Environment Systems and Decisions
https://doi.org/10.1007/s10669-024-09969-8

PERSPECTIVE

Dynamic Infrastructure Systems: advancing sustainable urbanization and climate change

Mauricio Sánchez-Silva[1] · Jack W. Baker[2]

Accepted: 27 February 2024

Abstract

Developing and maintaining infrastructure (e.g., roads, airports, water supply, communication networks, power plants, or hospitals) is a priority in a rapidly changing world. However, the gap between infrastructure needs and investments will continue to increase in the coming years, mainly impacting mid- and low-income countries. This problem is aggravated by the fact that traditional long-term planning approaches often lead to under- or over-designing infrastructure with the corresponding investment risks and environmental impacts. This article introduces the "Dynamic Infrastructure Systems" (DIS) concept as a new way to understand infrastructure design and management to support sustainable continuous growth, maintenance, and adaptation. In scenarios of deep uncertainty, infrastructure can best be designed and managed by creating a strategic vision of the future, committing to short-term actions, and establishing a flexible management policy to guide future decisions. This article is motivated by the urgent need to re-think how a key sector is managed and how to make it a positive contributor to sustainability. After the factual and conceptual discussion of the main principles behind DIS, we present a framework for its implementation in practice and discuss barriers and challenges to this vision.

Keywords Dynamic infrastructure · Sustainability · Flexibility · Management · Built environment

1 Introduction: Infrastructure in the context of sustainable development

The past sixty years have seen unprecedented socioeconomic development. The global population tripled, and life expectancy increased by 50%. In addition, urbanization increased 70%, especially in mid- and low-income countries, GDP grew by 800%, and the value of exported goods and services in the US alone increased by 1000% (World Bank Data 2023; ASCE 2023). These dynamics have also created stresses on aging infrastructure and rapid growth of CO_2 emissions, which severely impact sustainability. In the case of infrastructure (e.g., roads, airports, water supply, communication networks, power plants, or hospitals), a sector that takes a large share of the world's GDP and contributes 40% of global CO_2 emissions (Pomponi and Moncaster 2017; United Nations Human Settlements Programme 2022), there is an urgency to find novel technical solutions to close an infrastructure investment gap that has been growing steadily worldwide during the last decades. This task requires efficient use of limited funding and careful prioritization of investments across sectors and regions. In this article, we will examine the challenges and needs for a new infrastructure development and management approach, emphasizing its contribution to a more sustainable built environment.

The infrastructure deficit to support rapid urbanization is growing, particularly in emerging and developing economies. For example, the average urbanization of South American countries has reached a value close to 80% on average (World Bank 2018; Moran et al. 2018). In these regions, cities are characterized by growing informal settlements that lack basic infrastructure and services. City-related activities are also estimated to consume 78% of the world's energy and produce more than 60% of greenhouse gas emissions (World Bank 2018; Monteiro et al. 2017). A large share of emissions results from the extensive consumption of concrete and steel in construction (Raave et al. 2019; Watari et al. 2023;

✉ Mauricio Sánchez-Silva
msanchez@uniandes.edu.co

Jack W. Baker
bakerjw@stanford.edu

1 Department of Civil and Environmental Engineering, Universidad de Los Andes, Bogotá, Colombia

2 Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA

International Energy Agency). Consequently, in addition to moving towards more sustainable materials, which reduce the environmental footprint of production and manufacturing, it is also necessary to improve performance and longevity (Watari et al. 2023). It is estimated that the world could decrease its infrastructure-related carbon emissions by up to 50% by 2050 through a combination of measures that include making the life cycle of concrete structures more resilient through improved material performance, integrating structural design with risk-based durability modeling, and optimizing construction methods (Raave et al. 2019). Other key strategies include investing in energy-efficient infrastructure, reducing waste, and changing how we build (Global Infrastructure Hub 2021; Thacker et al. 2019). Thacker et al. (Intergovernmental Panel on Climate Change (IPCC) 2021) showed that infrastructure is vital to attaining all Sustainable Development Goals (SDGs).

Population growth and industrialization (mostly in developed countries) also have caused a dramatic growth in GHG emissions during the last 60 years (Hill et al. 2019). This has brought a climate change crisis with worldwide consequences, but with effects felt disproportionally in low-income countries with low resilience levels (Rozenberg and Fay 2019). For example, low-income countries are more likely to experience extreme weather events like floods, droughts, and heat waves. These events can produce food insecurity, water scarcity, displacement, and loss of life. While developing infrastructure in wealthy countries is required to support economic growth and maintain social investments, in mid- and low-income countries, it is also necessary to respond to rapid environmental changes, reach universal coverage of essential services, and foster a minimum economic growth.

Investments in infrastructure can be grouped broadly into (i) developing new infrastructure, (ii) maintaining existing assets, and (iii) adjusting existing infrastructure components (e.g., for climate change adaptation). Studies from several national and international organizations have provided broad estimates of infrastructure investment needs based on various criteria and possible future scenarios (Fig. 1). However, the optimal level of required infrastructure investment depends upon several technical and non-technical factors. Rozenberg and Fay (Environmental Programme 2022) state that the existence of trade-offs between competing goals means that infrastructure planning and investments are inherently political choices. Figure 1 presents a breakdown of investment needs in infrastructure by sector and region until 2030. Transportation and energy will take the largest share worldwide, and investments in social infrastructure (education, health, social services, etc.) are particularly large in North Africa, Southeast Asia, and Latin America. Required

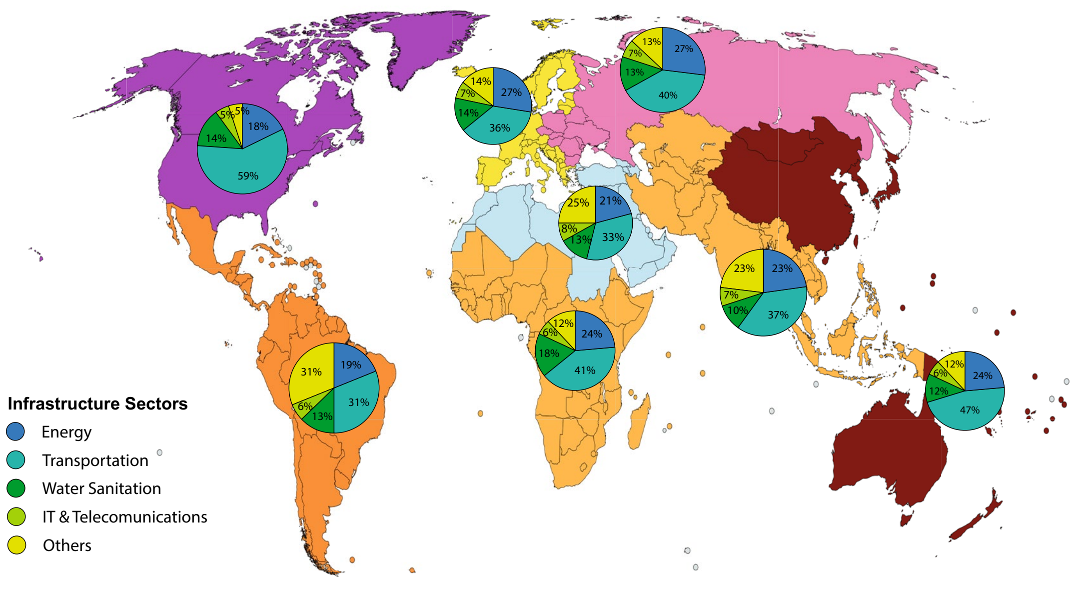

Fig. 1 Relative infrastructure needs by sector and world region as defined by the World Bank. The sector "other" includes infrastructure such as education, healthcare, social services, irrigation, and flood protection. Data are from multiple sources, mostly multilateral agencies, and regional banks (Pomponi and Moncaster 2017; Thacker et al. 2019; Asian Development Bank (ADB) 2017; Brichetti et al. 2021; Africa's Development Bank 2018; European Investment and Bank 2023; UN Inter Agency Task and force on Financing and Development 2023; McKinsey Global Institute 2016; The Global Competitiveness Report 2017; Sánchez-Silva 2019)

global annual investments in infrastructure are estimated at $3.5 trillion to $7.5 trillion, which is 4% to 8% of the world's GDP. Out of these values, annual investments in adaptation measures are estimated to be between 0.5 and 1% of the world GDP (Mauter 2021). Importantly, while needed investments in developing countries are smaller than in developed countries, it is, in most cases, beyond their financial capacity. For example, in the Americas, the US and Canada's needs in infrastructure until 2050 are about $13.2 trillion, while in Central and South America combined, this value is about $6.8trillion (Thacker et al. 2019). The former corresponds to an annual investment, until 2050 of about 1.75% of today's GDP, while for the rest of the Americas, it is about 4.6% (Thacker et al. 2019).

There is an urgent need for a change in strategy and focus. It has been argued that to bridge the value gap in the U.S. infrastructure, it is necessary to build back "wiser" by investing in digitized, versatile, distributed, and inclusive infrastructure systems (Acuña-Coll and Sánchez-Silva 2023). Others have emphasized the importance of flexible infrastructure management policies (Haasnoot et al. 2021; Zimmerman and Faris 2010) and building infrastructure to support ongoing adaptation (Albrechts 2004). In addition, some argue that it is necessary to design dynamic adaptive plans with a strategic vision of the future, commit to short-term actions, and establish a framework to guide future decisions (Ranger et al. 2010; Chester and Allenby 2019). It has also been recognized that current choices about investing in infrastructure will severely impact the world's future. For Thacker et al. (Intergovernmental Panel on Climate Change (IPCC) 2021), "Investment in infrastructure is at an all-time high globally; thus, an ever-increasing number of decisions are being made now that will lock-in development patterns for future generations." Likewise, Chester and Allenby (OECD 2017) state that "today, as we debate what the next infrastructure component should be, we should fundamentally question whether new infrastructure should be more of what we already have or something that does not exist yet. Until we reach that point, we will maintain lock-in and perpetuate systems that may already be obsolete."

In this article, we discuss the importance and value of a new infrastructure management approach based on continuous adaptation. We first examine the importance of incorporating flexibility in infrastructure management to create a more sustainable built environment; to illustrate this point, we reference cases that show this approach's potential. Afterward, we propose a new understanding of infrastructure as dynamic systems to recognize them as continuous flexible processes with a purpose. Then we present a general implementation strategy. Finally, we discuss current barriers and challenges to execution in practice.

2 The emergent idea of continuous adaptation in infrastructure

In many systems, including live organisms, a critical trait for dealing with environmental changes is the capacity to adapt continuously (Sánchez-Silva and Calderón-Guevara 2022). The idea of adaptation and flexibility can be extended to other systems, including infrastructure, where it is defined as "the ability of a system to respond or change some of its design or operational parameters easily to keep or add value continuously when subjected to internal or external demands" (Haasnoot et al. 2012). Flexible systems can manage an uncertain future by changing their physical characteristics or performance (behavior) when required to manage the evolution of external demands as they materialize. Flexibility and adaptation over time are not only determined by what is known or anticipated at present but also by the management policy (Haasnoot et al. 2013) and by what is experienced and learned as the future unfolds (Yohe 1990; Neufville and Odoni 2003). In is important to notice that flexibility and adaptability are interconnected and sometimes interchangeably used concepts. Flexibility is the capacity to easily alter the system's state or performance in response to unforeseen circumstances. It involves being open to different methods or solutions without fundamentally changing the underlying system structure. On the other hand, adaptation encompasses a more profound and enduring environmental adjustment. It involves a systematic modification or evolution in response to sustained changes, often leading to a transformation in the overall structure or strategy. While flexibility allows for short-term adjustments, adaptation implies a more sustained and strategic alignment with the evolving context, reflecting a more profound and lasting transformation.

Flexibility has recently emerged as valuable for infrastructure planning and management in a highly uncertain future (Haasnoot et al. 2021, 2011; Ranger et al. 2010; Hallegatte et al. 2012; Cardin 2014; Neufville and Scholtes 2011; Schwartz and Trigeorgis 2004; Swanson et al. 2010; Lempert et al. 2003), when it is impossible to make well-informed projections based on available data or to reduce uncertainty by gathering additional information (e.g., deep uncertainties) (Ben-Haim 2006; Quade 1989; Nembhard and Aktan 2010). Deep uncertainty refers to a type of uncertainty where decision makers and stakeholders do not know or cannot agree on the likelihood of different future scenarios. It is characterized by limited knowledge, and it is difficult to agree on the relationships between the key driving forces of change (Cardin 2014). Regarding infrastructure, uncertainties come from changes in demand (e.g., population growth), natural events (e.g., increasing sea level, wildfires), and financial and political stability. Thus, in the context of significant uncertainties in rapidly changing environments, the best course of action is to focus on designing clever management strategies. This is a key concept behind Dynamic Infrastructure Systems. Then, the focus is not on creating "unrealistic" predictive models but on developing systems capable of changing and modifying their structure and operation to accommodate and respond to environmental changes. Techniques such as Real Options Analysis, dynamic programming, decision trees, roadmaps, and robust decision-making are management strategies to handle these types of problems. Several authors have reported that incorporating flexibility improves financial performance between 10 and 30%, compared to designs generated using standard procedures (Ranger et al. 2010; Haasnoot et al. 2011; Hallegatte et al. 2012; Cardin 2014; Neufville and Scholtes 2011; Wehrle et al. 2021).

Case studies show the value of implementing flexibility in various types of infrastructure. Examples of flexibility in mechanical systems, such as operation of space and aircraft, have been studied widely (Saleh et al. 2000; Montulli 1986; Reisinger et al. 2021). In the built environment, Reisinger (Guma et al. 2009) studied flexibility in industrial building design to accommodate constantly evolving production processes and improve sustainability. For conventional buildings, Guma et al. (Geltner and Neufville 2018) studied four cases in North America and discussed the potential value of vertical phasing in real estate. A classic application is the construction and development of the Health Care Service Corporation (HCSC) building in Chicago, which was developed in two phases. In 1997, the first 30 stories were built; an additional 27 were added in 2010 in response to growing demand. Phasing real estate and facilitating changes in use is an attractive business opportunity (Empresa de Acueducto de Bogotá 2023) and significantly impacts CO_2 emissions.

The idea of flexibility has also been extended to urban planning, where it has great potential. For example, many cities, such as Chicago, Washington, and London, have developed local adaptation plans structured as a phasing process (Albrechts 2004; Haasnoot et al. 2011). Phasing development in basic infrastructure is natural. Figure 2 presents the evolving capacity of the water supply for the city of Bogotá. The city's water supply increases over time in response to the demand needs by successively adding new components (modularity). The response is based on forecasts, performance monitoring, and a strategic management plan. Note that there has been a sustained drop in water demand since the early 1990s due to some government programs to save water and the subsequent failure of a section of the tunnel that connects Chingaza with

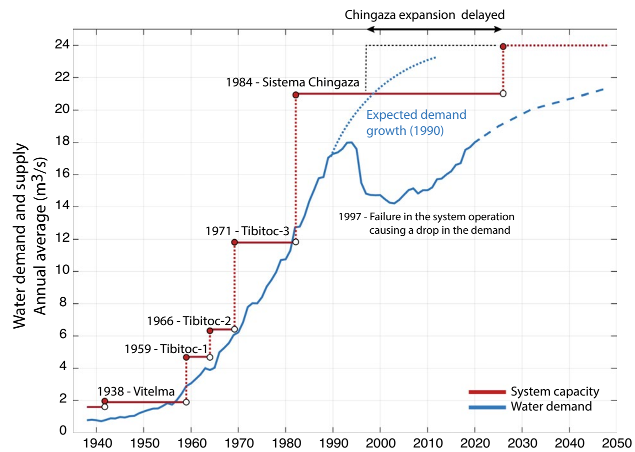

Fig. 2 Water supply and demand over time, for the city of Bogotá. Flexibility facilitates adjustments in capacity and allows to manage unexpected changes in demand (i.e., delay of the planned 1990s expansion until necessary). Data from Empresa de Acueducto de Bogotá (2023) Open data webpage. (https://www.acueducto.com.co)

Bogotá (Rosenzweig et al. 2011). Given the drop in consumption, the local government postponed the system's planned 1990's expansion plans until after 2025. This is an example of how the modularity of the system helped to respond more efficiently to unforeseen events.

For large essential infrastructure, significant work has been done on sea-level rise and flood management and protection problems (Yohe 1990). Some examples include New York (Delta Programme 2013), the Rhine Delta (Lowe et al. 2009), the Thames Estuary (Barnett et al. 2014), and the sea level rise problem in Southeastern Australia (Torres-Rincón et al. 2021a). In transportation, flexible principles have been applied to airports (Sánchez-Silva and Calderón-Guevara 2022; Haasnoot et al. 2011) and road networks (Pudjianto et al. 2020). In the energy sector, some initiatives have sought to prove the value of flexibility in facilitating cost-effective energy decarbonization (Torres-Rincón et al. 2021b). Furthermore, in the design of energy infrastructure, Torres et al. (Blockley 2010) studied floating offshore wind farms showing that the adaptable platform strategy has the potential to reduce the cost of energy by up to 18% by increasing the energy generation and the lifetime of some components of the wind farm.

In summary, numerous studies in different sectors have recently shown the immense potential of incorporating flexibility in the design and management of infrastructure. In the next section, we will present and discuss a conceptual framework encompassing existing ideas and a proposal to move forward.

3 Dynamic infrastructure Systems: an integrated flexible approach

"Dynamic Infrastructure Systems" (DIS) is proposed as a new framework for understanding and managing infrastructure. At the core it has the concept of flexibility, discussed above, but also includes elements necessary for maximizing infrastructure performance. It is argued that this approach may also contribute significantly to financial, social, and environmental sustainability, and to achieve SDGs. The following principles guide a DIS:

1. Systems should be modeled as processes designed to provide service continuously.
2. Systems must be designed to adjust and change when needed.
3. Systems must be sustainable to guarantee intergenerational responsibility.
4. Systems' value depends on the physical and socioeconomic setting, and the interaction with other systems.

The first principle states that infrastructures are not "artifacts" built and sporadically adjusted until they are replaced. Instead, Infrastructure should be considered an arrangement of processes that continuously serve a purpose (City of Chicago 2008). The goal in infrastructure design and management is to provide a satisfactory service continuously. Therefore, assessments and decisions should be made within the context of multi-criteria life-cycle analysis.

The second principle implies that the DIS structure and operation must be able to be modified when needed. This is only possible if it has some flexibility level embedded. Then, designing and planning for forecasted long-term demands and highly unknown events with irreversible courses of action are not reasonable options. deNeufville (Ranger et al. 2010) states that "there should be a shift in infrastructure development that moves away from fixed specifications, narrow forecasts and that avoids the `flaw of averages' design strategies, pushing many designs into underperformance." Flexibility can be achieved by designing for multiple uses, creating modular or scalable systems, using new materials and technologies, and adopting flexible management and governance frameworks (Pudjianto et al. 2020). Flexibility is a tool for integrated risk management that should be coherent with the manager's and stakeholders' needs, interests, and SDGs. Figure 3 illustrates the contribution of flexibility to risk management in financial and operational aspects of a project. Flexible designs imply an up-front cost of adding features that facilitate change. If no changes are needed in the future, these additional costs will be lost. Therefore, equipping the system with features that enable change comes with a

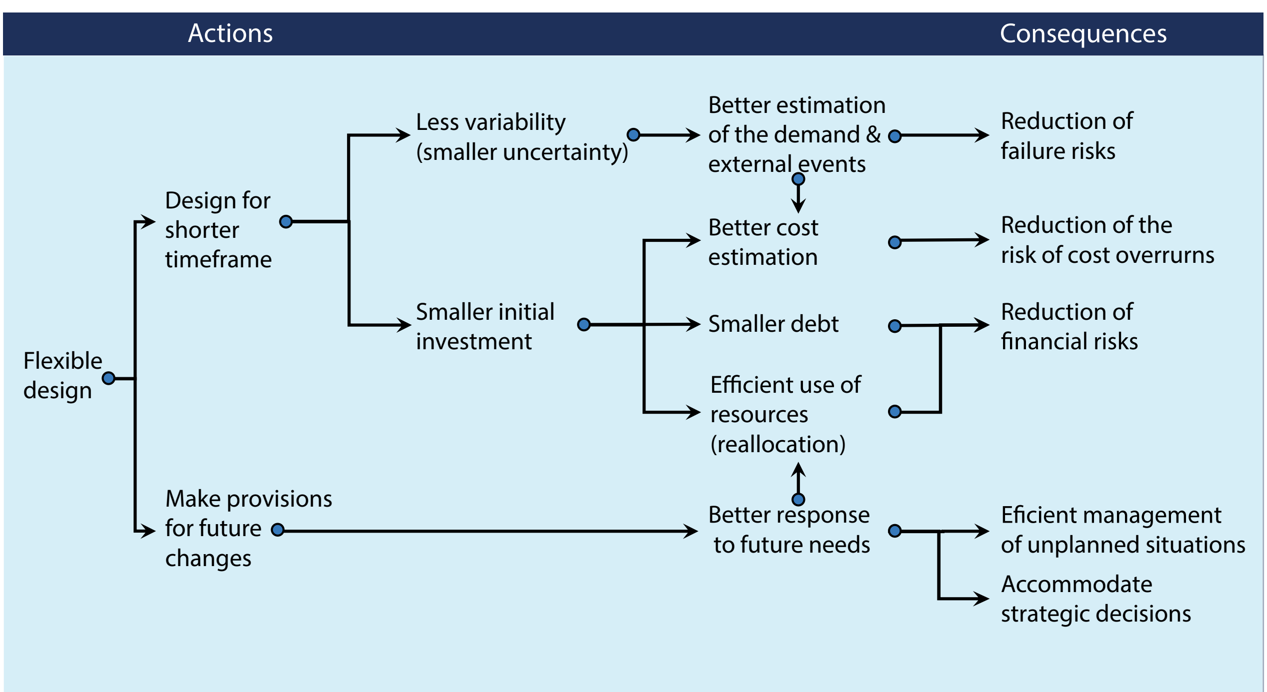

Fig. 3. Actions and consequences of incorporating flexibility in the development of Infrastructure. Flexibility is a tool to manage the risk of possible future losses in various project dimensions

risk. This idea has been used in many disciplines and sectors, such as finance markets, through the concept of "Real Options." In Real Options, the buyer pays, in advance, for the right, but not the obligation, of buying a particular good in the future at a given price. Real Options are a popular strategy to manage the uncertainties and volatility of future asset prices; somehow, flexibility emulates the fundamentals of Real Options. Then, the design of DIS requires the financial risk assessment of adding flexibility, which will show if it is a suitable strategy for the project. Flexibility is not suitable for all project types. In some cases, robust systems with long-time missions might be preferable.

Given the magnitude and duration of infrastructure investments, intergenerational responsibility and sustainability is vital. The third principle focuses on the need to move toward sustainable infrastructure, which contributes to the attainment of the SDGs by reducing greenhouse gas emissions, promoting clean energy generation, and integrating climate adaptation measures. In addition, sustainable infrastructure enhances resource efficiency by incorporating practices such as energy and water conservation, waste reduction, and recycling (circular economy). This minimizes resource depletion, lowers operational costs, and preserves natural ecosystems. Moreover, sustainable infrastructure fosters social equity by prioritizing accessibility, safety, and inclusivity. It ensures that infrastructure projects benefit all members of society, regardless of their socioeconomic status or physical abilities, leading to more equitable and resilient communities. Lastly, sustainable infrastructure supports long-term economic prosperity by attracting investments, creating green jobs, and stimulating innovation in sustainable technologies and practices. By integrating sustainability principles into infrastructure development, we can balance environmental preservation, social well-being, and economic growth.

Finally, a particular infrastructure system cannot be addressed as an independent project but as part of a built environment comprising interacting systems under specific socioeconomic conditions. For DIS to add value to society, it must positively integrate with other infrastructures and the socioeconomic environment, yielding cost and environmental benefits. Integrating projects' performance and evaluation with the surrounding environment is vital for sustainable development and contributes to better decisions. This means that DIS requires the active participation of actors at different decision levels. An example of an initiative in this direction is the Chicago City Plan, which highlights the importance of "interactions between a variety of infrastructures and a strong dialogue between interest groups in order to ensure the success of adaptation approaches in a complex society made up of innumerable vested interests" (Albrechts 2004; Ross et al. 2008).

4 Implementing Dynamic Infrastructure Systems

The DIS approach highlights the importance of the decision-making process in infrastructure design and management. It replaces the traditional approach, in which many decisions are made at the outset based on highly uncertain futures, by sequential decisions that respond to the system's evolving circumstances. Existing flexibility-based approaches recognize the importance of this decision-making strategy. Some examples include the Dynamic Adaptive Policy Pathways (Yohe 1990), the five-phase taxonomy procedure for the design and management of engineering systems (Neufville and Scholtes 2011), and the flexibility strategies for decision-making in real state (Geltner and Neufville 2018) and in civil infrastructure (Haasnoot et al. 2021, 2012). This section describes a comprehensive strategy (Fig. 4) to implement the Dynamic Infrastructure Systems principles into practice.

Phase 1 in Fig. 4 is understanding and modeling the system. Given the many actors, interrelationships, and transformations involved in its realization, infrastructure should be addressed as a complex system. From a "systems thinking" perspective, the state and functionality of infrastructure are the results of hierarchically arranged interconnected processes (City of Chicago 2008). Understanding infrastructure as a process implies that it evolves continuously to guarantee a predefined level of safety and service. This is a substantial change compared to traditional engineering process. Focusing on dynamics also makes it easier to understand the latent processes that define the system's performance. For example, in a concrete bridge, the focus should not only be on the repairing observed cracking, but on the underlying causal processes such as chloride ingress and cyclic loading.

In the design of DIS (phase 1 in Fig. 4), two elements are central: (i) the target demand; and (ii) the level of flexibility provided at the outset. Regarding the former, while in traditional design, the forecast of the operational demand is made for a distant future, in DIS, the demand is estimated over a shorter time window. This avoids overdesigns and reduces costs and emissions. Balancing short and long-term planning strategies is crucial for any project's success. Short-term plans address immediate challenges, while long-term strategies provide a vision and guide sustainable growth. Striking the right balance ensures responsiveness to current demands while positioning the project for future opportunities. It prevents myopic decision-making, promoting stability, innovation, and sustained relevance in a dynamic environment. A harmonized approach to short and long-term planning enhances adaptability, minimizes risks, and fosters enduring success in

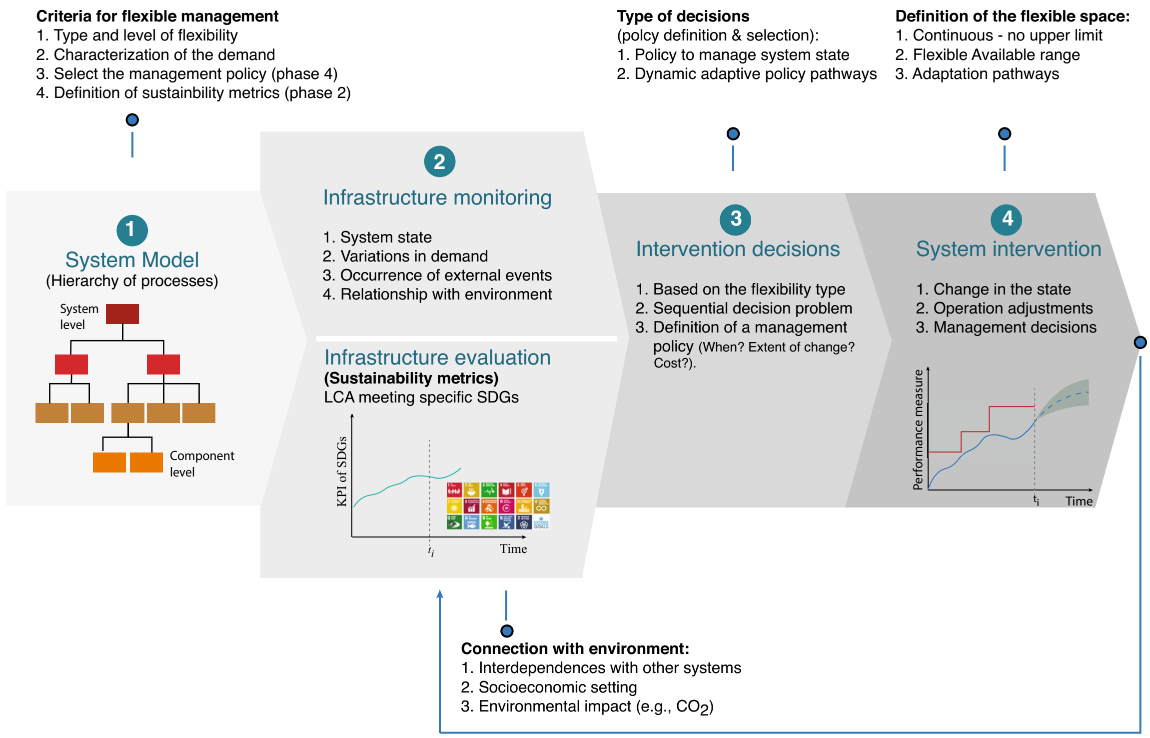

Fig. 4 Constitutive elements and interactions of Dynamic Infrastructure Systems decision-making process, represented by four phases

an ever-evolving physical environment. However, finding the right balance between short- and long-term goals is complex, and no unique, well-formulated strategy exists. Regarding the second element (i.e., adding flexibility at the outset), the system should have flexibility features that support future changes. Common forms of flexibility are scalability, which consists of increasing or decreasing the value of one or a set of variables; modifiability, which consists of adding new design and operational variables, as well as new functionalities; modularity, in which new subsystems can be deployed when required, may or may not inherit all the functions from the main system (Neufville and Scholtes 2011; Werners et al. 2021); and operability, the mechanism by which the operation and management are adjusted based on management requirements.

Upon implementation, phase 2 includes two tasks essential to the dynamic nature of infrastructure: i) monitoring and ii) continuous evaluation over the project's life cycle. Regarding the former, it is essential to consistently monitor the project's progress using Monitoring and Evaluation (M&E) tools. M&E provides evidence primarily supporting changes triggered by state variations (i.e., physical properties) or operation or management needs. Continuous monitoring and evaluation come at a cost and require a long-term commitment to the project, which usually diminishes with time. The UN states that less than 10% of the countries have an adaptation-dedicated M&E system in operation (McKinsey Global Institute 2016), which adds additional risks to compliance with the infrastructure adaptation objectives.

Phase 3 is related to intervention decisions, which are at the core of DIS. Decisions in DIS belong to what is called a sequential decision problem, in which it is necessary to continuously define when an intervention is required (motivations and performance criteria) and its extent (definition of needs). These changes may include modifications to the physical structure, the management strategy or to support the stakeholders' decisions. In addition, any decision must be accompanied by a measure of the value-added regarding costs, emissions, or any other sustainability indicator.

Phase 4 consists of the interventions that change the infrastructure's physical or operational state. These changes depend mainly on the predicted demand and infrastructure performance. Once the decision to intervene is made, the future demand and capacity should be forecast, and used to define the intervention. The size and frequency of interventions should be matched to guarantee a given quality service level. If interventions occur often, the quality of the service may be affected, and changes become inconvenient and costly. Whether technically based or not, a change depends on the space of options provided by the initial system flexibility. For cases where changes can occur in a continuous space or in the form of modular flexibility, the decision will depend on the Available Flexibility Range (AFR) (Haasnoot et al. 2021, 2012). This is the range where changes incur a much lower cost than changes outside the AFR. For example, in the case of the HSBC building described above (Geltner and Neufville 2018), any expansion beyond 57 stories would be costly compared to expansions between 20 and 57. Another option is to use adaptation pathways [67], which are alternative sequences of measures to realize a well-defined adaptation objective. The use of adaptation pathways in decision-making has been generalized under the idea of Dynamic Adaptive Policy Pathways (Yohe 1990). This model might be restrictive in the sense that pathways, once defined, remain unmodifiable through time.

Once a change to the system is implemented, the cycle is closed by returning to phase 2. In DIS, the value of the project over time depends on its ability to fulfill its objective continuously and the compliance with a project-related set of sustainability indicators. The evolution of these indicators should be considered as part of the decision to intervene in phase 3 of the process. In the construction sector (including infrastructure), this evaluation process is incipient partly because the implementation process is ambiguous, lacks clarity in the regulation and political will, and there is limited experience. For example, there is limited evidence of the effectiveness of adaptation actions because decisions assume that the intended results are being achieved (Mauter 2021).

5 Challenges in the implementation of dynamic infrastructure systems

Flexible approaches are increasingly appealing for infrastructure development. However, barriers to this approach include (i) inflexibility of standards and codes of practice, (ii) regulatory, operational, and legal aspects, (iii) long-term financing, and (iv) cultural resistance to change.

First, most design standards do not include flexible infrastructure development provisions. Codes of practice provide requirements to ensure safety under specific technical conditions, but there are few considerations regarding managing unplanned situations or integration with other systems. In addition, norms and standards severely limit the possibility of implementing new or alternative design strategies, including new technologies.

Second, regulatory barriers prevent adopting and implementing more flexible infrastructure solutions. Infrastructure planning and management are handled by multiple stakeholders across different government levels and industry sectors, and this fragmented decision-making hinders coordination efforts. A gap between engineers and some stakeholders limits the ability to link infrastructure with its socioeconomic setting. Finally, legal issues associated with contract specifications force all parties involved to maintain "well-known" formats despite their willingness to act differently. "Enhanced capacity in the planning, procurement and project management of infrastructure systems is necessary to ensure that sustainability is fully embedded in decision-making" (Intergovernmental Panel on Climate Change (IPCC) 2021).

Third, financing is critical in the implementation of DIS. In the case of publicly funded projects, there is a fear that local governments cannot secure the funding for future interventions due to political or budgetarily issues. This has been the main driving force behind the traditional approach of making large investments in long-lasting overdesigned infrastructure projects. Private investors may prefer DIS since the focus is shifted to the quality of the service provided and not on the development or management process. Thus, facilitating the access to resources as the project evolves. However, the lack of financial and legal instruments that facilitate private investments remains a barrier.

Finally, in a traditional sector such as infrastructure development and management, stakeholders, including engineers, policymakers, planners, and the public, tend to resist changing norms and practices. This resistance grows as changes imply significant variations to existing infrastructure or long-established ways of doing things ("status quo bias"). In addition, there is resistance because the benefits do not have an immediate effect on the project but can only be measured and appreciated over moderate or long-time horizons.

Consequently, the implementation of DIS will be successful if, in addition to its fundamental principles, there is a change in the infrastructure and built-environment sectors along the following lines:

- Designing dynamic infrastructure systems using standards that work across different jurisdictions or industries, using a broader approach beyond considering physical performance. There is also a need to revise standards and norms to emphasize the technical aspects concerning systems' evolution with time.
- Reconsidering assumptions of existing standards and regulations, to promote innovation and flexibility and make exemptions or regulatory waivers for specific projects, new technologies, or new methodologies. Innovation should occur on all fronts, from adopting the concept of DIS, to implementing new technologies, to revising performance criteria. It is essential to encourage experimentation and informed risk-taking. Finally, fostering flexible infrastructure requires shifting the focus toward the output (continuous minimum service quality level) instead of controlling the process.
- Rethinking the boundaries of infrastructure will contribute to better integrating it with the surrounding environment (social, economic, and environmental), thus promoting sustainability. A broader understanding of DIS involves redrawing the system to start from the natural

environment and integrating nature-based solutions (NBS) to create adaptive infrastructure and dynamic ecosystems. NBS can reduce vulnerability and increase diversity, providing a wide range of societal benefits. Rethinking these boundaries is crucial in introducing sustainable dynamic urban strategies.

- Guaranteeing financial and technical capacity to execute future project changes. It is essential to design administrative and legal mechanisms that secure funding for possible future infrastructure updates, such as with novel and creative financing mechanisms that combine public and private investments. The premises behind DIS are designed to attract the private sector and public–private partnerships into sustainable infrastructure management (Ross et al. 2008).
- Creating a new culture by promoting training and education programs for engineers, stakeholders, and local governments. It is necessary to build capacity and expertise in innovation and to develop new technologies that make it feasible to incorporate flexibility in different project types. It is also critical to foster knowledge-sharing and collaboration across different sectors and industries.

6 Conclusions

The urgent need for infrastructure investment to handle increasing external pressures is a technical and financial challenge. This article argues that it requires a shifting mindset towards a strategy grounded on managing uncertainty and adaptation to change. It means thinking in terms of "dynamic infrastructure systems" and applying its principles (process, flexibility, sustainability, and connectivity). In the DIS view, complex long-lasting infrastructure projects such as roads, airports, water supply, communication networks, power plants, or hospitals are envisioned as constantly adapting as the surrounding physical and socioeconomic environment evolves. A central element of DIS is its flexibility to adjust continuously to environmental changes or stakeholders' decisions.

The proposed approach is based on a sequential decision strategy with phased development, i.e., start small and change as required. This approach is central to managing uncertainty and reducing risks. It keeps future commitments open to avoid unwanted consequences and seize potential opportunities. Phasing development is a cost control strategy that favors financial and environmental sustainability (e.g., reduction of CO_2 emissions) by deferring investments until they are needed. Considering infrastructures as dynamic systems also fosters innovation and the development of new design and construction technologies and opens the door to new financing alternatives. In summary, this article presents a new understanding of infrastructure development that is consistent with sustainability goals and can be a powerful tool to tackle climate change and the impact on mid and low-income countries.

Challenges to this shift can be overcome by developing public policies and leadership that generate a change in mindset. This shift in mindset must extend to all stakeholders, including government officials, urban planners, regulatory agencies, engineers, academics, and the public. In adoption, it is necessary to articulate benefits such as technological advancement, energy transition, sustainability, and the diversity of socioeconomic contexts. This means overcoming regulatory barriers that prevent adopting and implementing more flexible infrastructure solutions and revising norms and design standards to include flexible infrastructure development provisions. For example, shifting the focus toward the service quality instead of controlling the process. Finally, a change in the mindset can be advanced by implementing training and education programs that target engineers, local governments, and the public.

Acknowledgements The authors would like to thank the Department of Civil and Environmental Engineering at Stanford University for the Shimizu Professorship granted to the corresponding author in 2023. Also, thanks to Professor L.A. Camacho for the data and analysis that supports the production of Fig. 2.

Author contributions MSS wrote the main manuscript text and prepared figures 1-4. JWB revised and edited the manuscript. All ideas presented are the result of the join work of all authors. All authors reviewed the manuscript.

Funding Open Access funding provided by Colombia Consortium. We, the Authors, declare that we have no conflicts of interest, and no external funding is associated with the submitted paper. We have not received any financial or other benefits from any organization or individual that could be perceived as a conflict of interest. We also declare that this paper has not been submitted to or published in any other journal or conference.

Declarations

Competing interests The authors declare no competing interests.

References

Acuña-Coll N, Sánchez-Silva M (2023) Integrating systems thinking and flexibility in infrastructure management. Innov Infrastruct Solut 8:144. https://doi.org/10.1007/s41062-023-01106-9

Africa's Development Bank (2018) Africa's economic outlook: Africa`s great potential but little impact on inclusive growth

Albrechts L (2004) Strategic (spatial) planning reexamined. Environ Plann B Plann Des 31:743–758

ASCE (2023) https://infrastructurereportcard.org/making-the-grade/report-card-history/ International Energy Agency (IEA) (2019). The 2019 Global Status Report for Buildings and Construction was prepared by the for the Global Alliance for Buildings and Construction (GlobalABC). Co-ordinated by the United Nations Environment Programme

Asian Development Bank (ADB) (2017) Meeting Asia's infrastructure needs. https://doi.org/10.22617/FLS168388-2

Barnett JA et al (2014) Local coastal adaptation pathway. Nat Clim Change 4:1103

Ben-Haim Y (2006) Information-gap decision theory: decisions under severe uncertainty, 2nd edn. Wiley, New York

Blockley D (2010) The importance of being process. Civ Eng Environ Syst 27(3):189–199

Brichetti JP, Mastronardi L, Rivas ME, Serebrisky T, Solís B (2021) (IDB-Interamerican Development Bank). The Infrastructure Gap in Latin America and the Caribbean: Investment Needed Through 2030 to Meet the Sustainable Development Goals, https://doi.org/10.18235/0003759

Cardin M (2014) Enabling flexibility in engineering systems: a taxonomy of procedures and a design framework. J Mech Eng ASME 136:011005

Chester M, Allenby B (2019) Toward adaptive infrastructure: flexibility and agility in a non-stationarity age, sustainable and resilient infrastructure. Sustain Resilient Infrastruct 4(4):173–191. https://doi.org/10.1080/23789689.2017.1416846

City of Chicago (2008) Chicago Climate Action Plan https://www.chicago.gov/city/en/progs/env/climateaction.html

de Neufville R, Odoni A (2003) Airport systems: planning, design, and management. McGraw-Hill, New York

de Neufville R, Scholtes S (2011) Flexibility in engineering design. MIT Press, Cambridge, MA

Delta Programme, 2012 (2013) The Road Towards the Delta Decisions. Dutch Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, Agriculture and Innovation. http://www.deltacommissaris.nl/english/Images/Delta_Programme_2013_ENG_tcm310-334162.pdf (13.11.12)

Empresa de Acueducto de Bogotá (2023) Open data webpage. (https://www.acueducto.com.co)

Environmental Programme. Adaptation Gap Report 2022: Too Little, Too Slow. file:///Users/mauriciosanchezsilva/Downloads/AGR2022.pdf

European Investment Bank (2023) https://www.eib.org/en/index

Geltner D, de Neufville R (2018) Flexibility and real estate valuation under uncertainty: a practical guide for developers. Wiley, Oxford

Global Infrastructure Hub (2021) Global Infrastructure Outlook (2023) https://outlook.gihub.org/

Guma A, Pearson J, Wittels K, de Neufville R, Geltner D (2009) Vertical phasing as a corporate real estate strategy and development option. J Corporate Real Estate 11(3):144–157

Haasnoot M, Middelkoop H, van Beek E, van Deursen WPA (2011) A method to develop sustainable water management strategies for an uncertain future. Sustain Dev 19:369–381

Haasnoot M, Middelkoop H, Offermans A, Van Beek E, van Deursen WPA (2012) Exploring pathways for sustainable water management in river deltas in a changing environment. Clim Change 115:795–819

Haasnoot M, Kwakkel JH, Walker WE, Ter Maat J (2013) Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environ Change 23:485–498

Haasnoot M, Lawrence J, Magnan AK (2021) Pathways to coastal retreat. Science 372(6548):1287–1290. https://doi.org/10.1126/science.abi6594

Hallegatte S, Shah A, Lempert R, Brown C, Gill S (2012) Investment decision making under deep uncertainty application to climate change. The World Bank

Hill A, Mason D, Potter JR, Hellmuth M, Ayyub B, Baker JW (2019) Ready for tomorrow: seven strategies for climate-resilient infrastructure, 2019. Hoover Institution Press

Intergovernmental Panel on Climate Change (IPCC) (2021) Summary for Policymakers. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte V et al (eds) Cambridge University Press. In Press. www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

International Energy Agency. Net Zero by 2050 A Roadmap for the Global Energy Sector

Lempert RJ, Popper SW, & Bankes SC (2003) Shaping the next one hundred years: new methods for quantitative long-term strategy analysis (MR-1626-RPC). The RAND Pardee Center, Santa Monica, CA

Lowe JA, Howard T, Pardaens A (2009) UK Climate Projections Science Report: Lowe, J.A., Howard, T., Pardaens, A. UK Climate Projections Science Report: Marine and Coastal Projections. Met Office Hadley Centre, Exeter. Marine and Coastal Projections. Met Office Hadley Centre, Exeter

Mauter M (2021) Build back wiser. Science 373(6562):1417. https://doi.org/10.1126/science.abm3438.

McKinsey Global Institute (2016) Bridging global infrastructure gaps.

Monteiro P, Miller SA, Horvath A (2017) Towards sustainable concrete. Nat Mater 16(7):698–699

Montulli LT (1986) Lessons learned from the B-52 program evolution: past, present, and future. In: AIAA/AHS/ASEE aircraft systems, design and technology meeting, October 20-22, Dayton, OH

Moran D, Kanemoto K, Jiborn M, Wood R, Többen J, Seto KC (2018) Carbon footprints of 13,000 cities. Environ Res Lett 13:064041

Nembhard HB, Aktan M (2010) Real options in engineering design, operations, and management. Taylor and Francis CRC Press, Boca Raton, FL

OECD (2017) Investing in climate, investing in growth. OECD, Paris. https://doi.org/10.1787/9789264273528-en

Pomponi F, Moncaster AJ (2017) Circular economy for the built environment: a research framework. Clean Prod 143:710–718

Pudjianto D, Aunedi M, Djapic P, Teng F, Zhang X, Ameli H, Moreira R, Brandon N (2020) Role and value of flexibility in facilitating cost-effective energy system decarbonization. Prog Energy 2:042001

Quade ES (1989) Analysis for public decisions, 3rd edn. Elsevier Science, New York

Raave D, Tasan C, Olivetti EA (2019) Strategies for improving the sustainability of structural metals. Nature 575(7781):64–74

Ranger N, Millner A, Dietz S, Fankhauser S, Lopez A, Ruta G (2010) Adaptation in the UK: a decision-making process. Grantham Research Institute on Climate Change and the Environment and Center for Climate Change Economics and Policy

Reisinger J, Knoll M, Kovacic I (2021) Design space exploration for flexibility assessment and decision-making support in integrated industrial building design. Optim Eng 22:1693–1725

Rosenzweig C, Solecki WD, Blake R, Bowman M, Faris C, Gornitz V, Horton R, Jacob K, Le Blanc A, Leichenko R, Linkin M, Major D,

O'Grady M, Patrick L, Sussman E, Yohe G, Zimmerman R (2011) Developing coastal adaptation to climate change in the New York City infrastructure-shed: process, approach, tools, and strategies. Clim Change 106:93–127
Ross AM, Rhodes DH, Hastings DE (2008) Defining changeability: reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. Syst Eng 11(3):246–262. https://doi.org/10.1002/sys.20098
Rozenberg J, Fay M (2019) Beyond the gap: how countries can afford the infrastructure they need while protecting the planet. Sustainable fnfrastructure. World Bank, © Washington, DC
Saleh JH, Hastings DE (2000) On flexibility in design: analyzing flexibility of space systems. In: AIAA Space 2000 Conference and Exposition, Long Beach, CA
Sánchez-Silva M (2019) Managing infrastructure systems through changeability. J of Infrastructure Systems 25(1):04018040. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000467
Sánchez-Silva M, Calderón-Guevara W (2022) Flexibility and adaptability within the context of decision-making in infrastructure management. Struct Infrastruct Eng 18(7):950–966
Schwartz ES, Trigeorgis L (2004) Real options and investment under uncertainty: classical readings and recent contributions. The MIT Press
Swanson DA, Barg S, Tyler S, Venema H, Tomar S, Bhadwal S, Nair S, Roy D, Drexhage J (2010) Seven tools for creating adaptive policies. Technol Forecast Soc Chang 77:924–939
Thacker S, Adshead D, Fay M et al (2019) Infrastructure for sustainable development. Nat Sustain 2:324–331. https://doi.org/10.1038/s41893-019-0256-8
The Global Competitiveness Report 2017–2018 (2017) World Economic Forum.
Torres-Rincón S, Sánchez-Silva M, Bastidas-Arteaga EA (2021a) Multistage stochastic program for the design and management of flexible infrastructure networks. Reliab Eng Syst Saf 21:107549. https://doi.org/10.1016/j.ress.2021.107549
Torres-Rincón S, Bastidas-Arteaga E, Sánchez-Silva M (2021b) A flexibility-based approach for the design and management of floating offshore wind farms. Renew Energy 175:910–925. https://doi.org/10.1007/s11081-021-09614-2
UN Inter Agency Task force on Financing and Development. Closing the infrastructure gap (2023) https://developmentfinance.un.org/closing-the-infrastructure-gap
United Nations Human Settlements Programme (2022) World Cities Report. https://unhabitat.org/sites/default/files/2022/06/wcr_2022.pdf
Watari T, Hata S, Nakajima K et al (2023) Limited quantity and quality of steel supply in a zero-emission future. Nat Sustain 6:336–343. https://doi.org/10.1038/s41893-022-01025-0
Wehrle E, Palomba I, Vidoni R (2021) Modeling, design and optimization of flexible mechanical systems. Appl Sci 11(15):7124. https://doi.org/10.3390/app11157124
Werners SE, Wise RM, Butler J, Totin E, Vincent K (2021) Adaptation pathways: a review of approaches and a learning framework. Environ Sci Policy 116(2):266–275
World Bank (2018) Global Development Horizons: Capital for the Future - Saving and Investment in an Interdependent World. Washington, DC. (2013) http://hdl.handle.net/10986/13431 License: CC BY 3.0 IGO
World Bank Data (2023) https://data.worldbank.org/
Yohe G (1990) Imbedding dynamic responses with imperfect information into static portraits of the regional impact of climate change. International Workshop on the Natural Resource and Economic Implications of Global Climate Change, Interlaken, Switzerland
Zimmerman R, Faris C (2010) Chapter 4: infrastructure impacts and adaptation challenges. Ann New York Acad Sci 1196:63–86 https://doi.org/10.1111/j.1749-6632.2009.05318.x