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Sustainable Infrastructure 4.0 - Value Chain Integration through Federated Digital Platforms

Prof. Konrad Nübel [1], Prof. Michael Bühler [2] and Dr. Thorsten Jelinek [3,*]

[1] Technical University Munich, konrad.nuebel@tum.de
[2] Konstanz University of Applied Sciences, mbuehler@htwg-konstanz.de
[3] Taihe Institute, thorstenjelinek@taiheglobal.org
* Correspondence: Konrad.nuebel@tum.de ; Tel.: +49 89 28922411

Abstract: Twenty-first century infrastructure needs to respond to changing demographics, becoming climate neutral, resilient, and economically affordable, while remaining a driver for development and shared prosperity. However, the infrastructure sector remains one of the least innovative and digitalized, plagued by delays, cost overruns, and benefit shortfalls [1-4]. The root cause is the prevailing fragmentation of the infrastructure value chain [5]. To support overcoming the shortcomings, an integration of the value chain is needed. This could be achieved through a use-cased-based creation of federated digital platforms applied to infrastructure projects. Such digital platforms enable full-lifecycle participation and responsible governance guided by a shared infrastructure vision.

Keywords: Sustainable Infrastructure; Governance; Design, Protocols, Implementation, Value Chain, Digitalization

1. Challenge

Infrastructure is a priority for the G20 and has led to the establishment of the Global Infrastructure Hub, the Global Infrastructure Connectivity Alliance, G20 Principles for Quality Infrastructure Investment, and the G20 InfraTech agenda. The uptake and large-scale implementation of recommendations of these initiatives by G20 member states can still be improved. The G20's focus on investment finance needs to be complemented by an engineering design and delivery focus for sustainable infrastructure. Implementation visions and bankable sustainable infrastructure pipelines that bridge political cycles and are not prone to political risk are inadequate or lacking. Absent sustainable measures, flow-efficiency, sequential planning, discipline silos still determine common infrastructure practices.

As the process of infrastructure development and delivery is very complex, the best practice approach is to decompose the overall task into smaller components which are understandable and manageable. This approach, certainly, is a basic principle in our economy, based on division of labor. The process of infrastructure development and delivery in most countries is therefore a stepwise phase process, where the next phase begins as soon as the preceding phase is closed. The level of granularity of planning increases with each phase until it is brought to a constructible planning state. Such linear consecutive processes are called "waterfall-models" [6].

Each phase is executed independently and has its particular composition of stakeholders. Often, project leadership also changes across different phases. The process is so segregated that a common understanding of the entire process does not exist among the majority of relevant stakeholders, and the process itself regularly loses sight of the desired outcomes. As a result, problems in the process are usually addressed in a specific phase or even within a sub-phase, while the entire process model is hardly questioned. This approach is seen as a common way of avoiding change.

Consequently, such complex multi-stakeholder processes tend to lead to a multi-dimensional principal-agent dilemma in which asymmetric information policies predomi-

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nantly increase local efficiencies in the functional silos of the project. However, the optimization of the benefits of the overall system, or even more, the interests, needs and requirements of the infrastructure asset users move entirely out of sight.

To understand the root causes, problems must first be addressed and related to the specific phase or component of infrastructure development and delivery. It is then necessary, but not sufficient, to develop recommendations at the level of the specific problem; it is not sufficient since the overall problem of asymmetric information cannot be solved at the specific level of granularity. Moreover, the problem of slow planning processes or administrative hurdles will not be solved simply by accelerating the planning processes nor merely by reducing administrative hurdles. Instead, a system change is required.

In other industry sectors, we see that value creation evolves through trusted networks of collaboration, so-called value networks [7]. The underlying multistakeholder and multidisciplinary ecosystems increasingly become the backbone of our digitalized world, mobilizing specialized actors that share values, governance principles and common goals. Value networks are interactive, integrative and agile, and focus on people's needs. In infrastructure development and delivery, however, such value chain integration is lacking [8] and very important to achieve usability and sustainable goals.

We can conclude that the global infrastructure gap [9] and the need develop sustainable infrastructure cannot be eliminated by taking only the financial aspects into account; the whole value chain of development and delivery has to be transformed into an integrated system, a value network, focused on end user needs and requirements as well as a much broader approach to value creation. The root cause is the existing fragmentation and lack of cooperation within the infrastructure value chain. Sequential (waterfall) planning and resource-efficiency (focusing on silos) are still common practice, compared to the necessary flow-efficiency and agility (across the value network), preventing a more impactful realization of broader goals.

2. Proposal

Traditionally, value is created within the boundaries of an enterprise or a value chain. In contrast, digital platforms challenge incumbents by changing how a value network consumes and provides products and services. Digital platforms, which utilize an ecosystem of autonomous agents to co-create value, have the potential to overcome the existing fragmentation of the infrastructure value chain [10]. The sharing and reusing of data and pioneering technologies - such as cloud/edge computing, artificial intelligence, digital twins, IoT/smart sensors, 5/5.5G, and distributed ledgers – can help to integrate the value chain and thereby enhance infrastructure productivity, efficiency, and affordability. Such platform-driven integration can also spur innovation through ecosystem participation and accelerate the achievement of the broader objectives of decarbonization, resilience, and human-centered infrastructure [11].

This article proposes digital platforms for infrastructure as mobilization and learning platforms to address and overcome the limitations of the existing platform economy [12, 13]. Mobilization platforms bring existing expertise together to create shared outcomes. They enable and make multistakeholder co-creation processes more effective throughout the entire infrastructure lifecycle. Mobilization is needed not only to integrate the various silos of infrastructure delivery into a single process and project, but also to create entire infrastructure ecosystems that are open to outside parties who can build complementary products and services. Mobilization platforms can and should evolve into learning platforms. Learning platforms provide the level of agility, resilience, and antifragility that is needed for continuous improvement, innovation and adaptation to a rapidly changing environment [14,15]. Modelling digital platforms as learning platforms will help to coordinate and accelerate the digitalization of infrastructure and the transformation of infrastructure production and delivery methods [16].

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Utilizing the concept of mobilization and learning platform as an underlying value and structure of digital platforms, the potential upside of infrastructure digitalization can be tremendous. Digital platforms for infrastructure can help to:

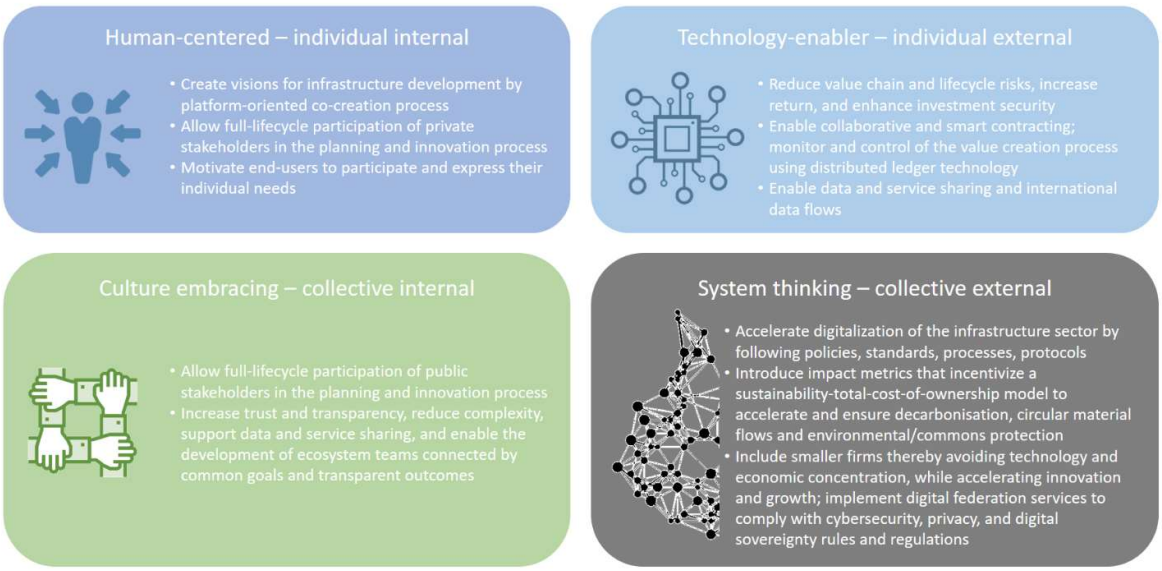

Figure 1. Holistic perspectives on infrastructure development.

For the classification a holistic model, [17] is used. Importantly, digital platforms can enable the transformation towards Sustainable Infrastructure 4.0, but they won't intrinsically realize those benefits or resolve the challenges associated with traditional infrastructure. Considering their dual-use and disruptive character, advanced technologies can even be part of or worsen humanity's challenges [18,19]. This is why governments introduce new laws and regulations that should make advanced technologies and digitalization secure and safe while serving the needs of society. Therefore, this article is premised on the assumption that governance and therefore some degree of coordination and regulation are crucial for a successful transition toward Sustainable Infrastructure 4.0.

3.1. Mobilization and learning platforms for infrastructure

The path of working towards the creation of a digital platform for the design, construction and operations of built environment assets creates a tremendous opportunity. The development process could not only improve the symmetry of knowledge amongst the stakeholders, but also lead to the converges of existing systems within the value chain into a mobilization and learning platform. Platform creators and key platform participants should take into consideration five dimensions of this iterative process of "systems convergence and platform emergence" to harness the benefits of such transformation process (Figure 2): governance, design, protocols, implementation, and use cases. Each dimension is presented in detail in the subsections below.

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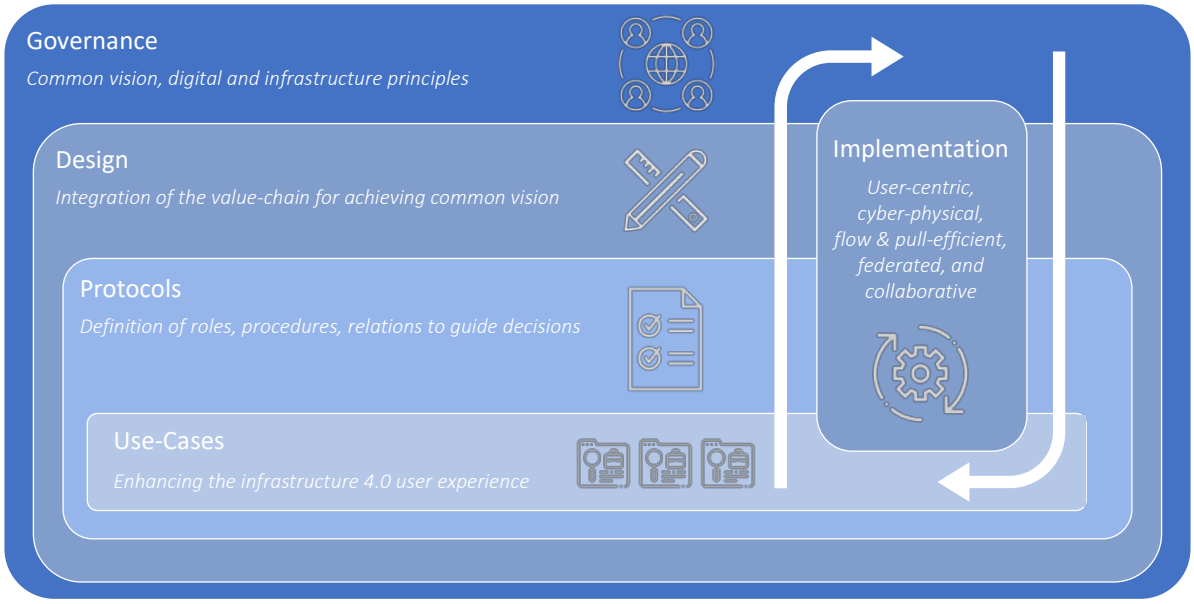

Figure 2. Five dimensions of implementing a mobilization and learning platform.

3.2. Analysis of the five dimensions

3.2.1. Governance

As indicated above, technology itself won't solve the limitations of traditional infrastructure. On the contrary, the OECD [20] identifies infrastructure mainly as a governance challenge. However, a digital platform doesn't simply operate without governance but already emulates a governance structure that determines rules as well as facilitates and regulates the interaction of participants and the sharing of data and data services [12]. This is why governance is the most crucial dimension of planning, developing, and operating a digital platform for infrastructure. If governance can be construed as the possibility for collaboration directed by common principles as well as a space that limits human autonomy, a platform provides the opportunity to restrict unwanted behaviour and enable or incentivize desirable behaviour for the purpose of reaching common goals [21].

The OECD [20] lists a set of infrastructure governance challenges that need to be addressed to avoid the existing infrastructure governance gap [22] merely being replicated through a poorly designed digital governance structure. According to the OECD, a sound infrastructure governance framework requires (1) a shared strategic vision for infrastructure service needs; (2) a strategy for mitigating integrity risks; (3) a common method of infrastructure delivery that balances political, societal, economic, and strategic interests; (4) a sound regulatory design and approach; (5) a consultation process to meet the demands of the general public; (6) policy coordination across the different levels of government; (7) a long-term infrastructure strategy that ensures both affordability and assets performance; (8) data for fact-based decision-making; and (9) infrastructure systems that are resilient and adapt to new circumstances. In addition, infrastructure governance should also incentivize and reinforce environmental and social sustainability standards.

For the purpose of developing a digital platform, those overarching governance requirements, which are mainly targeted at governments, need to be translated into more specific rules across three different domains of hard and soft governance, including (1) the digital infrastructure and data governance domain, (2) the infrastructure project life cycle domain, and the (3) legal, regulatory, and industrial standards domain.

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From a platform design perspective, digital federation services [23] function as the specific technological and digital representation of those different governance requirements and manifest as digital platform protocols [24]. The term federation emphasizes the governance aspect of mobilization and learning platforms. Based on the design and specification of those protocols, a platform can therefore enforce a desired degree of value chain integration through information transparency and the possibility of collaboration based on shared data spaces and data services. Platform governance can therefore represent the aspects of integrated project delivery [25].

Importantly for the development and operations of such a federated digital platform, the article recommends mapping the core regulations, standards, and processes of infrastructure delivery as well as the regulatory requirements concerning cybersecurity, privacy, and data sovereignty (see Figure 3). Both sets of federation services – one for infrastructure, the other for the digital infrastructure and data ecosystem – constitute the core governance framework of an emerging digital platform for infrastructure delivery. While cloud providers and hyperscalers will naturally focus on federation services regarding the trustworthiness of the digital infrastructure and data ecosystem, the federation services concerning the virtualization of the development, design, construction, and operations processes for the built environment assets still need to be developed.

As presented in the following, such a governance structure is not realized through a traditional top-down systems integration approach. On the contrary, this comprehensive platform is realized in a flexible, bottom-up approach by focusing on scalable and marketable use cases that eventually be-come part of an infrastructure ecosystem.

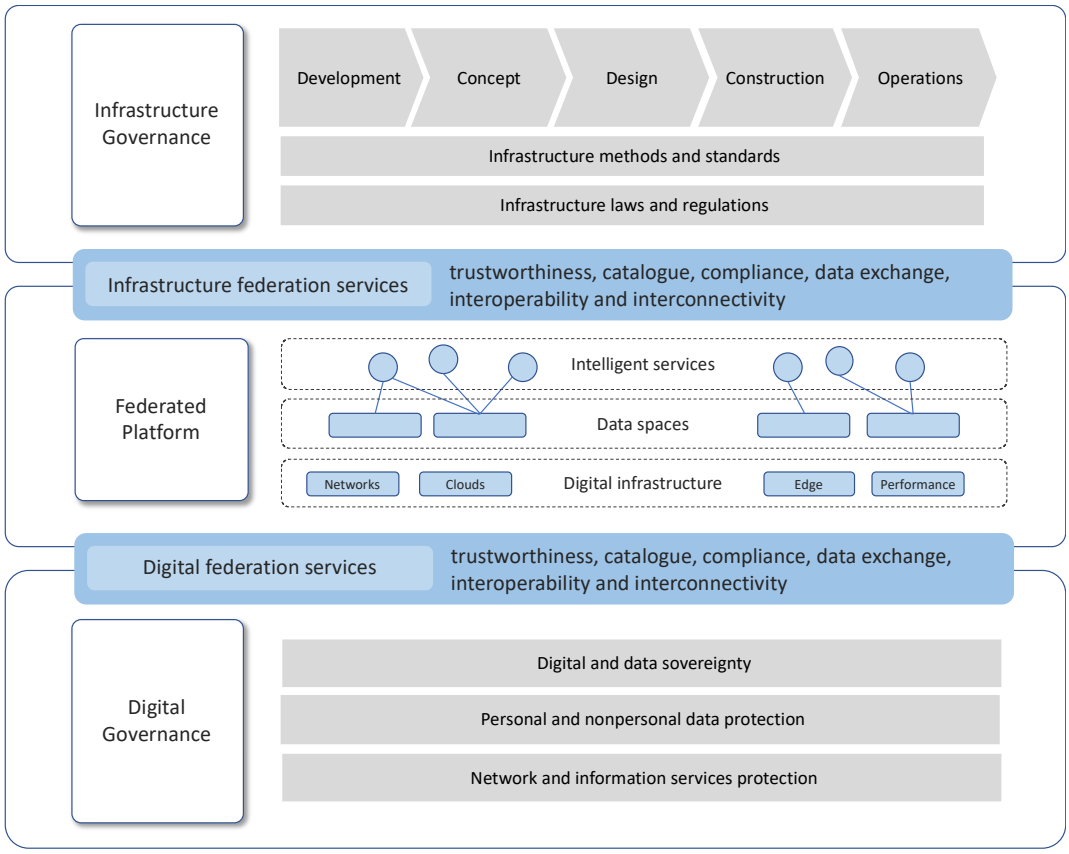

Figure 3. Governance structure of the federated digital platform for infrastructure

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3.2.2. Design

The design of an infrastructure platform starts with developing the governance framework outlined above by taking into consideration hard and soft governance requirements. Hard governance relates to existing laws and regulations that tend to determine design choices. Soft governance requirements mainly relate to standards, processes, and legacy systems. Their manifestation within the new platform is an iterative process evolving over time. Hence, to manage the platform development in an agile way, the platform design should be centered around the development of use cases, which also leaves space for exploration and experimentation.

A platform tends to grow along its most effective use cases first and then gets shaped by the ecosystem that surrounds it. Therefore, prioritized used cases have to be identified, developed, and implemented. Use cases should be or must have the potential to become business cases, since only competitive and marketable concepts will foster their adaptation and scalability. The platform develops with the development and adaptation of its best business cases [26]. The scalability of use cases is achieved by structuring, standardizing, modularizing, and connecting with existing solutions. Promising business models could already be created using existing data and employing exponential technologies. Design decisions have been made concerning the degree of intelligent automation, data sharing, and collaboration across organisational boundaries. Such a design approach allows for relocating innovation to an emerging ecosystem and a huge network of outside firms. However, use cases must be identifiable within the infrastructure process and life cycle.

Furthermore, to overcome the value chain fragmentation and lack of collaboration within the infrastructure industry on public-sector projects, a multi-stakeholder as well as a multi-phase perspective must be taken and an integrated project team including the project owner must be formed [27]. The learnings from the UK's National Digital Twin initiative [28], two decades of building information modelling [29] and experience of other industry sectors should be considered, including procurement of hospitals and highways using the integrated project delivery ("IPD") approach [30].

While the platform's digital architecture should be based on the principles of security and privacy by design/default to ensure trustworthiness, the infrastructure use case architecture should be based on the principles of collaboration and flow-efficiency by design. The collaborative framework must include the early involvement of all stakeholders and needs to be outcomes-based. It must measure metrics of operational results to validate success or failure of outcomes, including traditional metrics such as output performance in term of cost, time, scope and quality but also other indicators such as resilience, environmental standards, and social impact. The collaboration framework needs to include an effective dispute resolution mechanism as well as pain, gain, and risk sharing [31].

Although the focus of this policy brief is on public infrastructure, including public-private-partnerships, the policy brief considers any infrastructure as being part of the commons. Such premise fundamentally influences the design of the platform. This is not to say that market dynamics are neglected. On the contrary, the platform design is premised on the profit ideal. Social and environ-mental sustainability standards no longer stand in opposition to market and profit considerations, yet conflicting goals need to be addressed. Thus, the core design principle should remain premised on the triple bottom line: people, planet, and prosperity[32]. Value creation has to be incentivized and should be derived from the shared infrastructure vision and governance principles.

3.2.3. Protocols

Protocols, which are agreed-upon or accepted sets of rules or standards for procedures, constitute a more granular level of platform design. Defining platform protocols

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helps to translate governance and design requirements into concrete procedures and source code [33]. They represent the specific roles of platform participants and their tasks, relations, and decisions associated within each domain and between the domains of governance. They guide decisions towards achieving shared values and objectives. Protocols function as a common language for stakeholders to develop the platform without the need to become too technical. A low- and no-code environment increase the adaptability of the platform and the integration of use cases [34].

As indicated in Figure 2, a set of protocols constitutes the federative services that enable trusted collaboration and data sharing across an ecosystem. Their definition allows for mirroring, optimizing, and streamlining infrastructure processes alongside the value chain, in relation to virtual and physical assets, and facilitating a seamless information exchange between stakeholders. Protocols can make pain points related to non-synchronized delivery processes or low-quality problems transparent and help to monitor the development and delivery process of infrastructure projects [35].

Protocol metrics should be implemented to track the realization of common objectives. Legitimate protocols cannot be developed without stating the vision and objectives as already outlined by the governance and design frameworks. In contrast, existing metrics can be realigned with the broader goals and strategy to make them meaningful. In essence, protocols directly address the governance gap and the myriad of challenges associated with traditional infrastructure delivery. However, protocols are never final but need to adapt to a constantly changing environment and increasing complexity [36].

3.2.4. Implementation

To respond to an increasingly complex and changing environment, which is marked by constant crises, requires an effective combination and application of implementation values and methods that support agility, resilience, and anti-fragility. Agility is a form of adhocracy and emphasizes flows and iterations. Resilience promotes self-organization and robustness through rapid adaptation, while antifragility suggests that improvement occurs even in the face of shocks [15,37]. Such project and work flexibility are required to manage digital technologies that are themselves disruptive. Today's dynamic development is supposed to intensify in the future, as the world is further changing towards an era of ubiquitous digitalization, heightened cyber-physical risks, and structural instabilities [38].

While those methods are applied within the ICT industry, they rarely find application within the infrastructure and public sector. Thus, setting up a dynamic governance structure and developing a digital platform for use-case-based infrastructure development can create tension between technology, infrastructure, and public-sector participants. However, the infrastructure industry has developed its own set of innovative planning and delivery methods that should be considered and combined with those of the ICT industry.

Accordingly, those infrastructure methods are user-centric and flow- and pull-efficient, emphasize value generation, seek to reduce waste, and pursue perfection. In particular, lean construction requires the adaptation of lean principles originating from the Toyota Production System ("TPS") to the construction sector. Lean thinking is the antidote to waste [39]. Target Value Delivery ("TVD") is a management practice that drives the design and construction to deliver customer value within project constraints [40]. The Last Planner System ("LPS") is a collaborative production management system [41]. Integrated Project Delivery ("IPD") is a construction project delivery method that seeks efficiency and involvement of all participants (people, systems, business structures and practices) through all phases of design, fabrication, and construction [30]. Promoting the digital platform to the infrastructure sector is an opportunity for those methods to become the new modus operandi and help to realize the broader goals [16].

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3.2.5. Use Cases

Use cases are at the centre of the transformation towards a future era of infrastructure planning and delivery that is cyber-physical, user-centric, flow- and pull-efficient, and carbon-neutral. Infrastructure 4.0 also suggests the emergence of new business models and incentives for innovation and inclusive development [42]. In the course of this transition, use cases should increasingly represent a dynamic cyber-physical world that functions as a domain of smart and automated planning, construction, and operations. The underlying digital infrastructure and data ecosystems are distributed, interoperable, and interconnected and ensure cybersecurity, privacy, and data sovereignty (see Figure 2).

The development of use cases can start with individual applications and existing data. In the course of the platform implementation, a growing number of use cases increasingly constitutes as an ecosystem of trusted and open data spaces with links to other industries and regions. However, it is important that use cases are embedded from the outset within the digital and infrastructure governance and process frameworks in order to set the basis for overcoming the existing fragmentation of the value chain.

For governments to kick-start the development of mobilization and learning platforms, an inventory of micro and macro use cases should be identified, compiled, and prioritized using examples from the industry (e.g., interoperability standards for BIM data exchange), national government initiatives (e.g., the UK's Infrastructure Client Group's Project 13), G20 initiatives (e.g., InfraTech stock take of use cases), and the latest supra-governmental initiatives (e.g., Gaia-X federated digital platform) as well as examples of digital mobilization and learning platforms from other sectors, which will provide transferable knowledge. The promotion of use cases and the development of platforms can be accelerated through government funding and market mechanisms. Existing cloud platform systems and hyperscalers, such as Amazon, Google, and Microsoft, need to increase their trustworthiness through enhancing cybersecurity, privacy, and sovereign data exchange. Smart infrastructure development and management could offer a compelling set of transformative use cases.

3.3. Outlook

Governments should promote the introduction of federated platforms for infrastructure planning and delivery and mandate multi-stakeholder and multidisciplinary teams to design and implement the most promising use cases to accelerate the transition towards Infrastructure 4.0.

However, as already stressed above, technology and digitalization alone will not resolve the governance and strategic gap of the infrastructure industry. Thus, to complement the implementation of platforms, governments should establish National Infrastructure Councils to develop visions, realize long-term strategic planning, and develop and implement new participative models of infrastructure development. With the creation of national infrastructure councils, governments can make an extraordinary contribution to new and more vision-oriented, sustainable, and participatory planning and infrastructure delivery. They can provide and generate evidence-based proposals for action and act as a knowledge centre and independent think tank, putting infrastructure development back at the centre of societal attention. National infrastructure councils should govern local infrastructure councils, which are local/metropolitan agencies that plan, procure, and manage assets using the infrastructure platform model. In addition, a global network of national infrastructure councils and agencies could establish a fertile ecosystem of international experts bringing together global knowledge and research in this field.

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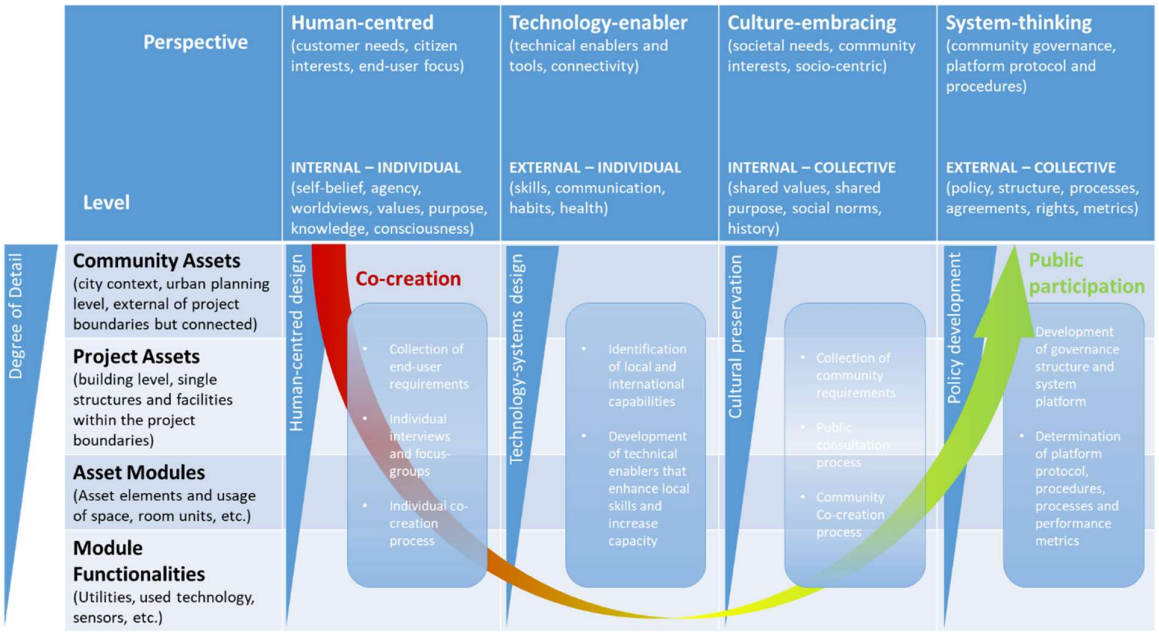

Figure 4. Holistic model of infrastructure development

As the basis for strategic discussions and decision-making concerning the future of infrastructure and the implementation of a learning platform, this policy brief does not propose specific technologies, but a holistic model of infrastructure development, as depicted above (Figure 4), that helps to embark from linear waterfall models that have lasted over decades.

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Additional Contributions:

Content contributors as follows (in alphabetic order)
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Norman Anderson, CG/LA Infrastructure, nanderson@cg-la.com (all other contributors alphabetically); Prof. Glenn Ballard, UC Berkeley, gballard@berkeley.edu; Dr. Mark Bew, PCSG Limited, mark.bew@pcsg.co.uk; David Bowcott, Aon Risk Solutions, David.Bowcott@aon.ca; Kai Broek, Capgemini Invent, Kai.Broek@capgemini.com; Prof. Gerd Buziek, Esri Deutschland GmbH, g.buziek@esri.de; Dr. Isabel Cane, OECD, Isabel.Cane@oecd.org; Raffaele della Croce, OECD, Raffaele.DellaCroce@oecd.org; Prof. Harry Dimitriou, University College London, h.dimitriou@ucl.ac.uk; Dale Evans, Project13, dale@deadvisory.com; Dr. Volker Kefer, Verein Deutscher Ingenieure, president@vdi.de; Isidora Kosta, World Economic Forum, isidora.kosta@weforum.org; Thomas Maier, G20 Global Infrastructure Hub, thomas.maier@gihub.org; Prof. Ibrahim Odeh, Columbia University, odeh@columbia.edu; Prof. Rafael Sacks, Technion Israel Institute of Technology, cvsacks@technion.ac.il; Thomas Schmid, Bavarian Construction Industry Association, T.Schmid@bauindustrie-bayern.de; Prof. Hajnalka Vaagen, Norwegian University of Technology, Hajnalka.Vaagen@ntnu.no

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Appendix A

The article contributes as policy brief to the T20 "Task Force 7: Infrastructure Investment and Financing" and the policy areas "digital infrastructure", "infrastructure governance", and "technological advances" and builds upon the "G20 Principles for Quality Infrastructure Investment" by enhancing the "G20 InfraTech Agenda." The policy brief also contributes to the G20 Infrastructure Working Group (pol-icy areas preparation and management) and supports the UN SDGs 9, 11, 13, and 17. This policy brief is based on research and numerous expert interviews carried out since July 2020. An international workshop to finalize the policy brief was held in Munich on 2 April 2021.

The policy brief addresses the following policy areas: exploiting technological advances for infra-structure development; strengthening infrastructure governance: openness, transparency and inclusion of local communities; new initiatives and mechanisms to support digital infrastructures; and integrating environmental criteria into infrastructure investment.

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