1. Digitalizing infrastructure: active management for smarter networks

Juan Montero and Matthias Finger

1.1 INTRODUCTION

Infrastructure is affected by the digitalization process that is transforming the economy and human activities in general. Unfortunately, digitalization has become a buzzword or, even worse, an empty term, used by vendors to sell expensive equipment and services to make any infrastructure, or even whole cities, “smart.” This has created a lot of confusion and it is difficult to identify what the key elements in this transformation are, and the right decisions to be adopted by infrastructure managers to fully exploit the new technologies.

The aim of this book is to identify the structural transformations in infrastructure management delivered by digital technologies. Beyond the buzzwords, digital technologies are transforming the way infrastructure is managed. The transformation is so deep that it is even affecting the structure of these industries, disrupting the role of traditional infrastructure managers.

Section 1.2 identifies the key technologies that are triggering the digitalization process. First, a massive amount of data is being generated by the installation in the infrastructure of all types of data-producing devices. Second, data are transmitted through telecommunications networks. Third, data are processed by increasingly sophisticated technologies. Computers are implementing machine learning algorithms to automate data management and decision-making.

Digital technologies are affecting infrastructure in the same way as other industries. As more data are produced, and data processing is improved in terms of scale and functionality, decision-making can be optimized. Furthermore, any procedure in an organization, as well as the interactions with third parties, can be automated. As information processing can be automated, costs can be reduced. In any case, infrastructure presents some specificities.

Section 1.3 analyzes the most immediate transformations digitalization is triggering in infrastructure management. Digitalization can increase efficiency in the management of physical assets, and can reduce the cost of design,

construction and maintenance of physical assets. In this way, infrastructure management can optimize the management of its physical assets.

Section 1.4 describes how the most transformative impact of digitalization in infrastructure does not affect each specific physical asset, but the more intangible role of an infrastructure manager to coordinate the different physical elements to conform an efficient network. Each infrastructure-based industry has evolved over time into a network industry in order to exploit potential complementarities between different physical assets to reduce costs and provide users with a seamless experience. The coordination of complex systems such as infrastructure-based industries requires good information as well as the possibility to execute the changes necessary to fully exploit network effects.

Digitalization enables infrastructure managers to become more active in the management of infrastructure, identifying and exploiting new complementarities. Active management has the objective to better coordinate physical assets and the users of such assets. Value is created as new network effects are fully exploited.

Section 1.5 identifies that the full exploitation of digital technologies for the creation of new network effects faces the structural challenge of the fragmentation of infrastructure-based sectors. Even in the more concentrated industries, a single organization owns and manages a limited amount of physical assets. Other managers might be competing with their own infrastructure. Assets are usually limited to a single territory (a region, a country, or just a city), and coordination across territories is necessary. In some industries, infrastructure management is vertically separated (for instance, airports are separated from airlines), sometimes as regulatory obligations.

The digitalization process in fragmented sectors, as is the case with network industries, requires the cooperation of different players to be fully implemented. Data sharing is necessary, but this is only the beginning. The next steps are standardization in data form, data quality and interfaces for the exchange of data. Full data governance in infrastructure ecosystems is yet to be created. Furthermore, technology by itself cannot change behavior in the case of an infrastructure manager who refuses to coordinate with other players.

Section 1.6 identifies how new players in the data layer, the digital platforms, can take a leading coordination role in complex fragmented ecosystems, displacing traditional infrastructure managers. Digital platforms are exploiting digital technologies to position themselves as neutral players in a position to coordinate remaining organizations in complex ecosystems. Coordination does not require owning and operating the underlying physical assets. On the contrary, coordination can be undertaken by the organization that makes the most efficient use of technology to identify and exploit new network effects across organizations. Traditional markets are evolving into multisided markets

where platforms intermediate between the assets and services produced by third parties.

Digitalization empowers infrastructure managers to more effectively coordinate individual physical assets into efficient networks. At the same time, it empowers digital platforms to become the system coordinators if they are in a position to outperform traditional infrastructure managers in this fundamental role of building networks out of physical assets. Over the next decade, the most fundamental competition between traditional infrastructure managers and digital platforms will take place, determining how infrastructure is operated in the future.

Section 1.7 describes other challenges posed by digitalization, such as cybersecurity and data protection.

1.2 THE DIGITALIZATION PROCESS

The digitalization process affects infrastructure in the same form as it affects other industries and human activities. The three elements of the process are also present. First, devices are installed in the infrastructure to generate data. Second, data is transmitted. Third, data is processed. Digitalization in infrastructure industries has the same scope: the automation of data processing to increase efficiency.

1.2.1 Concept and Origins

Digitalization can be defined as the conversion of information (text, pictures, sound, or basically any type of information) into a series of digits, 0 and 1, which enables the automated processing of such information.

The origin of binary systems to encode information can be traced back to the punched cards used by textile manufacturers' semi-automated machines in the first half of the eighteenth century, as described by Knieps in Chapter 2 of this book. By means of punched cards carrying an array of positions, each of which could either be punched through or not, information on the fabric patterns could be stored and instructions provided to the machines enabling automation. Punched cards were later used for recording and executing music by a machine.

A more systematized use of punched cards to automate information management can be traced back to the origins of International Business Machines (IBM), and the use of punched cards for the 1890 US census and later when social security was launched in the USA in the 1930s (Cortada 2019). Tabulating machines could read the data stored on the punched cards, multiplying the data processing speed. Punched cards were used well into the 1950s.

Binary digits, called bits, are the basic unit of information. They can be stored on punched cards, but also on any device that can support two stable states: two distinct voltages or current levels allowed by a circuit, two positions of an electrical switch, two distinct levels of light intensity, or two directions of magnetization or polarization (Knieps, Chapter 2).

Transistors in integrated circuits are the building blocks for storing, processing and transmitting data in the form of bits, and therefore of digitalization. The transistor was invented in 1947 by John Bardeen, Walter Brattain and William Shockley, three researchers working at Bell Labs, the research branch of the US telephony monopoly. Shockley moved to his family's hometown, Palo Alto, to launch his transistor manufacturing company and attracted some of the world's best talent for his venture. Shockley's venture did not succeed, but as his first employees (the so-called "Traitorous Eight") started new ventures, the history of the Silicon Valley cluster took off.

1.2.2 Data Production

Data are the raw material in the digital economy and the digital representation of any piece of information that can be stored and processed by a computer. Data are not natural resources; on the contrary, they have to be produced. Originally, data was manually produced at a high cost in the form of punched cards. In more recent decades, data production has been automated, lowering the cost of digitalizing written records, sounds and images. The Internet is an important data production source. Electronic activity generates a large volume of data, which are tracked by an increasing number of companies. The fastest growing source of data, however, is the increasing number of sensors that are being embedded in many different items. The volume of data produced every year is growing rapidly, from 2 zettabytes in 2010, to 59 zettabytes in 2020, to an expected 149 zettabytes in 2024 (IDC 2020).

Infrastructure management has always required the best information for design, construction, traffic metering, and so on. The acquisition and processing of information was cumbersome and expensive. Infrastructure managers often had very limited information about the infrastructure and had to rely on conservative theoretical estimates about the status of the infrastructure, maintenance needs, traffic flows, capacity, life expectancy, and so on. Consequently, they were often limited to passively managing the infrastructure.

Digitalization enables infrastructure managers to dramatically increase the information they have about the infrastructure. Many types of sensors can be installed in the infrastructure to produce data. Sensors can measure all kinds of parameters: temperature, pressure, vibration, and so on. Cameras can provide images, even in remote areas if they are installed in drones. Sensors can geo-localize vehicles, vessels, aircrafts, and the like. They can measure traffic

flows in a specific point of the infrastructure, from vehicles to electricity, water and gas, but also bits in telecom networks and letters and parcels. Infrastructure managers can produce large volumes of data about their infrastructure.

Data production poses some specific challenges for infrastructure managers. The most obvious one is that infrastructure can span thousands of kilometers (railways, electricity grids, submarine cables, etc.). Furthermore, it is often sparsely deployed around the territory. Infrastructure is deployed in dense urban areas, but also in rural areas. Some network elements are deployed in remote areas (for example, electricity grids running through mountains, submarine fiber-optic cables running deep in the ocean, aircraft flying). Data production at this scale is far more challenging and expensive than digitalizing content was in the media sector, or digitalizing production plants is in the so-called Industrial Revolution 4.0. Nevertheless, data production is only the first step in the digital transformation.

1.2.3 Data Storage and Processing

The most fundamental challenge in the digital transformation is the capacity to transform raw data into useful information that can be applied for specific purposes. This is particularly challenging, as sorting through massive volumes of data presents diseconomies of scale. Sorting becomes more difficult and expensive as the number of items to be sorted increases: “The unit costs of sorting, instead of falling, rises” (Christian and Griffiths 2016). Data storage and processing has to be automated to make sense of the increasing volume of available data. This has been the role of transistor-fueled computers.

Computers were conceptualized by Alan Turing in his seminal paper “On Computable Numbers” (Turing 1937). Machines that could make a single set of calculation were already available. Turing proposed the development of stored programs that would allow machines to run any type of calculation. Reprogrammable instructions could be stored in the same storage used for data. IBM developed one of the first stored-program computers in 1948, as it started to transition from punched cards to computers.

Military applications fostered research in computing. In 1957, IBM started deploying computers for the Semi-Automatic Ground Environment (SAGE) run by the US Air Force, a system that would create a network in addition to the data produced by radars deployed around the territory to provide a single image of airspace over the USA. Russian missiles could be spotted and a military reaction triggered automatically. It was the first time digital technology was used to create a mirror image of reality at a massive scale – a digital twin.

SAGE was a precedent of what digitalization would enable in the form of producing, storing and processing data. The point of departure was the production of relevant data. This was the role of the radars deployed across US terri-

tory. Radar was a technology developed by the Office of Scientific Research and Development, in charge of coordinating scientific research for the war effort, in close collaboration with the Massachusetts Institute of Technology (Zachary 1997). An early challenge was storing the large amounts of data that radars were producing. IBM developed the AN/FSQ-7 computer to support SAGE. The project generated 80 percent of IBM's revenues from computers between 1952 and 1955 (Cortada 2019). Two AN/FSQ-7 computers (one for back-up) occupied 2,000 sq.m., and these are still the largest computers ever built. The SAGE technology was transferred early for civil purposes. In 1960, IBM was contracted by American Airlines for the production of SABRE (Semi-Automated Business Research Environment), a computer reservation system that is described by Arnold and Casullo in Chapter 7 of this book.

Transistors in integrated circuits empowered stored-program computers; they also substantially reduced the size of electronic components in computers. The famous Moore's Law (named after one of the "Traitorous Eight" and co-founder of Intel) observes that the number of transistors in an integrated circuit has been doubling every two years. As a result, ever-smaller computers have more storage and processing capacity.

The mainframe computers of the IBM era gave way to personal computers (PCs) in the late 1980s. Small companies and private individuals could buy small-size, low-cost computers for the management of their affairs. In this way, business processes were digitalized: paper documents became electronic documents, every company's records could be digitalized, and so on. PCs reinforced the distinction between hardware, produced by different companies, and software, a multi-billion dollar industry with a large number of actors. They also brought in a new actor, Microsoft, which provided the operating system that acted as a bridge between the hardware and the software installed in a PC.

A further evolution enabled by Moore's Law was the smartphone, a hand-held device with a storage and processing capacity multiplying the capacity of the AN/FSQ-7 computer and early PCs. Smartphones accelerated digitalization, as they acted simultaneously as a data storage and processing device, a data transmission device and, just as importantly, as a data-generating device. Smartphones gather huge amounts of data about the user's personal offline activities: the geo-localization of the user, voice recordings, pictures, videos, and so on. Smartphones have enabled the digitalization of our daily lives.

Just as smartphones have digitalized many personal services, the so-called internet of things (IoT) has the power to digitalize basically any human activity. As an increasingly large amount of data is produced by all kinds of sensors, new strategies have been necessary to automate the data processing by computers. This is the ultimate cornerstone of the digital transformation.

Sophisticated algorithms and artificial intelligence (AI) are necessary to process big data. Algorithms are enabling the full exploitation of big data (Iansiti and Lakhani 2020). The *Oxford English Dictionary* defines an algorithm as “a process or set of rules to be followed in calculations [...] especially by a computer.” Sophisticated algorithms are necessary to put in order and make sense of the massive amounts of data generated by sensors and other data-collecting devices, thus making them relevant.

Algorithms are increasingly using machine learning techniques. These are not a set of fixed rigid commands connecting an input to a consequence. On the contrary, algorithms examine available data in order to learn from previous experiences and subsequently transform raw data into new information and link it to consequences. Algorithms improve themselves with each interaction; they are becoming more and more predictive (Agrawal et al. 2018).

The ultimate challenge of digitalization is to rely on artificial intelligence to automate decision-making, taking into account all the available data. It “is all about taking many traditional processes and embedding them in software and algorithms” (Iansiti and Lakhani 2020: 113).

Infrastructure management can largely benefit from digitalization, as it enables a transition from the rather traditional passive management of assets to a more active management empowered by data and the capability to automate decisions based on such data. The management of large complex systems such as infrastructure-based sectors can be improved by having deeper knowledge of all the available assets and processes and identifying new complementarities between them.

Artificial intelligence poses regulatory challenges, particularly when applied to general interest activities such as infrastructure management. AI applications have to be robust and accurate, which requires good-quality training data, keeping records of data and algorithms, being able to provide adequate information about the application, and ensuring human oversight (European Commission 2020).

1.2.4 Data Transmission

A necessary complement to the production and processing of data is the transmission of such data. Transistors increased the reliability and reduced the cost of long-distance transmission of electronic signals. In parallel, computers were used for switching calls, dramatically reducing the cost of switching communications among the hundreds of millions of telephone users across the world. But this was only a secondary effect of digitalization in telecommunications. More importantly, digitalization increased the number of points to be connected by communications networks. Communications networks not only connected people to talk (telephony), but also connected data-producing units

with computers (as in SAGE) and computers with other computers to exchange data.

The idea that computers would be connected was advanced early on. In 1960, J.C.R. Licklider, a psychologist turned computer scientist, envisioned the creation of a network of computers connected by telecommunications infrastructure in his seminal paper “Man–Computer Symbiosis”. Licklider wrote: “The picture readily enlarges itself into a network of such centers, connected to one another by wide-band communication lines and to individual users by leased-wire services. In such a system, the speed of the computers would be balanced, and the cost of the gigantic memories and the sophisticated programs would be divided by the number of users” (Licklider 1960). Licklider’s contribution was not only theoretical. In 1962, he was appointed head of the Information Processing Techniques Office at ARPA, the United States Department of Defense Advanced Research Projects Agency (the successor of the Office of Scientific Research and Development). ARPA wanted to save resources by pooling all the computing capacity of the different projects across universities and research centers financed by ARPA.

The Bell System in the USA started to provide communications services to connect computers owned by the same organization. Private lines connecting different locations owned by the same customer were increasingly popular among the owners of computers across different locations. In 1966, the Federal Communications Commission (FCC) launched a prescient consultation under the title “In the Matter of Regulatory and Policy Problems Presented by the Interdependence of Computer and Communications Services and Facilities.” As described in the consultation, “Effective use of the computer is [...] becoming increasingly dependent upon communication common carrier facilities and services by which the computers and the user are given instantaneous access to each other” (FCC 1966).

ARPA had the bold ambition to create a large network connecting a high number of computers. One of the options for ARPA was to create a centralized network connecting computers, following the traditional structure of the telephone network. It was proposed to set up the switching point in Omaha, near the geographic center of the USA where the US Air Force had facilities (Hafner and Lyon 1996). Licklider’s ARPA had a better idea: an innovative network model developed at the RAND Corporation by Paul Baran for the US Air Force and described in the paper “On Distributed Communications” (Baran 1964). Instead of centralizing switching in a single node (centralized network), or even a reduced number of nodes (decentralized network), Baran proposed establishing redundant links between the different points to be connected in such a way that communications would be handled from point to point without being switched in a centralized node. In other words, every point in the network would have switching capabilities, every point would be a small

node. The US Air Force had identified that the centralized network of the Bell System would collapse in case of a nuclear missile attack, and Baran was commissioned to identify an alternative to solve this problem. His solution was the distributed network and his graphical representation is shown in Figure 1.1.

Figure 1.1 Graphical representation of networks

Baran spent five years trying unsuccessfully to convince the Bell System to implement a packet-switched distributed network. His proposal was not only dismissed, but he was put through a training course with 94 speakers to explain to him how a telephone network works, so he could understand why his idea was not feasible (Hafner and Lyon 1996).

ARPANET, the network financed by ARPA, would prove the engineers in the Bell System wrong. On October 29, 1969, the first connection of ARPANET, between UCLA and Stanford, started to operate (Ryan 2010). This was the beginning of the Internet. The challenges were enormous. Each university had developed its own communications protocol to connect their computers. They were not interested in changing their systems to adopt a new common standard. The solution was to keep each independent network working under its own rules, and to create a protocol on top of them so that the different networks could communicate with each other. The solution was to create a network of networks. A specific, simple protocol was developed for the different networks to interact. The Internet protocol (TCP/IP) created a new layer on top of the different networks that enabled the interaction of previously

isolated computer networks. It would not be necessary to fully standardize the pre-existing networks in order for them to interoperate. Each network would use its own standards, but all of them would be able to interoperate thanks to a new standard on top of the legacy local standards.

Over the years, ARPANET evolved into a civil network connecting universities and research centers, under the leadership of the National Science Foundation. Other national networks were also connected. The network of networks grew organically as more and more networks started to use the TCP/IP protocol and interoperate with the networks originally integrated in ARPANET. In 1995, the network evolved into a new architecture, with commercial entities managing network access points. The Internet was ready to go mainstream: Internet access services would be provided by Internet service providers (ISPs); large Tier 1 telecommunications carriers would manage the backbone of the Internet; and traffic would be exchanged in Internet exchange points (IXPs). The modern evolution of the network of networks is described by Stocker and Knieps in Chapter 3 of this book.

Telecommunications networks supporting Internet traffic evolved in parallel to the evolution of the Internet. Access to the Internet diversified. The initial coaxial cable connections increased capacity through the introduction of XDSL technologies, and were substituted by optical fiber connections providing homes and offices with broadband access to the Internet. In parallel, cellular networks provided wireless mobile access to the Internet. The different generations of mobile technology have increased the capacity and reliability of the service, as described by Knieps in Chapter 2 of this book. The backbone of the Internet relies on very high-capacity fiber-optic cables connecting cities and continents. A fundamental evolution has been the transition of all communications to the package-switched routing using the IP protocol, even for voice services. Baran's idea from 1964 has become a reality.

We have devoted attention to the evolution of the Internet as the network of networks because we anticipate that this model of infrastructure coordination will influence the way other infrastructure industries evolve into networks of networks as they digitalize. Interoperability between different elements of infrastructure can be facilitated by coordination in the data layer to form virtual networks on top of physical networks. The challenges the Internet is facing today, particularly the need for specific tools for coordination (see Stocker and Knieps, Chapter 3), might be the challenges of the future in other network industries.

The transmission of data generated by infrastructure poses specific challenges. Regular telecommunications networks cannot always ensure connectivity in remote areas. Network deployment along infrastructure has been a common requirement in spectrum auctions. Nevertheless, it has been common practice for some industries to deploy their own telecom infrastruc-

tures, particularly optic fiber. This has been the case in electricity, railways, and some roads. In some cases, spectrum has been reserved for industry-specific networks, such as railways and air traffic control.

A further connectivity challenge is the increasing demand of quality in connectivity. There is a tendency to push data processing to the network edge: this is known as edge computing (see Stocker and Knieps, Chapter 3). Transmitting data from a remote location to the data center of an infrastructure manager to be processed and then sending back data with instructions can be overly time-consuming. More and more data processing is taking place closer to the assets in order to reduce latency and delay. It has been forecasted that, by 2025, 80 percent of data processing will take place not in centralized data centers, as today, but in edge computing (vehicles, connected assets and computing facilities closer to the user (Gartner 2017)). Consequently, connectivity in remote areas needs to be of higher quality. 5G networks provide not only higher bandwidth, but also lower latency and delay. 5G is the telecommunication technology that will enable smart networks (Knieps, Chapter 2).

1.2.5 Digitalization as a Process

Digitalization is an evolving process. An ever-growing volume of information is being digitalized, and an ever-growing share of information can be automatically managed.

The digitalization process can be traced back more than a century, with the digitalization of the 1890 US census. Digitalization gained momentum in the late 1960s as computers became increasingly powerful and became interconnected, enabling the automation of back-end business procedures such as aviation reservation systems. Digitalization accelerated in the 1990s, as PCs went mainstream and millions of individuals interconnected their PCs through the Internet, which allowed the digitalization of personal communications (email), and all kinds of mass-market, customer-oriented procedures. Smartphones were the tool that allowed billions of individuals to join the digital world and, even more importantly, to digitalize many day-to-day personal activities. The ultimate evolution of the digitalization process is the automation of complex systems thanks to the IoT. As sensors can be installed in any location, device and asset, a “digital twin” can be created *in silico*, facilitating the coordination of complex systems such as infrastructure-based industries.

A data layer is emerging on top of physical reality, which virtually recreates it. Sensors, cameras, meters and other devices can be installed in the physical assets that capture and transmit data to the infrastructure manager. Such data can recreate the status of the infrastructure in the data layer, as well as the usage of the infrastructure for the provision of services (capacity, traffic flows and payments).

As organizations acquire massive amounts of data about their assets and activities, they are in a better situation to manage them. Algorithms are then able to identify opportunities to improve the organization of the system, thus increasing efficiency (see Finger and Montero, Chapter 11). The underlying reality can be transformed and improved. This is also the case with infrastructure.

The impact of digitalization runs deeper than the mere optimization of certain activities due to information management automation. Digitalization has the power to transform business activity as well as our societies. Digitalization has been compared to the process of electrification (Carr 2008). Electrification optimized certain production processes, but it had a deeper transformative effect: electrification redefined assembly lines, it modified our cities (electric elevators made higher buildings possible), and it modified human activity rhythms (electric light enabled activity at night). Digitalization will have a deeper impact, as it affects a more fundamental element: how humans communicate, interact, and organize in complex societies.

We are just starting to identify the economic and social transformations triggered by digitalization. First, the efficiency gains derived from digitalization are substantial. The ability to gather more information enables the optimization of all kinds of procedures, organizations and systems. Digitalization is creating wealth. Digitalization can create measurable efficiency gains in the form of cost reduction in the design, construction and maintenance of infrastructure. It can also enable a more active infrastructure management by controlling both capacity supply and demand. It can improve the coordination of fragmented systems. Four different efficiencies can be identified in infrastructure-based industries: (1) end-to-end efficiencies, (2) vertical efficiencies, (3) horizontal efficiencies, and (4) so-called deep efficiencies (see Finger and Montero, Chapter 11).

Second, digitalization is triggering a transformation in human interaction, including the way in which companies, systems and markets organize and interact with each other. The most evident transformation is the increasing role of intermediaries in the data layer. The most successful players are digital platforms organizing ecosystems around them (multisided markets) with the ability to coordinate large numbers of individuals, assets and companies. They use digital technologies to identify and exploit the optimization opportunities. Platforms have a role to play in infrastructure-based industries.

Third, a small number of digital platforms are monopolizing a large proportion of the value created by digitalization. Amazon, Apple, Facebook and Google control the assets in the digital economy: the operative systems in key devices such as smartphones, the largest amount of data on human activity, the most sophisticated AI technology, and so on. They are disrupting traditional industries and extracting a high share of value as they create, intermediate, and

then organize the ecosystems around them. Infrastructure-based industries are starting to face disruption.

1.3 DIGITALIZING DESIGN, CONSTRUCTION AND MAINTENANCE

Infrastructure managers can use digital technologies to reduce costs in the operation of the physical assets they own, and digital technologies can be used to reduce design and construction costs. This cost represents a fair share of total costs in all infrastructure industries. Furthermore, digital technologies can reduce maintenance costs. Maintenance of infrastructure is also an important cost chapter in all infrastructure industries, and a requirement to ensure safety. Expensive preventive maintenance can transition to condition-based maintenance and even to predictive maintenance. Digitalization enables better traffic metering, thus reducing charging costs.

1.3.1 Infrastructure Design and Construction

Technology can reduce the cost of design and construction of infrastructure. Automated computer design can reduce design costs. Technology can further enhance design and construction methods by better coordinating all the participants in a network.

Building information modeling (BIM) has been described as “a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building’s life-cycle” (Succar 2009). BIM enables the better coordination of all actors involved in a design and construction project as information is shared and processes optimized.

BIM has the potential to substantially reduce infrastructure construction costs. In the case of roads, cost reduction by using this technology for the design and construction of the infrastructure has been estimated to be between 15 percent and 20 percent against the traditional design system (Blanco and Chen 2014). This has been considered potentially disruptive (see Cruz and Sarmiento, Chapter 4).

1.3.2 Infrastructure Maintenance

Technology can also reduce the cost of maintenance of infrastructure. Traditionally, managers would plan necessary interventions in the infrastructure based on the average life expectancy of each element (“preventive maintenance”). As a complement, managers would intervene if a fault was

detected (“corrective maintenance”), which might be too late if the fault led to the collapse of the infrastructure.

Technology is transforming maintenance. The IoT has allowed the installation of sensors in all the elements of any infrastructure. In this way, the infrastructure manager can monitor the status of such elements, and maintenance can be tailored to the real condition of the infrastructure, enabling “conditions-based maintenance” for infrastructure (Jardine and Banjevic 2006).

Furthermore, intelligent algorithms can make use of existing data to predict the need of maintenance, enabling the so-called “predictive maintenance” (Daneshkhah et al. 2017).

Maintenance costs can be reduced, as interventions take place when they are absolutely necessary, and not based on a conservative theoretical analysis or, even worse, when costly and unfortunate faults take place. As an example, for railway rolling stock, it has been estimated that “condition-based maintenance” can reduce costs by between 10 and 15 percent, while predictive maintenance can reduce costs by a further 10 percent (McKinsey 2016).

Furthermore, sensors allow infrastructure managers to rapidly identify a fault as soon as it takes place – repair terms can be reduced, further reducing costs, and they can also react to faults by, for example, diverting traffic.

1.3.3 Traffic Metering

As already described, traffic metering is of the utmost relevance in most infrastructure industries as fees are usually imposed on users based on the amount of transported items. Fees are different based on the electricity, gas and water that is consumed, on the kilometers of roads that are transited, on the minutes of telephone conversation that are made, and so on. Metering the usage of an infrastructure generates a cost. The cost is higher when measuring takes place in the periphery of the network, as is the case with electricity, gas and water networks. Meters have to be installed at each point of consumption and the information has to be transferred to the infrastructure manager for the production of invoices. Furthermore, measuring and charging can disturb the traffic flow, as is often the case with road tolls, which have traditionally obstructed traffic and created congestion at peak times.

Digital technologies enable new metering solutions that provide real-time information to infrastructure managers, sometimes at a lower cost than traditional meters, and they minimize impact on traffic flows, particularly in road transport.

Smart meters have been popular in the electricity industry (see Rossetto and Reif, Chapter 9). Smart meters automate consumption measurement and the transmission of information from the consumer premises to the infrastructure

manager data center. There is no need for in-person control of the meter in the customer's premises, or for periodic updates of theoretical consumptions with observed consumption. The so-called "smart meters" are reducing the cost of charging users in the electricity industry (European Commission 2015). Smart meters enable infrastructure managers to have access in real time to consumption patterns, which enables a more efficient management of the network (see Section 1.4).

While smart meters exist in other network industries, they have not been as popular as they are in electricity, mostly due to the high cost of meters when compared with the price of the asset transported by infrastructure. This is often the case in the water industry, as the low price of water does not always justify the investment except in areas with water scarcity (see Espinosa Apráez, Chapter 10).

In road networks, smart tolling can substantially reduce costs (see Cruz and Sarmeto, Chapter 4). Furthermore, smart meters can also reduce external costs. In Taiwan it has been identified that electronic tolling in road transportation can reduce congestion (by 60.1 percent) and CO₂ emissions (by 12.4 percent) (Tseng et al. 2014).

1.3.4 Conclusions

Digital technology can significantly reduce costs for an infrastructure manager. Even if implementing new technical solutions is a cost in itself, such an investment has been shown to pay off in many different contexts. Technology can reduce the cost of infrastructure design, construction and maintenance. For example, it has been estimated that, on average, a 30 percent reduction in CAPEX can be expected from the implementation of the leading technologies in the road industry (Cruz and Sarmeto, Chapter 4). A systematic description of cost reduction in the maritime sector can be found in Tsvetkova, Gustafsson and Wikström in Chapter 5 of this book.

In any case, it is always important to identify the existing incentives. Infrastructure managers might not have the right incentives to reduce costs. Monopoly disincentivizes innovation and no innovation takes place in competitive markets if innovation is a pure public good (replicable at negligible cost). On the contrary, incentives might be excessive if infrastructure managers can monopolize cost reductions and not pass them on to customers in the form of lower prices, as has been identified in France for smart electricity meters (Court des Comptes 2018).

1.4 ACTIVE INFRASTRUCTURE MANAGEMENT

Digital technologies are not only transforming the construction and maintenance of infrastructure; they are also transforming infrastructure management, particularly the control of the load factor. Digital technologies empower infrastructure managers to have real-time granular information on traffic flows, and even to predict future traffic flows. Furthermore, digital technologies can support active management of the load factor (that is, the relationship between demand for the use of the infrastructure) and supply, in the form of capacity. Active management can transform the role of infrastructure managers and reinforce their role as coordinators of complex systems, increasing efficiency as they exhaust network effects.

1.4.1 Active Management

Infrastructure presents obvious network effects: the larger the number of users, the larger the pool to distribute the high fixed sunk costs of building and operating the infrastructure, resulting in lower average prices for each user. It is not by chance that infrastructures are considered network industries. However, as network industries, they may also face negative network externalities, particularly in the form of congestion. If demand exceeds capacity, the service is degraded.

The main challenge for all infrastructure managers is to get as close as possible to the sweet spot where infrastructure has the most intense use without reaching congestion. In other words, the most efficient infrastructure management is met when the load factor, defined as the ratio of the average load divided by the maximum capacity in a given time, is 1 (the infrastructure is used at its peak capacity all the time), without leaving any demand unmet.

This is particularly challenging, as infrastructure managers traditionally had little information, and even less control, on the load factor in their networks. Infrastructure managers would design and construct infrastructure for an optimal capacity based on the available information and forecasts, as well as on the available resources. Infrastructure is built to last for decades and once it has been built, capacity is very rigid and it is difficult and expensive to expand it to meet increases in demand. Once the infrastructure was built, infrastructure managers would mostly manage the load factor in a passive form. In some cases, infrastructure managers would just passively accept all requests to use the infrastructure and just assume the risk of congestion and service degradation: cars would be stuck in traffic, ships would wait outside ports to be loaded/unloaded, telephone calls would not be completed, and letters would be late. In other cases, infrastructure managers would take a more active role in the man-

agement of the load factor, mostly for security reasons. Access to railways and airports would be scheduled months in advance according to predefined, rigid, and usually very conservative schedules. In the same way, access to electricity networks would be managed according to very conservative estimates, so as to avoid blackouts. The fact that many infrastructures were managed as monopolies reinforced conservative passive management of infrastructure.

Digital technologies can be used to obtain real-time granular information on traffic flows in all segments of the network. For the first time, managers have the capability to identify when infrastructure is approaching congestion. Furthermore, as infrastructure managers obtain access to more and more data, with the use of more sophisticated algorithms, they are in a better position to predict traffic flows even before congestion takes place.

Even more importantly, digital technologies empower infrastructure managers to actively manage their networks. On the one hand, they can actively manage demand, by incentivizing specific traffic flows against others. Dynamic pricing is the main tool, but not the only one. On the other hand, digital technologies empower infrastructure managers to actively manage supply. Infrastructure tends to be very rigid, and it has been traditionally impossible to increase capacity to meet peaks in demand. Digital technologies empower such increases in capacity.

Infrastructure management is gradually evolving from passive management – as reflected in the old expression “build it and they will come” – to active management, as infrastructure managers have more information and more tools to actively drive demand and actively operate supply, having more control of the load factor.

1.4.2 Demand Management

Digital technologies provide new tools for the management of demand. On the one hand, traffic flows can be measured in real time making use of sensors in the infrastructure. Self-learning algorithms can predict traffic flows as they sort through historic data. On the other hand, digital technologies enable infrastructure managers to actively manage demand.

Infrastructure managers are improving the visibility they have about traffic flows. Vehicles making use of infrastructure are increasingly geo-localized as they are tracked by different sensors, making use of different technologies (GPS, cellular networks, etc.). While this might seem like a basic feature, it is only recently that it has been widely implemented in some industries and it is still a challenge in other industries. There are different digital solutions for the geo-location of land motor-vehicles (Cruz and Sarmento, Chapter 4), maritime transport (Tsvetkova, Gustafsson and Wikström, Chapter 5), and aircraft (Arnold and Casullo, Chapter 7). Railways are lagging behind.

Passengers and cargo can be individually tracked. A coach with passengers can be tracked by the company operating the coach by making use of a GPS device, but passengers can also be tracked through their smartphones making use of digital apps. Cargo in a vessel can be tracked by the vessel owner, by installing sensors in the vessel itself, but also by the cargo owners, as they install sensors in the merchandise. As the cost of sensors is dropping, any asset can be tracked, even parcels and letters (see Jaag, Chapter 8).

Even fluids can be tracked by sensors installed in the infrastructure, as is the case with electricity (Rossetto and Reif, Chapter 9), water (Espinosa Apráez, Chapter 10), and certainly bits in telecommunications networks.

Machine learning algorithms can be applied to interpret data generated by sensors to have granular real-time information about the traffic flows in a network. Congestion can be identified as it emerges. Furthermore, sophisticated algorithms sorting through massive quantities of historical data can predict the evolution of traffic flows. Congestion can be predicted. Finally, real-time data and algorithms can be used to identify incidents in traffic flows: car accidents blocking road traffic, delays in aviation and railways, and so on.

Having real-time information about traffic flows is interesting in itself. It can help to forecast traffic flows for the design and construction of infrastructure. It can help to charge for the use of the infrastructure (see the example of roads in Cruz and Sarmiento, Chapter 4). It can be used to reduce incidents (see the case of blackouts in electricity in Rossetto and Reif, Chapter 9) and used to identify and react to incidents (for car accidents, see Cruz and Sarmiento, Chapter 4).

However, the most fundamental change derived from digitalization and the capability to have more information about traffic flows is the possibility of actively managing traffic flows; that is, the demand for capacity in the infrastructure.

Lack of data has traditionally limited the capacity to actively manage capacity demand. In some cases, demand management was absent altogether. Infrastructure would passively admit as much traffic as generated, assuming the risk of congestion. This has been the case with roads. Road managers had no ambition to manage traffic flows. Vehicles would have unrestricted access to the infrastructure, congestion being the assumed result of excess in demand. Over time, some measures have been introduced to reduce congestion, such as information being displayed so users can avoid congested roads, some traffic being restricted in peak periods (for instance, trucks in certain hours and days of the year), and so on. Digitalization can change this approach.

Other infrastructures are managed in a similar form. Telecommunications networks are not designed for a peak in demand, and in case demand exceeds the available capacity, calls cannot be initiated (or they are dropped) and Internet traffic is delayed, as the public Internet is managed following

a best-effort principle (Stocker and Knieps, Chapter 3). Postal networks work under the same assumption, and ports are also managed using the same principle. Ports do not reserve capacity for scheduled vessel arrivals – they merely serve vessels as they arrive, mostly following the “first-come, first-served” rule. Vessels might have to wait for hours and even days in case of congestion, when they could have traveled at a slower pace saving fuel (and emissions) had they known they would have to wait in a queue (Tsvetkova, Gustafsson and Wikström, Chapter 5).

Digital technologies empower infrastructure managers to actively manage traffic flows. Port-call optimization is an obvious example. Ports can optimize their capacity if they coordinate all the necessary services to be available at the time expected for vessel arrivals, which would be more certain if ports could have access to vessel geo-location data. Furthermore, ports could optimize capacity if it was distributed fairly over time; booking arrival and unloading slots for ships would negate the need for them to “rush-to-wait.” Smart algorithms can dynamically assign capacity in real time, and modify slots if necessary due to delays caused by poor weather conditions. Port-call optimization could reduce costs both to ports and to vessels (Tsvetkova, Gustafsson and Wikström, Chapter 5). Even telecommunications networks could improve traffic management using the right technologies and the right incentives, ensuring the right quality of service for each type of traffic (as described in Stocker and Knieps, Chapter 3).

Technology provides instruments to adapt demand to capacity. As infrastructure managers have new tools to predict traffic flows, they can incentivize the use of the infrastructure in off-peak periods against the use in peak periods. Infrastructure managers have always tried to manage demand. The novelty is that infrastructure managers can now predict peak/off-peak usage in real time with far more accuracy, depending on several factors (time of the day and year, weather, specific events, etc.). They can build more sophisticated pricing schemes, based on metering and billing. For example, smart meters in electric networks are increasing sophistication in the pricing of the service, with incentives to reduce consumption when demand is peaking (Rossetto and Reif, Chapter 9).

Infrastructure managers can also respond to fluctuations in demand in real time through dynamic pricing. They can automatically adapt their metering and billing systems, as well as inform users in real time to help them make consumption decisions. Infrastructure managers can also reduce congestion by distributing traffic across the network in ways that are more efficient. Discounts can be offered to users if they take alternative roads, or if they take alternative railway services, possibly with a detour that requires more time. Such network management is possible if the infrastructure manager has better knowledge in real time of the situation of the network (or is in a position to

predict it effectively) and has the ability to respond in real time with new alternative capacity and new prices.

Dynamic active management of traffic flows has the potential to optimize even those networks that are already managing demand. This is the case in aviation and railways. Security reasons, particularly in aviation, make passive management impossible. Aircraft cannot wait for hours to be granted a slot to land at an airport, as happens in ports. Trains cannot simply access tracks without coordination. In both cases, access to the infrastructure is actively managed. Infrastructure managers formally assign the right to use the infrastructure at a specific time (a slot in airports and track access right in railways). However, such capacity management has not evolved for decades and is very inefficient. In European railways, as the industry has been vertically separated and liberalized, railway operators have to apply for track access rights to be assigned by the infrastructure manager once a year for a rigid predefined schedule to be in place for the whole year, starting in mid-December. The process is highly bureaucratized and heavily regulated, including the intervention of independent regulators in cases of conflict (Montero, Chapter 6).

The management of capacity in aviation is even worse, as the management of airport slots has to be coordinated with air traffic management (ATM) so aircraft do not collide in the air. Specific organizations were set up in the mid-twentieth century by the different states to manage air traffic, making use of radar technology. Old technologies and poor coordination between fragmented national air traffic authorities have limited capacity increase to meet the sustained growth in air traffic. Congestion is common (Arnold and Casullo, Chapter 7).

Digital technologies can be implemented to improve demand management in railways and aviation. Capacity allocation can be optimized if infrastructure managers have better information about traffic flows; for instance, if it is possible to predict traffic flows, then infrastructure managers can react in real time to actual traffic conditions by geo-locating aircraft and trains, and actively managing traffic. Traffic is planned conservatively to ensure security. If infrastructure managers have better information and can react on the spot with more powerful digital tools to unexpected elements (bad weather, delays, etc.), rearranging traffic in a more optimized and safe manner, traffic management can be made more dynamic, to the point where it is not necessary to arrange traffic months in advance according to very rigid schedules.

Electricity networks provide the ultimate example of infrastructure management. Electricity voltage has to be stable in the network, which requires the most active management by the infrastructure manager. The infrastructure manager must control the introduction of electricity by generators and, at the same time, its extraction by consumers. Traditionally, managers were conservative in the management of traffic flows to ensure the stability of the network

and to avoid blackouts while ensuring continuity in supply to consumers. Digital technologies empower infrastructure managers to have more information about electricity generation and consumption (meters), which enables a more dynamic management of the infrastructure, and a substantial reduction in costs. This is already happening in the transport segment of the network and increasingly in the distribution segment (Rossetto and Reif, Chapter 9). Sophisticated pricing provides a powerful tool to manage demand in real time.

1.4.3 Supply Management

Digital technologies not only make it possible to adapt demand to capacity, but also to adapt capacity itself to demand. Software-defined networking (SDN) can dynamically adapt capacity to demand by virtualizing infrastructure (Knieps 2017) and providing capacity as a service, rather than as a fixed asset.

The concept of SDN appeared in telecommunications as a solution to adapt the existing telecommunications infrastructure to the growing demands of big data. Not only are data flows growing at an exponential rate, they are not as predictable and stable as traditional voice flows. Furthermore, data flows sustain operations of growing relevance that cannot simply be suspended in case of congestion of the network, as was the case with voice traffic.

SDN decouples the physical infrastructure layer from the control layer, and uses software to dynamically adapt capacity in the physical layer to existing demand. If a customer demands more capacity, it is provided in real time. If a customer demands little capacity at a given time, the vacant capacity is used to serve other customers. This is particularly useful for managing bandwidth in large datacenters. Along the same lines, deep-packet inspection (DPI) allows traffic supporting critical applications to be prioritized over non-time-sensitive traffic. “Bandwidth on demand” services are already a reality (Kreutz et al. 2015).

The concept of SDN is being exported to other infrastructure industries, such as electricity. It was originally used for the provision of electricity to datacenters themselves, as a solution to ensure the supply of electricity to critical applications, but SDN is being proposed as a solution to dynamically manage electricity networks. For example, at times of low load, the voltage and operating frequency of the network can be reduced, lowering the cost of operation of the network (Rossetto and Reif, Chapter 9).

The concept of SDN can be exported to transportation. Smarter management of capacity can take the form of smaller vehicles to provide mass-transit services when it is identified that demand is low. Larger and more vehicles can be dynamically assigned when a peak in demand is identified in real time through sensors and predictive algorithms.

As a result, a larger control over the load factor empowers infrastructure managers to adapt the existing capacity of the infrastructure to cope with growing demand without congestion. This ability can also be used in case of unpredictable events, such as black-outs and accidents. In this way, costs can be reduced substantially.

1.4.4 Smarter Networks

Digital technologies empower infrastructure managers to implement more active management of their infrastructure. Such active management mostly consists of identifying and exploiting new complementarities in the organization of the infrastructures, either between the different elements that comprise the network or between the network and the users. Digital technologies empower new network effects that increase efficiency in the management of the network.

While it is not always obvious, the management of infrastructure comprises not only construction and maintenance of the physical elements that comprise the infrastructure, but a more intangible activity of coordination of different infrastructure elements to generate a network out of fragmented physical elements. Infrastructure managers guarantee common standards across different pieces of infrastructure at a national or even supranational level. This is the case with interoperable telecommunications assets, common road characteristics, common rail gauges, electrification standards, signaling in railways, and so on. Over the decades, infrastructure managers have built not only physical assets, but standards and procedures to ensure the complementarity of such assets, for instance through interoperability. They have transformed fragmented physical assets into networks, creating value through this transformation.

Digital technologies enable infrastructure managers to better identify and exploit new complementarities, new forms to manage the fragmented assets they control, and optimize the coordination to seamlessly provide an optimized service. Infrastructure management is a complex task, as infrastructure is formed by a high number of assets, often scattered across the territory. The coordination of such assets is often subject to long-lasting traditions and ways of doing things, even to rigid regulations. Many such rules have, as their scope, the coordination of the fragmented assets into fully functioning networks. However, such rules might have very high transaction costs. They might be the result of outdated procedures and technologies. The digitalization of infrastructure empowers infrastructure managers to fully exploit network effects across their assets. This often requires reviews of long-lasting procedures, standards and rules, and even formal regulations on the way infrastructure is operated.

The more active the management of infrastructure, the more relevant the role of the infrastructure manager in this intangible role of building networks on top of fragmented infrastructure. All infrastructure managers have the opportunity to use technology to optimize the coordinated operation of the physical assets that comprise the network. Digitalization facilitates more active management of the infrastructure precisely because it reinforces the intangible role of the infrastructure manager as the system coordinator that identifies and exploits complementarities and network effects. Digitalization helps infrastructure managers build smarter networks.

Active infrastructure management requires full exploitation of the data that can be produced by the infrastructure manager. Infrastructure managers have to produce as much relevant data as possible by installing key sensors in the physical assets they own. Such sensors have to produce massive amounts of data. Such data have to be made available for the organization so that machine learning algorithms produce a digital mirror of the infrastructure, a digital twin *in silico*. Only when data are able to provide information about all the elements that comprise the network can such data be run through algorithms to optimize the operation of the network. Algorithms will be developed not only to automate previously existing functions, but also to develop new forms to exploit the network thanks to the new capabilities made possible by digital technologies.

Just as disruption by digitalization started in the mid-1990s, industrial organization literature advised creating parallel independent units to deal with disruptive innovation (Christensen 1997). It was understood that the legacy organization would not be in a position to transform itself to adapt to disruptive innovation, so only a separate organization would be in a position to develop new innovative products. Many infrastructure managers created such innovation units, labs and so on, many of which are still active. Experience shows that the transformative capability of such units is rather small.

It has been identified that the full exploitation of digitalization in an organization requires a certain level of centralization and requires all the organizations to be involved in the transformation. The most recent literature on industrial organization, inspired by success stories in digital transformation, suggests that the entire organization needs to be involved (Iansiti and Lakhani 2020). All departments have to make their data available for the organization in a consistent form, such data must be embedded into software and algorithmic decision-making, and, finally, decision-making at all levels in the company must be driven by the optimized artificial intelligence processes (Iansiti and Lakhani 2020). Once the process is completed, “we can now build [Artificial Intelligence] and [Machine Learning] models on top of everything. We can search across the entirety of our data sets and do analysis on them.”¹

This is particularly the case in infrastructure management. Active infrastructure management requires the participation of all the organization to produce the relevant data comprising all the assets and all the procedures. If some parts of the company are not digitalized, the digital twin cannot be completed, complementarities cannot be fully exploited, and network effects will not be exhausted inside the organization.

1.5 COORDINATION OF FRAGMENTED INFRASTRUCTURE ECOSYSTEMS

A fundamental challenge for infrastructure managers is that they are only managing a segment of a large complex system, in which other actors with different roles participate, including public authorities. Digitalization can only deliver the best results if all actors engage in the process. Cooperation starts with data sharing. However, some actors have proven reluctant to cooperate in the process, at least at the same pace as their counterparts. Data is only an instrument that can lead to a more efficiently coordinated complex system, but data cannot force actors to coordinate.

1.5.1 Complex Fragmented Systems

Fragmentation is both a challenge and an opportunity for the digitalization of infrastructure. Infrastructure managers are only an element in complex systems. Fragmentation challenges the creation of digital twins in the data layer, as different organizations control their own data and are not always ready to share it. Without such data, it is not possible to develop and implement the machine learning algorithms to automate processes across the whole system. However, fragmentation represents an opportunity, as digitalization can create value by better identifying the complementarities in complex systems and by improving coordination in such systems. However, specific tools have to be developed.

The history of most infrastructure sectors has been the evolution from single assets to large organizations coordinating complex systems to fully exploit scale and network effects. From a railway line to a national railway system; from a vessel to a shipping company with a fleet of large container vessels connecting the largest ports in the world, where they operate their own terminals; from an electricity installation serving a factory, to large regional systems integrating large-scale generation plants, transport, and distribution infrastructure. Monopolization was the natural result of this trend in many infrastructure sectors.

Despite growth to reach scale and exploit network effects, infrastructure managers rarely operate isolated systems, but only a segment of a more complex system. Infrastructure is often vertically separated from the provision

of transport services. Companies managing roads, airports and ports do not operate transport services. Different companies operate trucks, coaches, aircraft, and ships. Horizontally, infrastructure management is also fragmented, as infrastructure managers have a limited geographical scope, and services across territories require the coordination of different infrastructures. This is mostly the case with international services. In regions with a high number of closely related small countries, such as Europe, fragmentation is a fundamental challenge.

Furthermore, since the early 1990s, regulation has reversed the concentration trend in infrastructure management. Deregulation and liberalization have introduced further horizontal fragmentation, as newcomers have been allowed to enter the market in competition with incumbent operators, often state-owned monopolies. This has been the case with telecommunications, transport and electricity, among others. Furthermore, regulation has imposed different degrees of separation in vertically integrated companies exploiting infrastructure and the services on top of it. This has been the case with separation in the European electricity and railway markets.

Infrastructure managers operate in highly fragmented and complex systems. Aviation provides a good example. Airports tend to operate as isolated ventures, but they form part of an international network of airports, used by hundreds of airlines, which have to be coordinated by national air traffic control entities. The system becomes even more complex when aircraft manufacturers, ground-handling service providers, travel agents and passengers are taken into account. Transport is formed by different modes, each of which is complex in itself, with little or no coordination across transport modes. A similar picture can be drawn for the energy sector.

The current coordination of such complex ecosystems is expensive, rigid, and does not always deliver in terms of the efficiency. First, some companies internally coordinate large and complex systems. Second, market mechanisms play an increasingly relevant role in the coordination between different companies. Third, a mesh of international organizations, trade associations, conferences, and bilateral meetings support the coordination of such complex ecosystems. Finally, regulation plays an increasing role, in the form of standard-setting, interoperability obligations, access to infrastructure regulation, and so on, with independent regulatory authorities playing an increasing role in the management of infrastructure. Still, transaction costs are very substantial, the systems are very rigid and averse to innovation, and coordination tends to be poor.

1.5.2 Coordination in the Data Layer

Digitalization provides an alternative model for the coordination of fragmented complex systems. Instead of integrating assets into a single organization to impose a hierarchical coordination to fully exploit network effects, digital technologies enable efficient coordination in the data layer of independent organizations, creating a network of networks.

It is interesting to return to the experience of how the Internet evolved. The Internet is not a network managed by a single organization. On the contrary, it was born with the objective of interconnecting pre-existing isolated computer networks so they could interoperate and form a single network. The term “internet” is an abbreviation of “interconnected network.” Further, the Internet was not built through the standardization of a pre-existing infrastructure. On the contrary, the strategy was to create a new standard on top of the pre-existing standards in each computer network, the TCP/IP (Transmission Control Protocol/Internet Protocol), based on a layer approach. Instead of modifying the pre-existing physical layer, new common layers would be standardized on top of it, creating a virtual logically interconnected network.

This approach was imposed by ARPA (an entity of the US Department of Defense), as a condition to receive funding for the acquisition of computers in the framework of military research projects. It was not the result of a voluntary coordination between universities and research centers. However, ARPA did not impose a hierarchical model under its control, but was satisfied with imposing interoperability in a fully distributed network. ARPA did not have a commercial interest, so it did not try to monopolize the value created by the interconnected network.

Digitalization is creating a new layer on top of physical assets: the data layer. Physical assets are replicated *in silico*, creating a digital twin of each physical asset and each organization. Furthermore, a digital twin can be created for the whole ecosystem, not only for a single organization. The digital twin can also include all the interactions between the different actors in the ecosystem: other infrastructure managers, transport service providers, customers, and so on.

Coordination in complex ecosystems can take place at the data layer. As the construction of the digital twin evolves, it is possible to automate specific coordination functions involving different actors. The efficiency gains to be obtained by improving coordination in a complex system are obvious. The more complex and fragmented an ecosystem is, the higher the efficiency gains and the opportunities to transform the sector. On the contrary, when an industry is managed as a close ecosystem, the need to coordinate with third parties is smaller. This would be the case with water systems and postal companies.

The construction of digital twins in the data layer starts with the exchange of the data by the different organizations in the same ecosystem. Data is the

raw material for the construction of the data layer. However, organizations are becoming very strategic in the management of their data and are increasingly reluctant to share a resource that might become a competitive advantage or, even more relevant, the catalyst for change in the structure of the system.

1.5.3 Data Pools and Data Sharing

Digital transformation requires the production and exploitation of data on all relevant assets and processes. This is proving a challenge inside a single organization, and it is certainly even more difficult when data has to be shared across organizations. There are different solutions.

Some organizations are thriving based on the concentration of massive amounts of data, particularly the large US and Chinese digital platforms. Companies such as Google, Facebook, and their Chinese counterparts, have developed a successful business model consisting of the exchange of services for data. Users receive all types of zero-rate services (search, email, social networks, etc.) in exchange for data that is generated while using the service. Digital platforms can also amass massive volumes of data by intermediating in business transactions between third parties, as is the case with Amazon in retail and Uber in transportation. As intermediaries, platforms acquire data from business users providing products and services in the market, as well as data on consumption from users acquiring the products and services. Digital platforms are not keen to share the data they acquire with third parties, given that data and the artificial technology tools to process data represent their competitive advantage, the so-called “data advantage.”

Traditional companies struggle to compete with the large digital platforms in the acquisition of data. They can optimize data generation in their processes, but such data will always be limited to their operations, and therefore of limited value in order to coordinate with the rest of their ecosystem. There is obvious value in the exchange of data between players in the same ecosystem (business-to-business data sharing, or B2B). By sharing data, traditional organizations can create a large data pool to support their digital transformation.

The simplest approach is the bilateral exchange of data between organizations that are working closely together. This is the case with ports and shipping, railway infrastructure managers, railway operators, and so on. Since business processes and contracts for the exchange of services are already in place, it is relatively easy to upgrade the existing arrangements to include data sharing.

More challenging, but also more fruitful, is the creation of data pools by sharing data across multiple organizations. From an operational perspective, the combination of data from different sources poses serious interoperability challenges. There are increasing efforts to manage data according to FAIR principles: findability, accessibility, interoperability, and reusability. Data

quality is another problem. Further than that, the creation of data pools faces a governance problem. The organizations sharing data must agree on the conditions of such a sharing, including the technologies to be used and the identity of the organization managing the data pool. The European Commission has started to work on a regulation on data governance, which includes rules on data sharing services provided by neutral parties, including a notification obligation, using the data only for the declared purposes, ensuring security, and so on. The possibility to create “data cooperatives” is included in the draft regulation.²

Data sharing poses a more fundamental challenge: organizations are increasingly reluctant to share their data; they are afraid to share a valuable resource and lose potential “data advantages” they might have. On a deeper level, organizations are reluctant to share data as they are aware that data sharing is just a tool for more coordination, more demanding integration of assets and services into new networks in the data layer and, potentially, losing control of their assets.

Infrastructure managers are often accused of refusing to share their data and to integrate into virtual networks. They might not have incentives to share their data and to work closely with other actors, as they enjoy market power and even legal monopolies, and are satisfied with the status quo. Downstream companies that depend on the use of infrastructure tend to face more competition, and are increasingly asking for the acceleration of the digital transformation of their ecosystems, putting pressure on infrastructure managers, who they perceive as slowing down reform practices. This would be the case with shipping companies demanding more data sharing with ports, and also with airlines demanding the digitalization of air traffic management.

Compulsory data sharing might be necessary for the creation of strategic data pools. The European Union has set the principle that “a data access right should only be sector specific and only given if a market failure in this sector is identified/can be foreseen, which competition law cannot solve.”³ However, the Commission has identified ten strategic sectors that would benefit from the creation of a European “data space,” committing to overcome legal and technical barriers to data sharing, devoting financial resource to the creation of such data pools, and in some cases to imposing data sharing obligations. Transport and energy are identified as strategic sectors for the creation of data spaces.

The European Union has already started legislative action to incentivize and occasionally impose compulsory data sharing in transportation. Action has been sector-specific. In maritime transport, a regulation has been adopted to create the Maritime Single Window⁴ and there are plans to adopt a regulation on electronic freight transport information (Tsvetkova, Gustafsson and Wikström, Chapter 5). In land transportation (road and railways), the Directive on Intelligent Transport Systems⁵ imposed National Access Points concen-

trating data on transport from different providers (Montero, Chapter 6). Data sharing and governance rules for the digitalization of air traffic management are under preparation (Arnold and Casullo, Chapter 7).

Energy is another strategic sector for which the European Commission has decided to create a specific data space. The Commission has proposed adopting legislation setting out the interoperability requirements and procedures for access to data. In the electricity industry, data sharing is perceived as an instrument to create new market mechanisms for better coordination of the different actors in the industry (Rossetto and Reif, Chapter 9).

1.5.4 Retail Platforms and Data Sharing

Digitalization provides interesting tools to optimize access by consumers to services. Digital platforms are aggregating the supply of services, even across industries, facilitating decision-making for the consumer. This poses a fundamental challenge for traditional players.

Aviation poses the first and probably one of the most elaborate examples of digital platforms in the network industries, as well as the first experience of regulation of a digital platform (see Arnold and Casullo, Chapter 7). As already advanced at the beginning of this chapter, the technology developed by IBM for the US Air Force in the 1950s was later used for the first computer reservation system, SABRE. Amadeus would later develop the European counterpart, in a good example of cooperation between airlines to share data and create a data pool of flights so that travel agents would have access to data on available flights and prices, and also the possibility to book and pay for a ticket. Amadeus would later become an independent company, intermediating between airlines (and also railway undertakings, hotels, and so on) and both traditional and online travel agents. Data provided by airlines would be standardized and quality assured. The digital platform, on the contrary, would be subject to transparency and non-discrimination obligations in the display of the aggregated supply. Tensions are common, as the largest airlines tend to think that such a digital intermediary is unnecessary, as they can commercialize their own products by directly engaging with passengers, and save the commissions charged by the digital intermediary.

Digital platforms can aggregate the supply of all kinds of services, as well as services in the network industries. The more fragmented an industry is, and the poorer the coordination of the fragmented supply, the larger the potential of the digital platforms. Uber's entry in the urban transportation industry was facilitated by the extreme fragmentation and the lack of coordination in the taxi industry. Uber created a network on top of cars, a network at the data layer, creating major efficiencies (reduction in waiting times for passengers and reduction of empty runs to drivers). Over time, passengers would use the

digital platform directly to have the cars dispatched to them, reaching the point where some passengers understood that the transport service was provided by Uber, and not by the independent driver. Uber, of course, would take a commission for the intermediation and coordination of the underlying services.

Urban transportation provides obvious opportunities for digital platforms to aggregate the supply of urban transport services, all services, into a seamless multimodal proposition in the situation to compete on price and convenience with private vehicles. This is the proposition in the name mobility-as-a-service (MaaS) (see Cruz and Sarmento, Chapter 4 and Montero, Chapter 6). Passengers would directly approach the platform to contract the combination of transport services optimized by the platform's algorithms to meet passenger needs. Incumbent transport service providers are losing their direct relationship with the passenger, being intermediated and increasingly coordinated by digital platforms. Large urban transport providers are reluctant to participate in these types of schemes (Carballa-Smichowski 2018), just as large airlines are reluctant to collaborate with computer reservation systems.

Under the data sharing label, platforms are often requesting not only access to data, but to the right to distribute the goods and services provided by traditional companies. Digital platforms have the aim of intermediating traditional players, aggregating not only data about their services, but also the possibility to contract and pay for them.

The creation of network effects is not limited to one industry. Platforms can aggregate the supply across different industries. This is the case with various long-distance transport modes in computer reservation systems and different urban transport modes in MaaS, as with various electricity producers, particularly new alternative generation producers (Rossetto and Reif, Chapter 9). Furthermore, platforms can identify and exploit new complementarities across industries, such as the coordination of transport and electricity services for the management of electric vehicles and so on (Finger and Montero, Chapter 11). This poses a fundamental challenge to the current institutional arrangement for the regulation of infrastructure, which is strictly separated in silos with different regulators for each type of infrastructure.

1.5.5 Business-to-Government Data Sharing

Business-to-government (B2G) data sharing means that private companies supply data that a public authority (re-)uses for public interest purposes (Alemanno 2018).

Public authorities play different roles in infrastructure management. They exploit their own infrastructures, either directly or through state-owned enterprises. They are also important customers of such services when provided by private entities. Furthermore, public authorities have powers to impose obli-

gations on infrastructure managers and service providers to ensure safety and other public values such as continuity of the service, affordability.

Digitalization can facilitate state intervention and public interest purposes. Better information can facilitate the role of the state as a regulator of infrastructure-based industries. Public authorities might have the ambition to use digital technologies to better coordinate fragmented systems, updating a leadership role they often had in these sectors. As an example, local governments are taking a leadership role in MaaS projects, and in general in Smart City projects.

Public authorities are increasingly active in the acquisition of data for the development of their policies, and employ a variety of tools to have access to data; they also generate data from their own assets and activities. Public authorities have a central role in modern societies, and therefore enjoy a privileged position to generate relevant data. Public authorities can generate data for their own activities and they can also share such data with private entities. There is increasing legislation obliging public authorities to share their data with private citizens, such as the EU Directive on open data and the re-use of public sector information.⁶

Public authorities can also engage with private entities to have access to data generated by private entities on a voluntary basis. Public authorities can buy data in the market from data intermediaries, just as any other person can. There are increasing examples of companies “donating” data to public authorities as part of corporate responsibility programs. Public authorities are creating adequate governance frameworks to ensure the right organizational structures receive the data, as well as legal certainty for the donors (High-Level Expert Group on Business-to-Government Data Sharing 2020).

Public authorities can also nudge data owners to share their data, and they can use their power as users of infrastructure-based services through public tender conditions to have access to data. They are increasingly defining data sharing as a condition in granting its use in the public domain. This is often the case for the new micro-mobility shared fleets of bicycles and scooters. Data sharing is increasingly imposed as a condition in tenders for the provision of public services, particularly in transportation.

Finally, public authorities are imposing data sharing obligations on private entities through the adoption of legislation. While there are clear general interest objectives that justify such a requirement, obligations should be proportionate and guarantee personal data protection rights.

1.6 DISRUPTION: NEW PLAYERS AND NEW MARKET STRUCTURES

1.6.1 Platformization

While digital technologies empower infrastructure managers, they can also disrupt infrastructure industries and existing infrastructure managers. There is abundant literature on disruption caused by digitalization (e.g., Christensen 1997; Gans 2016). The infrastructure industries are being disrupted by new players in the data layer, the digital platforms, which are outperforming traditional managers in the coordination of infrastructure, creating larger and more powerful network effects.

Digitalization enables infrastructure managers to fully exploit network effects inside their organizations. With more data, and new tools to manage such data, infrastructure managers are in a position to identify and exploit new complementarities and coordinate their assets in a more efficient form. Digitalization helps infrastructure managers build the most efficient network from the assets they own.

However, the more fragmented a sector is – and infrastructure industries tend to be highly fragmented – the more relevant the collaboration is between different actors. Efficiencies derived from digitalization will only materialize if actors share data and, even more importantly, actors are ready to transform business processes to fully exploit new complementarities identified in the data layer. Infrastructure managers have the challenge to collaborate with other actors, often competitors, to build the most efficient network from the assets owned by different organizations.

Experience shows that traditional players are reluctant to share their data and engage in new forms of collaboration. This is definitely the case in the infrastructure-based industries. Collaboration for the digitalization of these industries is proving to be challenging. There are a high number of actors and some of them (particularly those with market power position) cherish the status quo. The traditional collaboration structures are slow and expensive. New governance models for data sharing and making use of data are not mature. Finally, collaboration poses competition law challenges. Even the simplest forms of collaboration, such as port-call optimization, are not materializing (Tsvetkova, Gustafsson and Wikström, Chapter 5). Some players are even pushing to terminate data sharing in long-lasting collaboration schemes, such as computer reservation systems in aviation (Arnold and Casullo, Chapter 7). The largest players in each industry perceive their larger network effects as a competitive advantage over smaller competitors.

Disruption in infrastructure industries is coming not from smaller competitors, but from new players in the data layer with the capability to aggregate supply from different traditional players and build the largest network effects. As infrastructure is digitalized, and a mirror is created at the data layer, new players have the ability to identify and exploit new network effects, not only within each organization (direct network effects), but also across organizations (indirect network effects), exhausting algorithmic network effects (Montero and Finger 2021).

The more fragmented an industry is, and the smaller the collaboration between industry players, the higher the chances are that a newcomer active in the data layer, a digital platform, will make use of data and algorithms to exploit new complementarities and acquire a competitive edge (Tsvetkova, Gustafsson and Wikström, Chapter 5). This has been the case with Uber and the taxi industry, the most fragmented transport industry where network effects were completely absent (Montero and Finger 2021).

Digital platforms are becoming leaders in the new data layer. Once an industry is digitalized and a data layer is created on top of it, transaction costs can be drastically reduced. The Internet reduces communication costs to zero; algorithms reduce search costs, information costs and bargaining costs. Digitalization enables mechanisms to increase trust and reputation (OECD 2017). Digital platforms are exploiting digital technologies and the reduction in transaction costs to intermediate in the provision of goods and services, aggregating the supply from different traditional players, coordinating assets in a smarter form, and making them available for users. Digital platforms are taking the lead in the identification and exploitation of new network effects.

Digital platforms are transforming the traditional industrial organization paradigm of large vertically integrated corporations selling goods and services to consumers, into a new model in which online platforms create a multisided market facilitating interactions between supply and demand (Rochet and Tirole 2003; OECD 2009; Evans and Schmalensee 2016). Digital platforms transform the market structure, becoming the coordinators of the ecosystem around them. “Platformization” is the process of transformation of a traditional market into a multisided market coordinated by a platform. Platformization is already mature in the media industries, very advanced in telecommunications, and starting in transport and energy (Montero and Finger 2021).

Experience shows that digital platforms do not aim to substitute traditional infrastructure actors. They have no ambition to build their own infrastructure or displace traditional players in the design, construction and maintenance of assets. On the contrary, digital platforms aim to intermediate the goods and services produced by third parties, aggregate them into a single offer, and coordinate the different assets and services in a more efficient form thanks to the use of digital technologies.

Digital platforms aim to displace traditional players as coordinators of the complex systems in each industry. Having access to all the supply, and not merely to the assets owned by a single firm, and having the power of digital technologies, they are in a position to build network effects at a much larger scale than traditional players. This is the ultimate reason why the more fragmented an industry is, the higher the chances of platformization.

As transaction costs are reduced, new service providers working at a small scale can enter the market. Small and non-professional service providers can enter markets previously dominated by large firms. Non-professional drivers can provide transportation services (Montero 2018). User-generated content becomes increasingly relevant in the telecommunications and media industries. Consumers are starting to produce electricity at their premises and, thanks to platforms, are in a position to exchange it with other users (Rossetto and Reif, Chapter 9).

The larger the pool of actors interacting through the platform, the larger the network effects; the more interactions, the smarter the platform becomes (algorithmic network effects). The value created by online platforms should not be underestimated. Network effects grow as the number of users grows. Interesting studies are being developed on the valuation of network effects (for a critical analysis, see Briscoe et al. 2006). Platforms are internalizing massive network effects as they pool incredibly large volumes of users. The most successful platforms measure users by the billions (e.g., Facebook, WhatsApp, YouTube).

Digital platforms are transforming traditional infrastructure network industries into multisided markets. The traditional direct link between service providers and users is being substituted by an intermediated relationship, in which an online platform intermediates in the relationship and matches service providers and users. Service providers become a mere component in a multi-sided market, the service is “commoditized,” and the online platform takes the lead in the coordination of the system.

1.6.2 Challenges Posed by Platformization

Platformization poses new challenges to traditional players in infrastructure-based industries. First, digital platforms introduce new competitive pressure on traditional service providers. Platforms provide new commercialization possibilities to smaller competitors in the network industries. As network industries are opened to competition, smaller competitors struggling to replicate the incumbents’ commercialization networks have access to powerful commercialization networks created by digital platforms. This has been the case, for instance, in the railway industry (Montero, Chapter 6). Furthermore, platforms enable market entry to new entities, particularly

non-professional service providers trying to commercialize spare capacity in assets they own. Platforms empower the sharing economy. This is the case of spare capacity in private cars (Montero 2018), or of “prosumers” in the electricity market (Rossetto and Reif, Chapter 9).

Digital platforms’ competitive pressure is increased not only because they enable market entry to new players, but also because consumers are empowered by access to more information. Platforms reduce information asymmetries as they provide consumers with more visibility about contracting options offered by different suppliers. Consumers can compare contracting conditions, including prices.

Second, platformization commodifies the products supplied by infrastructure managers. Digital platforms not only aggregate supply, but over time they try to homogenize service conditions. In order to build network effects, platforms try to standardize the services they intermediate, so that consumers can easily recognize them and they have a seamless experience across different service providers. Homogenization is a requirement for building new network effects on top of assets owned and operated by third parties. As the underlined products supplied by third parties are homogenized, competitive pressure is further increased – service providers can only compete on price.

The final stage in the process of platformization is reached when digital platforms have the power to coordinate the underlying services. Consumers perceive the service as provided by the platform, according to the conditions defined by the platform. The underlying service providers become mere providers of interchangeable assets, working for the platform’s algorithms and adding no value to the service. The platform becomes the organizer of the service and it sets prices and the rest of conditions, monopolizing the value created by the new industrial organization model. Infrastructure managers end up becoming the managers of “dumb” infrastructures, as platforms displace them from the intangible role of building networks on top of fragmented assets.

Third, a structural effect of platforms on the funding of infrastructure can be identified. As infrastructure managers become mere sides in a multisided market and the role of the platform is reinforced, platforms achieve the power to apply pressure to reduce the price of the underlying services, as well as the power to extract value from the industry in the form of commissions for the provision of the service. There is evidence from other industries, particularly the media industry, that platforms might end up diminishing the value traditionally captured by infrastructure managers, either because such value is captured by the platforms themselves (commissions), or because it is eroded by the new competitive pressure created by the platforms. Even if platforms bring efficiency to the infrastructure industries, they might increase the difficulties for funding the creation and maintenance of infrastructure.

This evolution poses a challenge not only to traditional players, but also to regulators. Regulatory intervention to guarantee principles such as the continuity of infrastructure-based services, affordability and non-discrimination, traditionally took the form of obligations imposed on the entities exploiting infrastructure and services. The general interest in the correct functioning of infrastructure is not going to be terminated in the case of platformization of these markets. However, new regulatory tools might be necessary to make public intervention effective, tools that involve imposing obligations on digital platforms.

1.6.3 The Digitalization Dilemma

Digitalization poses a dilemma to traditional players, including infrastructure managers. On the one hand, digitalization increases efficiency in the management of infrastructure. As described, digitalization, algorithms and automation reduce the cost in the design, construction, maintenance and operation of infrastructure. On the other hand, as digitalization creates a data layer on top of the infrastructure, new players can use the data to transform the structure of the industry. Online platforms can create multisided markets in which infrastructure managers become just one side in a multisided market, a commoditized provider of services under the coordination of the digital platform. The platform reduces the value traditionally captured by the infrastructure manager, as new competitive pressure destroys value and the platform has the ability to capture its own share of value. This is particularly relevant in infrastructure network industries, as the availability of funds for the construction and maintenance of infrastructure has to be ensured.

This is the digitalization dilemma: when traditional players digitalize their operations, they are facilitating the transformation of their industry into a multisided market, with a third party, the online platform, eroding the value traditionally captured by the infrastructure manager, and taking the role of the coordinator of the market, and the power that such a position entails.

Infrastructure managers, as well as regulators, are not bound to be mere spectators in the process of digitalization and emergence of new market structures. Lessons can be learned from other industries that have been put under a platform, or “platformed” (Montero and Finger 2018). Infrastructure will always be necessary. Infrastructure managers have to adapt to the evolution of the market structure and find the right place in the new ecosystems; in fact, traditional infrastructure managers have been adopting different strategies.

Infrastructure managers might be tempted to reduce the speed of digitalization, or even not to digitalize their infrastructures at all, in order to delay the rise of platforms in their industries. This might not be a wise strategy and does not appear to be in the general interest. Efficiencies derived from digitalization

are too significant to be ignored. Even more importantly, this strategy might not work in the long run. As in a traditional “prisoner’s dilemma,” competitors (where they exist) might embrace change and monopolize the benefits of a good relationship with the platform operator, making the position of the traditional player even weaker.

Even infrastructure networks run by a monopoly might not succeed in avoiding the rise of a platform by delaying digitalization. The infrastructure manager installing sensors can extract data about infrastructure, but third parties can also extract it in the most creative ways. For example, data on traffic can be extracted from passengers’ smartphones, from sensors installed in vehicles using an infrastructure, from sensors installed in the cargo being transported, by meters used by the users of electricity networks, and so on. Platforms can be built over data generated by third parties, not only data generated by the infrastructure managers themselves.

Traditional companies can expand into neighboring segments in order to create larger network effects. This strategy can be identified in the maritime industry; as large shipping companies have grown large fleets of container ships, they operate their own terminals in ports, and are providing logistic services in the hinterland (Tsvetkova, Gustafsson and Wikström, Chapter 5). A similar strategy can be identified as some traditional players become multi-utilities (Espinosa Apráez, Chapter 10).

Infrastructure managers can vertically integrate into the data layer and build platforms for their industries. This is a common strategy and there are many examples of infrastructure managers creating platforms, such as railway operators, shipping companies, telecom operators and electricity utilities. They have an ambition to intermediate not only in the provision of their services, but also in the provision of services by third parties, sometimes close competitors. Obviously, other service providers are suspicious and tend not to participate in platforms managed by competitors, as they are afraid they would be discriminated against – in favor of the operations of the competitor managing the platform. There are successful platforms led by vertically integrated companies, such as Amazon Marketplace, but it seems clear that not all players in an industry can become platform operators. This is not the way forward for all infrastructure managers.

The challenge for all actors (infrastructure managers, candidates to become platforms, users, public authorities funding infrastructures, and also regulatory authorities) is to ensure the emergence of a balanced and sustainable competitive environment. However, the system will only be sustainable if the new value created is fairly distributed, and particularly if infrastructure managers are not deprived of the funding necessary for maintenance and construction.

1.7 FURTHER CHALLENGES

Digital technologies create new risks in the management of networks. Technology is a cost in itself, and a burden if the wrong choices are made in its deployment. Furthermore, technology not only empowers infrastructure managers, but also infrastructure users. They can modify their usage patterns and find alternatives to reduce their expenditure. Therefore, uncertainty in the distribution of traffic flows might increase. Finally, technology brings new security risks in the form of cybersecurity threats.

First, technology is a cost in itself, which adds to the already high costs associated with the deployment and maintenance of infrastructure. While it is true that there is large potential to increase efficiency in the operation of infrastructure thanks to technology, there is the risk of the investment not paying off.

Investment in technology will not deliver results in different scenarios. The wrong technology might be deployed, in such a way that efficiency is not created. Along the same lines, the technology deployed might bring benefits, but these are limited as the life cycle of digital technologies tends to be much shorter than that of traditional infrastructure. Constant investment and upgrades might be necessary.

Second, technology not only empowers infrastructure managers; it also empowers users, giving them more information about alternatives, and the ability to switch to such alternatives. Infrastructure managers have traditionally operated with little or no competition, either from direct competitors (monopolies have always abounded in infrastructures) or from other infrastructures, offering some degree of substitution. Technology is now offering new alternatives.

Digitalization has created new services that directly compete with traditional infrastructure-based services. In some cases, the new digital services are displacing the old physical services. Postal services are the best example, as letter mail is being displaced by electronic mail at a rate of 4 percent to 7 percent annually worldwide (Finger et al. 2014). Under these circumstances, it is evident that revenue has severely declined (see Jaag, Chapter 8).

Digitalization has helped new service providers enter the market, reducing the traffic managed by traditional infrastructure managers. This is the case with long-distance car-pooling services in the sharing economy (Montero, Chapter 6). Railways faced limited competition from air and particularly road travel in countries such as France, where the service was provided by SNCF under exclusive rights and parallel coach services were traditionally prohibited until the 2015 “Loi Macron.” Recently, technology has empowered passengers to contact private drivers to get a ride to their destination through more sophisticated forms of car sharing. As a result, railways experienced passenger losses

of 6–10 percent in 2015 (Montero 2018); coach companies in Spain claim a 20 percent revenue reduction for the same reason (Montero 2018).

Digitalization is not only enabling users to select infrastructure-based services, but also to optimally combine them. This is particularly the case in transportation, as different networks provide partial services and often lack a door-to-door service (for both passengers and goods). Digitalization and algorithms allow users to identify the existing options and the fastest/cheapest combinations of transport modes. Therefore, users can migrate to new transport modes as they have better information.

In this framework, not all infrastructure has the same potential to reduce costs, or to reduce them at the same pace or amount due to digitalization. Road transportation costs might be substantially reduced as automation (autonomous vehicles) is implemented for freight and passenger transportation. Road transportation might gain a competitive advantage over railways. These secondary effects are beyond the control of infrastructure managers and they add uncertainty in the planning of investments in infrastructure.

Cybersecurity is a new risk associated with the digitalization of infrastructure. Digital technologies create new vulnerabilities. Services can collapse due to software bugs or attacks by hackers. Infrastructure managers must invest in technology to solve the vulnerabilities created by digitalization (see Espinosa, Chapter 10).

The most advanced nations are imposing obligations on infrastructure managers to protect infrastructure from cyberattacks. The legal category of “critical infrastructure” has been defined both in the USA and the EU. Public authorities have defined which infrastructure is considered to be critical for the well-being and security of society. Communications, transport, energy and water are considered critical infrastructure, as is the information technology sector. Specific plans are defined by public authorities, and each manager of a critical infrastructure must define its own plan against cyberattacks. Information is shared between public authorities and infrastructure managers, as well as between governments of different nations.

Privacy is a new challenge. As infrastructure managers start managing an increasing volume of personal data, they come under the scope of data protection legislation. This is particularly the case of the European Union and Regulation 2016/679 (General Data Protection Regulation). All processes involving personal data have to be defined by taking into consideration the implication on privacy (privacy by design). Data breaches have to be communicated to the authorities; companies that fail to do so are subject to hefty fines that might reach 4 percent of annual worldwide turnover (Espinosa, Chapter 10).

Overall, technology is introducing more uncertainty into the management of infrastructure networks. Even if technology is providing new instruments

to predict and manage traffic flows, technology is also empowering users to make more effective use of existing infrastructures, and to introduce more competition among infrastructure providers.

NOTES

1. Ludo Hauduc, general manager of Microsoft core platform team, in Iansiti and Lakhani 2020, pp. 108–9.
2. European Commission COM(2020) 767 final. Proposal for a regulation of the European Parliament and the Council on European data governance, Data Governance Act, November 25, 2020.
3. European Commission, A European strategy for data, COM (2020) 66, February 19, 2020, p. 13.
4. Regulation (EU) 2019/1239.
5. Directive 2010/40/EU.
6. Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information, OJ L 172/56, June 26, 2019.

REFERENCES

- Agrawal, A., Gans, J., & Goldfarb, A. (2018). *Prediction Machines: The Simple Economics of Artificial Intelligence*, Boston, MA: Harvard Business Review Press.
- Alemanno, A. (2018). Big data for good: unlocking privately-held data to the benefit of the many. *European Journal of Risk Regulation*, 9(2): 183–91.
- Baran, P. (1964). *On Distributed Communications: I. Introduction to Distributed Communications Networks*, Santa Monica, CA: RAND Corporation.
- Blanco, F.G.B. & Chen, H. (2014). The implementation of building information modelling in the United Kingdom by the transport industry. *Procedia – Social and Behavioral Sciences*, 138: 510–20.
- Briscoe, B., Odlyzko, A. & Tilly, B. (2006). Metcalfe’s law is wrong – communications networks increase in value as they add members – but by how much? *IEEE Spectrum*, 43(7): 34–9.
- Carballa-Smichowski, B. (2018). Determinants of coopetition through data sharing in MaaS. *Management and Data Science*, hal-01872063.
- Carr, N. (2008). *The Big Switch: Rewiring the World from Edison to Google*, New York: W.W. Norton.
- Christensen, C.M. (1997). *The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail*, Cambridge, MA: Harvard Business Review Press.
- Christian, B. & Griffiths, T. (2016). *Algorithms to Live By: The Computer Science of Human Decisions*, London: William Collins.
- Cortada, J.W. (2019). *IBM: The Rise and Fall and Reinvention of a Global Icon*, Cambridge, MA: The MIT Press.
- Court des Comptes (2018). Les compteurs communicants Linky: tirer pour les consommateurs tous les bénéfices d’un investissement coûteux. Rapport public annuel 2018, February 2018.

- Daneshkhah, A., Stocks, N.G. & Jeffrey, P. (2017). Probabilistic sensitivity analysis of optimised preventive maintenance strategies for deteriorating infrastructure assets. *Reliability Engineering & System Safety*, 163: 33–45.
- European Commission (2015). Study on the cost benefit analysis of smart metering systems in the EU Member States, by ICCS-NTUA & AF Mercados.
- European Commission (2020). *White Paper on Artificial Intelligence – A European Approach to Excellence and Trust*, COM(2020) 65, 19.2.2020.
- Evans, D.S. & Schmalensee, R. (2016). *Matchmakers: The New Economics of Multisided Platforms*, Boston, MA: Harvard Business Review Press.
- FCC (1966). *Notice of Inquiry in the Matter of Regulatory and Policy Problems Presented by the Interdependence of Computer and Communications Services and Facilities*. Docket F.C.C. No. 16979, November 9, 1966.
- Finger, M., Bukovc, B. & Burhan, M. (eds.) (2014). *Postal Services in the Digital Age*, Amsterdam: IOS Press.
- Gans, J. (2016). *The Disruption Dilemma*, Cambridge, MA: The MIT Press.
- Gartner (2017). Technology insight: edge computing in support of the internet of things. Report July 13, 2017.
- Hafner, K. & Lyon, M. (1996). *Where the Wizards Stay Up Late: The Origins of the Internet*, New York: Simon & Schuster.
- High-Level Expert Group on Business-to-Government Data Sharing (2020). *Towards a European Strategy on Business-to-Government Data Sharing for the Public Interest*, retrieved from <https://ec.europa.eu/digital-single-market/en/news/experts-say-privately-held-data-available-european-union-should-be-used-better-and-more>.
- Iansiti, M. & Lakhani, K.R. (2020). *Competing in the Age of AI: Strategy and Leadership when Algorithms and Networks Run the World*, Cambridge, MA: Harvard University Press.
- IDC (2020). *Worldwide Global DataSphere Forecast, 2020–2024*, retrieved from <https://www.idc.com/getdoc.jsp?containerId=US44797920>.
- Jardine, A.K., Lin, D. & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mechanical Systems and Signal Processing*, 20(7): 1483–510.
- Knieps, G. (2017). Internet of Things, future networks and the economics of virtual networks. *Competition and Regulation in Network Industries*, 18(3–4): 240–55.
- Kreutz, D., Ramos, F.M., Verissimo, P.E., Rothenberg, C.E., Azodolmolky, S. & Uhlig, S. (2015). Software-defined networking: a comprehensive survey. *Proceedings of the IEEE*, 103(1): 14–76.
- Licklider, J.C.R. (1960). Man–computer symbiosis, *IRE Transactions on Human Factors in Electronics*, HFE-1(1).
- McKinsey (2016). Huge value pool shifts ahead – how rolling stock manufacturers can lay track for profitable growth. Report September 2016.
- Montero, J. (2018). Regulating transport platforms: the case of carpooling in Europe. In *The Governance of Smart Transportation Systems* (pp. 13–35), The Urban Book Series, Cham: Springer International Publishing.
- Montero, J. & Finger, M. (2018). Platformed! Network industries and the new digital paradigm. *Competition and Regulation in Network Industries*, 18(3–4): 217–39.
- Montero, J. & Finger, M. (2021). *The Rise of the New Network Industries: Regulating Digital Platforms*, New York: Routledge.
- OECD (2009). Two-sided markets, Policy Roundtables, OECD Publishing, Paris, retrieved from <https://www.oecd.org/daf/competition/44445730.pdf>.

- OECD (2017). Trust in peer platform markets: consumer survey findings, OECD Digital Economy Papers, No. 263, OECD Publishing, Paris, retrieved from <https://doi.org/10.1787/1a893b58-en>.
- Rochet, J.C. & Tirole, J. (2003). Platform competition in two-sided markets. *Journal of the European Economic Association*, 1(4): 990–1029.
- Ryan, J. (2010). *A History of the Internet and the Digital Future*, London: Reaktion Books.
- Succar, B. (2009). Building information modelling framework: a research and delivery foundation for industry stakeholders. *Automation in Construction*, 18(3): 357–75.
- Tseng, P.H., Lin, D.Y. & Chien, S. (2014). Investigating the impact of highway electronic toll collection to the external cost: a case study in Taiwan. *Technological Forecasting and Social Change*, 86: 265–72.
- Turing, A.M. (1937). On computable numbers, with an application to the entscheidungsproblem. *Proceedings of the London Mathematical Society*, 2–42(1): 230–65.
- Zachary, G.P. (1997). *Endless Frontier: Vannegar Bush, Engineer of the American Century*, New York: Free Press.