network infrastructure.

Networks also have economies of scope. A coaxial or fibre-optic cable can provide telecommunication, internet, shopping, warnings, and many other services. Aircraft transport passengers and freight, and provide other services. Economies of scope may lead to competition among infrastructures, as in the case of telecommunications where copper wire, cable, fibre-optic, and wireless offer competitive services, and in some cases result in overcapacity. Managing those competitions in the public interest is difficult.

Economies of scale and scope may also hinder market competition. Marginal cost pricing fails to recover the full costs of service. Assigning all the fixed costs to local telephone service would allow the telephone companies to force everyone else out of the scope markets. There is no unambiguous way to assign the ways of pricing the network services, including peak-load pricing.

6.4 Developing a theory of infrastructure transformation

Some critical infrastructure problems can be addressed with models and theories that narrowly focus on the complex technical system. However, dealing with most of the important infrastructure problems requires simultaneous consideration of technical and social complexity. Research is, thus, needed into the development of a generalised infrastructure theory that can explain, and be useful in planning and implementing, infrastructure transformations.

Infrastructure transformations can occur along at least three axes: the technology/physical network, the economic structure, and the institutional environment. They involve relationships between subsystems of the infrastructure in question, other infrastructures, and other societal systems. Improved theory in this area could reduce unanticipated consequences of policy decisions that arise from poorly considered relationships between infrastructure and other societal systems. There should be a major research effort to develop basic principles underlying models of infrastructure transformation.

In conducting research on infrastructure transformation, these questions seem relevant:

- Is it possible to build useful models that integrate the social science and technical aspects of these infrastructures more comprehensively?
- Can we develop a theory linking the technical characteristics of an infrastructure to the relative opportunities and advantages associated with centralised planning and of distributed allocation of resources by letting ‘the market’ decide?
- What can we learn about how infrastructures evolve that will help in creating better transformation methods? The internet is relentlessly decentralised and yet it is (so far) flexible, robust, and able to incorporate new technologies. What are the enablers here and to what extent could they be transferred to other domains?
- What hybrid technical, economic, and sociological models can be used for studying the formation, propagation, and effectiveness of standards and protocols?
- How can the tradeoffs in all aspects of central vs. local control be determined?

7 Methodological development

7.1 Goal

This research would develop methods and tools to support the processes of infrastructure transformation, building on the knowledge created in developing system models and the cross-domain comparisons. The history of infrastructure development indicates that many of the challenges to infrastructure transformation are not technical, but are social. They are associated with the difficulties in reaching a common understanding of need, approach, costs and expectations among the decision makers and other stakeholders involved with the development of a specific system. Because infrastructures provide a wide range of interconnected public capabilities and services, numerous varied stakeholders have common and competing interests with respect to the design, development, and operation of these systems. Some participants have decision-making roles, while others affect the development and operation of infrastructure as users or through their political influence. Decision makers and other stakeholders need means for seeing, experiencing, and experimenting with infrastructure alternatives and their implications. In this line, a major research effort should be to develop methodologies to increase effective communication, understanding, and alignment among stakeholders with diverse backgrounds, objectives, levels of technical understanding and jurisdictions.

The uncertainties, associated with the scale and level of investment, coupled with difficulties in prototyping or conducting experiments on infrastructure, present another challenge to critical infrastructure transformation. Therefore, a second methodological goal should be to develop procedures to allow decision makers to manage their risks and opportunities better. These should involve means to extrapolate experimental results and increase understanding of the implications and emergent properties of potential infrastructure changes. The research should also explore the role of flexibility as the enabler of the system to adapt to the future as it actually evolves, so often very differently from initial expectations.

7.2 Transformation models for implementing systems change

Research should attempt to develop generic models of systems transformation that could be used in practice (with appropriate calibrations based on the type, scale, scope, and location of the planned change). Because this proposed research involves multiple stakeholders, implementation should involve wide collaboration with practitioners. It, thus, involves both facilitation and action research.

Key elements of these models will be common. They should include the identification of stakeholders, the development of a shared vision and a strategic plan, as well as implementation. They should also explicitly recognise the negotiated nature of change, in which stakeholders have common and competing interests (Walton et al., 1994). In particular, the research should invoke non-blaming learning from 'disconnects' that emerge in the implementation process. Such disconnects are generally predictable and if addressed constructively, provide valuable insights into underlying organisational dilemmas (Cutcher-Gershenfeld and Ford, 2005). Core elements of this model have been utilised in a variety of systems change initiatives, including implementation of lean production systems and new operating systems in the auto industry and electrical utility sector, and calibrating national policy and practice on aircraft noise and emissions.

Application on the scale of infrastructure transformation will require extension and development of the methods.

The concept of lateral alignment may be particularly relevant to these efforts. The literature on system change covers both top-down re-engineering and bottom-up process improvement change models. On the other hand, lateral alignment and change has been identified as a key limitation in many organisations and contexts (Galbraith, 2001). As most of the potential changes being explored in critical infrastructures may depend on this feature, several important research questions need to be investigated. What does effective lateral alignment require specifically? Some possibilities are:

- a stable and effective flow of information, knowledge and decisions
- continuing achievement of outcomes relevant to all key stakeholders, in order to be sustainable
- stable forums that are not undercut by leader transitions
- distributed leadership capabilities that depend on influence, and not just authority
- balance among innovation, standardisation, and continuous improvement
- coordination across facility, enterprise, and industry levels
- trust and other intangible aspects of social relations.

In considering multi-stakeholder alignment, it is important to think about how innovation can be sustained in the transformation process. In many cases, multi-stakeholder input can result in regression to the norm and stasis. When innovation is critical, how can leadership be defined and how can it be exercised in a collaborative environment? These issues should be explored.

8 Application testing and evaluation

8.1 Goal

Research programmes on the development of infrastructure systems need to test and evaluate the methods and insights they develop. It would seem best that this be done in the context of specific, perhaps opportunistic, opportunities to explore the transformation of some infrastructure systems.

8.2 Approach

Researchers should identify potential models or methods to apply in actual infrastructure issues. They should then enlist industry and government partners to identify transformation issues and opportunities, and to collaborate on applying the theoretical and empirical insights to specific real-world challenges.

The choice of cases is particularly important. The selection should emphasise situations that will push the methodologies; can be executed, documented, and carefully evaluated; and have high potential payoff from the overall infrastructure viewpoint. These criteria are necessary to maximise the research progress and impact. They also call for careful examination of many possibilities to identify the most promising few to pursue.

To increase the learning and impact of any infrastructure research program, it is desirable to work with other research efforts focused on specific domains of infrastructure. The objective is to leverage the effort applied to the infrastructure system of the systems with coordinated efforts, particularly in the technical systems.

9 Summary

This paper presents an ambitious research agenda for an important problem that is currently not addressed with the in-depth, broad multi-disciplinary approach it deserves. As a preliminary proposal, it needs to be discussed and improved. The authors look forward to engaging in this discussion.

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