# Intelligent Infrastructures

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# Intelligent Infrastructures

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# Foreword

Our society and economy have come to rely on services that depend on networked infrastructure systems, like highway and railway systems, electricity, water and gas supply systems, and telecommunication networks. A sustainable, efficient, safe, and reliable operation of these infrastructure systems is of crucial importance for the functioning of today's society. Currently, the operation of infrastructure systems is pushed to its limits. Infrastructure operators must survive in a competitive and regulated world where they have to maintain the operation whilst maximizing capacity utilization and revenue. Moreover, the variety of involved owners, operators, suppliers, and users has created enormously complex systems.

At the same time significant changes take place in the organization and the environment of various infrastructure sectors: the restructuring of the energy sector due to liberalization, the introduction of distributed electricity generation, the global temperature rise due to the climate change, the increasing traffic demand on railway, highway, waterway, and in the air, the pollution of the environment due to particles, $NO_x$ and $CO_2$, and the development of a Pan-European or global market with well defined legislation.

The increasing complexity as well as the significant changes going on in various infrastructure sectors demands the definition of new ways to manage such infrastructures. The difficulty in the management of these infrastructure systems is understood by considering the vast amount of actors acting in them: energy producers, operators, and consumers all work on one large international electricity network, ship brokers, ship owners, district water boards, and lock keepers all work on one large international waterway network. Achieving an infrastructure that from an overall point of view operates well, requires in some way or another managing or regulating the behavior of all these individual actors. This is clear from a European point of view, where regulations are determined for the various countries with the aim of achieving a Pan-European desired performance.

In this book, the authors show how passive networks can be transformed into intelligent infrastructures; they have succeeded to bring together a wide range of approaches to solve the complex task of infrastructure operation. In particular, the authors focus on the analogies and differences between different types of infrastructures, stimulating cross-infrastructural discussion. Research in supranational networks is important for a sustainable, prosperous, and reliable future.

Rotterdam, September 2009

Prof.Dr. Ruud Lubbers
Former Dutch Prime Minister,
Chairman of the Supervisory Board of the
Energy Research Centre of The Netherlands

# Foreword

Infrastructure systems constitute one of the prototype instances of a complex system in the sense of general systems theory. This theory has been introduced in the 1930s by Ludwig von Bertalanffy, a biologist, who was concerned with the accelerating differentiation of the scientific disciplines, the evolving diversity of conceptualizations and terminologies in these disciplines, and the emerging communication barriers between the disciplines. Von Bertalanffy was convinced that the trap of scientific silos can only be overcome if a meta-science is established which provides a common set of fundamental scientific concepts and problem solving strategies. This meta-science should – at least in principle – be applicable in all scientific fields and thus could contribute to bridge the gap between the sciences.

Inspired by the analysis of biological organisms and ecosystems, von Bertalanffy identified a general theory of systems as the core of this new meta-science. Such a theory should provide the scientific basis and the methods and tools for the representation, the analysis and understanding as well as the synthesis of any kind of system. A system is considered as a set of interacting, often hierarchically organized subsystems, with defined interfaces to its environment. The behavior of such systems is typically not only determined by the nature of the individual subsystems but in particular by the emergent behavior resulting from their competitive or cooperative interaction. Obviously, this characterization not only holds for any biological entity, a cell, an organ, or a complete organism, but also for any infrastructure entity which could be as diverse as the transportation systems in an urban region, the water supply and disposal network of a city, the telecommunication system on a continent, or the hydrogen production and distribution facilities of an industrial complex in the chemical industries. Infrastructure systems are not only composed of technological entities but also comprise decision making and disturbing human actors. Their use and evolution is strongly determined by the political, economical, and societal habits and norms. Though man-made and hence artificial, infrastructure systems share another feature with biological systems: they typically evolve as a consequence of a kind of selection pressure resulting from the apparent system behavior in its environment.

Since infrastructure systems are typically mission-critical entities in society and industry, the evolutionary development is not fully satisfactory. The complexity and the increasing interrelation of the infrastructure systems in the various sectors like industry, water, energy, communication, or transportation, calls for scientifically sound procedures for infrastructure systems design and operation which account for their socio-economic-technological nature. General systems theory provides a perfect foundation from which a theory of infrastructure systems can be deduced. Such theory has to bridge between existing scientific disciplines covering not only all the engineering sciences but also economics and sociology. This challenging mission can only be successful if a dedicated scientific community with a super-critical number of scientific groups around the world representing the essential scientific disciplines can be established. This is a complex systems problem in itself! One instrument to help make this happen is the publication of a series of monographs which have to both, raise awareness for the subject and introduce key areas of the emerging discipline for reference.

This book constitutes such an effort. It presents a collection of well-selected contributions associated with three selected types of infrastructure systems, namely electricity, road traffic, and water infrastructures. These three topical areas are introduced by two contributions which are of a more general nature. They discuss modeling and predictive control issues for infrastructure systems in general. The selection of contributions focuses on highly relevant topical areas, not only for geographical regions with an already well-developed but continuously reengineered set of infrastructures, but also for developing geographical regions where sustainable infrastructure systems are crucial for economical development. The topics of the individual contributions are nicely spread between infrastructure design and infrastructure control and operations. They also show the different perspective and scientific background of the authors and the diversity of methodologies employed.

This book will hopefully not only serve the purpose of disseminating research results but also of raising the awareness for the interesting, timely, and relevant research topics in the area of infrastructure systems. Together with the editors and authors, I hope that this book will find attention in the diverse systems engineering communities and thus contributes to the probably overdue formation of infrastructure systems engineering as a well-defined research field – with its own and distinct identity, but still well-connected with the established systems engineering communities.

Aachen, September 2009 Prof.Dr.-Ing. Wolfgang Marquardt

Member of the Scientific Advisory Board
Next Generation Infrastructures

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# Preface

Modern societies heavily depend on infrastructure systems such as road-traffic networks, water networks, and electricity networks. Nowadays infrastructure systems are large-scale, complex, networked, socio-technical systems, that almost everybody uses on a daily basis, and that have enabled us to live closely together in large cities. Infrastructure systems are so vital that their incapacity or destruction would have a fatal effect on the functioning of our society. The complexity of these systems is defined by their multi-agent and multi-actor character, their multi-level structure, their multi-objective optimization challenges, and by the adaptivity of their agents and actors to changes in their environment. The operation and control of existing infrastructures are fallible: too often people are confronted with capacity problems, dangerous situations, unreliability, and inefficiency.

To address these issues, infrastructures have to be made more intelligent, i.e., they should be equipped with senses, ICT programs, and actuators.They should be able to determine autonomously how to operate the infrastructure, taking into account the most up-to-date state of the infrastructure and the existence of several decision makers, such that ultimately the infrastructure is operated in a pro-active way and issues are resolved quickly. This book focuses on how to make infrastructures intelligent.

In this book a wide range of problems about how infrastructures are functioning today is discussed and novel advanced methods and tools for the operation and control of existing infrastructures are proposed. Different points of view on intelligent control of infrastructure systems (such as power networks, road traffic networks, water networks) are brought together. In particular, the question of how intelligence can contribute to solving the following problems that are common to many types of infra-structure systems will be addressed:

- How to more efficiently use available transport capacity?
- How to improve the reliability of service?
- How to make infrastructures more environmentally sustainable?
- How to enhance infrastructure security?

The book is divided into four parts: one generic infrastructure modeling and control part, and three parts considering particular infrastructures in detail. Each of the chapters addresses one or more of the above mentioned problem areas, therewith stimulating cross-infrastructural discussion on how to address the mentioned issues.

The contributions in this book are made by a large number of international scientists, some of which are also active within the subprogram Intelligent Infrastructures of the Next Generation Infrastructures Foundation (http://www.nginfra.nl/), which aims at developing theory and applications concerning novel modes for control and management of existing infrastructures. Together the contributions create a broad and profound coverage of the main issues related to the intelligent operation of infrastructures intended for researches, graduate students, policy makers, system operators, and managers working on organization, modeling, optimization, or control of infrastructures.

We wish to thank all authors for their high-quality contributions and the reviewers for their constructive remarks and suggestions; without them this book would not exist. Furthermore, we thank Ms. Hardy and Ms. Sherwood for their careful proof reading work, Ms. Jacobs and Ms. Pot for their guidance in the publication process at Springer, and the Next Generation Infrastructures Foundation for its financial support.

Thanks to the efforts of all people involved, we are convinced that the methods and tools presented in this book will give an invaluable support to a better understanding of the analysis and control of multi-actor multi-level infrastructural systems.

Delft, September 2009

Rudy R. Negenborn
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# Introduction

Z. Lukszo and M.P.C. Weijnen

## Service economy

Infrastructures are of vital importance for the economy and the society. The current proliferation of telecommunication and information infrastructures has a profound influence on the structure of the economy and on our social life, in analogy with historic events of infrastructure innovation, which have boosted economic growth, contributed to public health, changed our mobility patterns, and brought comfort to our homes. However, most of the present day infrastructures were laid out to service the development of an industrial economy, and seem inadequate as a backbone for a new economic structure that relies on information and knowledge intensive services more than manufacturing activities. The emerging service economy requires high reliability, flexibility, and quality of service rather than cheap utilities and commodity services [3].

There is evident public dissatisfaction with the performance of many infrastructures. Users asking for tailor made quality-of-service and service-on-demand are confronted instead with problems of road congestion, power outages, inadequate public transport, virus attacks on the internet and insecure financial services. In many of these instances it is not clear which actor should be held responsible and which actor or actors should be taking action for improvement of the infrastructure performance. Since most former infrastructure monopolies have been unbundled, followed by the introduction of competition in segments of the value chain, the ownership of the system and the operational responsibilities are often distributed. The multi-actor complexity of the system is further increased by the entrance of competitors on the market and the emergence of new players in new roles, such as traders and brokers. At the same time, the complexity of vital infra-structures is further increased by the event of new information and telecommunication infrastructure

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pervading in all traditional infrastructure sectors, holding tremendous promise for, e.g., smarter infrastructure capacity management, the emergence of new value added services and even active participation of consumers in infrastructure bound markets, such as the electricity market. As infrastructure operators are thus confronted with entirely new challenges, they are struggling with how to employ innovative information, communication and control systems to satisfy social demands and adequately serve the end-users, within constraints of affordability, safety, security, etc. Last but not least, the increasing interconnectedness between infrastructures which creates new interactions and interdependencies that may entail new and unknown risks, adds an extra dimension to this complexity [1].

These specific infrastructure related innovation challenges are reflected in the research programme "Next Generation Infrastructures" (run by the Next Generation Infrastructures Foundation, http://www.nginfra.nl/) initiated and coordinated by the Delft University of Technology.

## Next Generation Infrastructures

Next Generation Infrastructures represents an international consortium of public and private organizations working in a concerted research and development effort to improve the performance of critical infrastructures in the face of disturbances, changing economic conditions, emerging technologies, changing societal preferences, and end-user demands. The programme involves a variety of disciplines from the engineering sciences and the social sciences, so that it can effectively address the interdisciplinary challenges of infrastructure innovation and governance by technical, organizational, and institutional means. The programme is instigated by the growing public concern on the future reliability and quality of infrastructure related services. New approaches to the design, control, management, and regulation of infrastructure systems (more flexible, reliable, intelligent, and leaner) are required to counter new risks and vulnerabilities and avoid massive social costs in case of infrastructure malfunctioning. Rather than focussing on specific system components, the Next Generation Infrastructures research effort is aimed at understanding the structure and steering the overall behavior of infrastructure systems to ensure the satisfaction of societal demands and consumer interests. The predominant challenge at the overall programme level is to characterize the typical technological and social complexities of infrastructure systems, and to develop innovative ways for handling these complexities in the design, operation and governance of infrastructure systems. Therefore the mission of the pro-gramme is formulated as follows:

> "To stimulate and support the development of *more flexible*, *more reliable*, and *more intelligent infrastructures and services*, with respect for public values and consumer interests, and serve therewith a sustainable development of the economy, society and its natural environment".

The programme takes a cross-sectoral approach rather than just a sector or infrastructure specific approach, for two main reasons. In all public utilities and network industries the infrastructure network systems are going through similar processes of technological, economic and institutional change, while at the same time they are becoming more and more interconnected and interdependent, both within and across infrastructure sectors. For adequate management of these inter-dependencies it is vital to bridge the knowledge gap between experts in different infrastructure sectors and stimulate a process of cross-sectoral learning.

One of the main themes in the Next Generation Infrastructures research programme is Intelligent Infrastructures. It is aimed at developing intelligent methods and tools for the operation and control of existing infrastructures, deploying advanced information, communication and control technologies and systems. The central question it addresses is how to make better use of scarce infrastructure capacity, while at the same time improving reliability, safety, efficiency and environmental performance. For this aim an adequate balance between individual actor or subsystem interests and overall system performance should be found.

# Intelligent Infrastructures

The operation and control of existing infrastructures is often insufficient or inefficient: too often we are confronted with capacity problems and a lack of safety, reliability, and efficiency. Nowadays, infrastructure operators are in need of new (traffic) routing protocols, path selection and capacity allocation algorithms and on-line monitoring methods. The huge multi-actor complexity of today's infrastructure networks entailing conflicting interests and demands, the emergence of new technologies, regulations and societal demands, the increasing interconnectedness and interdependencies between infrastructures within and across infrastructure sectors, all hamper the effective and efficient operation and control of these systems. The urgent need for improving the performance of critical infrastructures creates a large demand for innovative optimization and control methods and challenges the scientific research community in [5]:

- Acquiring a deeper understanding of the physical and social network complexity of infrastructure systems and their socio-technical interactions;
- Dealing with more and more deeply distributed autonomous control and its effects on overall network behavior;
- Coping with new needs for flexibility (in time and functionality) in combination with more stringent demands on capacity utilization, reliability and quality of service, health, safety and environment;
- Dealing with the need for a well-defined decision-making process to guarantee the efficiency and effectiveness of decision making in the shorter and longer term for multi-actor, multi-level, multi-objective and dynamic problems.

The problems of different infrastructure sectors are similar: How to maximize the use of the available capacity? How to do this in the most efficient way? How to prevent congestion, without neglecting the proper safety precautions? Therefore,

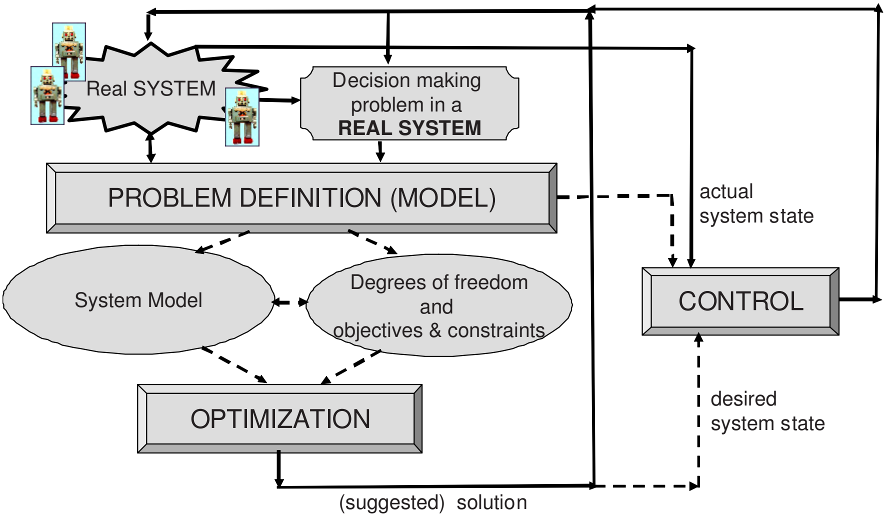

**Figure 1:** Modeling, optimization, and control scheme.

it is a challenging task to develop generic modeling approaches and control methods that can actually be implemented (e.g., by a regulatory authority) to influence local decision-making by a multitude of actors in respect of societal (overall) interests. In such a distributed approach a leader can coordinate the decision-making of distributed subsystems, but it is also possible that the interaction between the actors takes place without any coordinator. In these settings the decision makers are authorized to make decisions regarding their domain while agreeing to operate according to a common overall goal, or they interact in a non-cooperative way according to their own goals anticipating the responses of other actors and subsystems to their actions.

As large infrastructure systems are multi-level systems, composed of millions of physical components, involving different owners, operators and users, all primarily pursuing their own local performance objectives, there are no easy solutions to these problems. The Intelligent Infrastructures research programme accepted the challenge in its endeavor to answer the following core research question:

> How to influence the physical, organizational, economic and institutional configuration of an infrastructure system in such a way that predefined (dynamic) objectives are satisfied taking into account market and system constraints?

The schematic representation of the modeling, optimization and control problem as depicted in Figure 1 may at first sight look like a standard control theory problem formulation. After a proper problem definition and a modeling step, an optimization procedure results in an optimal system state and the desired values and profiles for the controller, which compares them with the actual system state and if needed performs an appropriate control action. However, as such a (dynamic) decision making problem in infrastructure systems is generally characterized by multi-actor, multi-criteria and multi-level complexity, it is extremely challenging to solve. For example, when looking at transport infrastructures, decision making can take place at many levels in the management and operation of the infrastructure, and it can range from the capacity utilization of national complex transport infrastructures down to urban traffic management and further down to decisions by individual drivers or travelers.

In such a system the objectives and constraints of any decision-maker may be determined in part by variables controlled by other authorities. In some situations, one decision maker may control all variables that permit him to influence the behavior of other decision-makers as in traditional hierarchical control. In essence, each actor is a decision-maker responding to external information: using this information as input he determines his own response. The extent of the interaction may vary depending on the particular environment and time dimension: in some cases, decision makers might be tightly linked, in other, they may have little effect on each other, if at all. *Intelligent* modeling, optimization, and control methods to cope with dynamic multi-actor, multi-level and multi-criteria problems are called for.

The term *intelligent methods* needs further explanation. Intelligence is an ill-defined concept, so depending on a purpose or domain different definitions can be given. The word comes from the Latin verb *intellegere*, which means “to understand”. Mostly, intelligence is used as an umbrella term to describe a property of the mind that encompasses many related abilities as the capability to reason, to think abstractly, to behave socially, to learn, to apply knowledge and experience to solve problems, to plan, etc. It may include traits as cleverness, knowledge, wisdom, creativity or autonomy.

In this book the term intelligent infrastructures refers to the application of advanced (intelligent) modeling, optimization and control concepts to cope with distributed multi-actor, multi-criteria and multi-level decision problems.

## Agent-based modeling of infrastructures

The common denominator of complex decision problems in the domain of public utilities and network industries is their socio-technical complexity. The physical network of an infrastructure system and the social network of actors involved in its operation collectively form an interconnected complex network where the multi-actor network determines the development and operation of the physical network, and the physical network structure and behavior affect the behavior of the actors. Unpredictable dynamic behavior of the system is often the result of the multi-agent and multi-actor character of the operation, the multi-level structure of the infrastructure system, the multi-objective optimization challenge, and the adaptivity of agents and actors to changes in their environment, together with non-linear response functions. To support the search for innovative control concepts aimed at improving the performance of existing infrastructures during normal as well as abnormal operation appropriate models should be developed. To model infrastructures as socio-technical

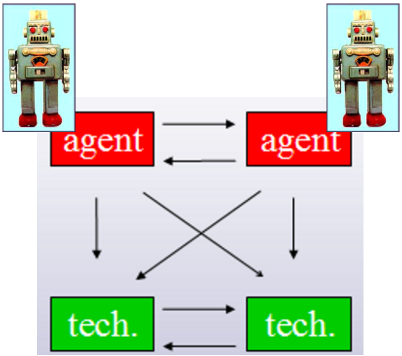

**Figure 2:** Infrastructure as interconnected system of autonomous agents interacting with technical subsystems.

systems the concept of agent-based systems composed of multiple interacting agents and physical elements is a promising approach [8], see Figure 2. The term *agent* can represent actors in the social network (e.g., travelers taking autonomous decisions which route to follow to avoid road congestion, or companies involved in the production of gas or the generation of power) as well as a control mechanism of a component or a sub-system in the physical network (e.g., controllers for irrigation channels aimed at guaranteeing the adequate delivery of water at minimal water spillage).

In general, agent-based concepts are applicable for (conceptual) modeling of complex systems if the following conditions are satisfied [7]:

- The problem has a distributed character;
- The subsystems (agents) operate in a highly dynamic environment;
- Subsystems (agents) have to interact in a flexible way, where flexibility means reactivity, pro-activeness, cooperativeness, and social ability.

Such models have already successfully been designed and implemented for various infrastructures, including transport, energy and industrial networks, as will be demonstrated in this book.

## Multi-level decision making

Capacity management at the operational level addresses day-to-day and hour-to-hour capacity allocation issues, which relate to how the flows (of goods, gas) are directed over the network. In the gas sector, international trade flows through the national grid should be controlled so as not to hamper an adequate supply of gas to national users by excessive use of transport capacity or quality conversion capacity. In the road transport sector, intelligent road capacity allocation principles are designed to achieve more balanced capacity utilization in time and space, i.e., to minimize congestion. In dynamic road pricing schemes price levels for tolls are

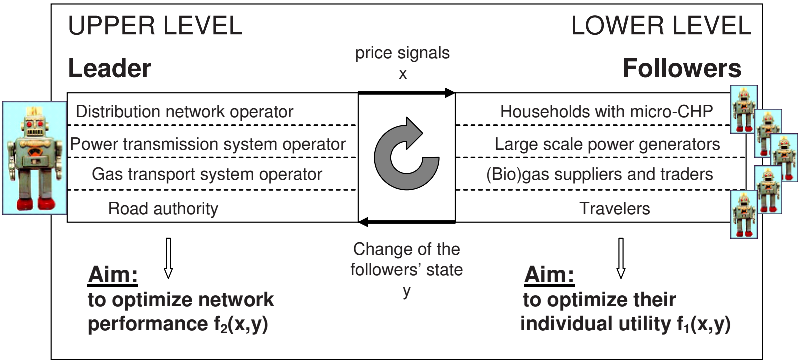

**Figure 3:** Schematic representation of bi-level decision problem examples found in energy and transport infrastructures.

dynamically varied over space and time depending on the traffic conditions in the network and the policy objectives of the road authority. A challenging question is what kind of operational models are needed to accommodate optimal distributed dynamic pricing schemes. In such a system price levels for tolls can vary over space and time dynamically depending on the traffic conditions in the network and the policy objectives of the road authority. A challenging question is what kind of operational models are needed to generate optimal distributed dynamic pricing schemes. Let us consider a network design problem in which the aim is to determine a set of (time-varying) road-pricing levels on road segments in a transportation network.

The aim of the road authority is to optimize system performance by choosing the optimal tolls for a subset of links within realistic constraints and subject to the dynamic route and departure time choice of the users, that is, the travel behavioral part. For a more detailed problem definition, see [4]. In this problem which can be represented as a bi-level programming problem we can distinguish two different submodels: the dynamic road pricing model of the road authority and the dynamic route and departure time choice model of travelers.

The problem of distributed dynamic pricing is not unique for the road infrastructure, see Figure 3. Similar issues are found in the operation of next generation electric power systems with many small-scale distributed generating units, such as gas turbines, photovoltaics, wind turbines, fuel cells, or micro combined heat and power (micro-CHP) units. These distributed technologies have many advantages, e.g., high fuel efficiency, modular installation, low capital investment, and relatively short construction time [2]. However, distributed generation in a competitive electricity market creates major uncertainties to the operation of the system: as (millions of) power users can switch to the role of power producers, the amount and quality of power produced in such a distributed system can vary enormously. Similarly, wind power fluctuations can pose management problems related to the frequency stability and the desired voltage profile. As a consequence of distributed power generation new control techniques need to be developed and implemented in order to guarantee

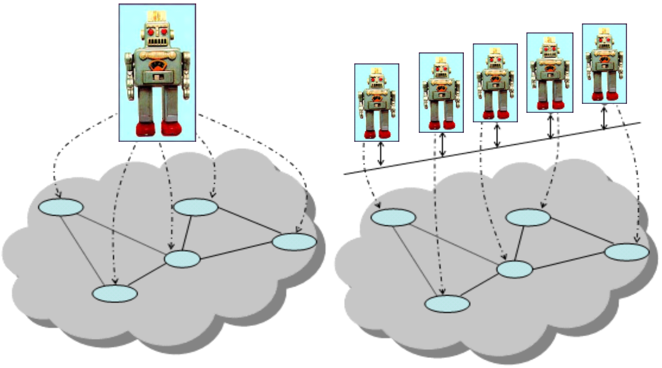

**Figure 4:** Single-agent versus multi-agent control of a complex network at a single level.

power availability and quality of service (such as frequency, bounds on deviations, stability, elimination of transients for electricity networks, and so on), so as to meet the demands and requirements of the users.

## Distributed control

Typically infrastructures are not controlled by a single agent [6]. Reasons for this may be found in technical constraints related to, e.g., communication delays and computational requirements, but also originate from more practical organizational and institutional issues like distributed ownership, unavailability of information from one subsystem to another, and restricted control access. The associated dynamic control problem should be broken up into a number of smaller problems, see Figure 4.

## Final remarks

Many new concepts aimed at improving operation and control, mostly relaying on distributed multi-agent strategies for multi-actor, multi-level and multi-control problems, are described in this book. In all presented cases the overall multi-agent system has its own overall objective, while the agents have their own individual objectives. To safeguard adequate functioning of the infrastructure the actions of the individual agents must be steered towards an acceptable overall performance of the system in terms of, e.g., availability, reliability, affordability, and quality of service.

This book presents a variety of approaches rendering vital infrastructure systems more intelligent. Evidently, advanced modeling, optimization and control strategies hold great promise to improve the efficiency, reliability, and resilience of infrastructure systems, without violating the sustainability and safety requirements which they are subject to, in fact, even improving their environmental and safety performance.

The techniques developed in the research contributions brought together in this book need to be made generic so as to be applicable to other types of infrastructure such as telecommunication, railway, water and gas networks, and to interconnected infrastructure systems across sectors. Despite the challenges waiting in the future, we are convinced that the methods and tools we can present today will turn out to be of invaluable support in understanding and solving the multi-level, multi-actor and multi-objective control problems which are characteristic for the operation of modern infrastructure systems.

Infrastructures offer many examples of settings in which multi-actor, multi-objective and multi-level decision making is daily practice and in which well-defined and thoroughly proven intelligent methods for modeling, optimization and control are called for. Virtually all of the methods assembled in this book are applicable for operations management in infrastructure systems. What we observe in practice is that different methods are being applied in combination, that computer-based simulation plays an increasing role, and that automation and computerization have strengthened the role of the lowest and most distributed level of actors in the hierarchy of decision makers, the individual consumers.

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