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A system of systems perspective

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Embracing multi-functionality in European infrastructure projects: A system of systems perspective

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ABSTRACT

Infrastructure projects undergo multiple changes throughout their lifecycle, adapting to new mobilities, technologies and environments. We build on the System of Systems (SoS) theoretical concept to understand the implications of such infrastructure transformations, specifically when projects move from a single purpose to hosting multiple functions. Using multiple case studies in Europe, we investigate which functions will likely be added to the original infrastructure and the rationale for adding these functions. Therefore, we expand upon the theoretical concepts of circularity, resilience, and social sustainability, wherein multifunctional infrastructure adapts, renews, and complements existing infrastructure.

1. Introduction

Infrastructure is primarily conceived to generate societal value and support communication, mobility, and other services. Critical infrastructure such as power and energy, transportation, and communication are crucial components of a functioning society [56]. These projects exist in a dynamic environment with multiple transitions across the lifecycle, such as climate change and the evolving demands of society [36]. The scope of this research is the operations phase of infrastructure projects, which includes the time between the beginning of the operations and the decommissioning of the asset.

Infrastructure projects are often designed and built with the specific aim of fulfilling a single function aligned with a well-defined objective. However, they undergo multiple changes throughout their lifecycle, adapting to new technologies and environments. By extending the construction boundary of a traditional project, the conceived lifespan of the infrastructure can be open-ended, flexibly incorporating opportunities in adjacent sectors and exploring potential synergies throughout a more extended operational period [28]. In the planning process of infrastructure projects, multiple functions are brought together, including housing, energy, nature, and transportation [18]. The project can be more flexible, adaptive, and sustainable by opening up the planning and design process beyond infrastructure. It could facilitate a shift from single-function infrastructure to multifunctional infrastructure, potentially fostering more inclusive development. Multifunctional projects can provide multiple benefits concurrently and maximize the value to society [21]. Thus, infrastructure projects undergo evolution by incorporating new functions over their extended lifecycles thereby interacting with society across different phases.

Multifunctionality research seeks to understand additional semiotic functions that interact with other functions or add another type of meaning in the public space. Current research explains how different functions may hinder or strengthen other functions and how a system of purpose speaks with another system of purposes [24]. We use concepts emerging in systems engineering and complex systems literature, offering a fresh perspective that views multifunctionality through a system of systems (SoS) lens. This viewpoint encompasses autonomy, belonging, connectivity, diversity, and emergence as defining attributes [44]. By adopting this perspective, it becomes more adept at addressing wicked, complex problems that demand an integrated and multifaceted response [26]. It can explain how different functions can strengthen each other in how one system of purpose speaks with another [24]. Considering the multifunctionality of infrastructure, we argue that such a SoS perspective provides an opportunity for efficient infrastructure

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arrangement when they operate in a dynamic system during its long lifecycle.

In our exploration, we leverage theoretical concepts related to value and resilience to comprehend the ramifications of infrastructure projects transitioning from single to multiple functions. As seen in the current European energy crisis, there's a drive to replace, renew, and expand existing energy grids [49]. This scenario leads to the proposal of a new hydrogen pipeline that could run parallelly, facilitating both full electrification and digitalization of transportation. We propose a need to fully theorize and conceptually explain how multifunctional infrastructure contributes to resilience and value for European society through a system of systems (SoS) perspective. Our research aims to delve into the understanding of asset renewal, expansion, and replacement through the lens of multifunctional infrastructures. This study endeavors to uncover additional value that contributes to societal needs and offsets potential adverse effects. Specifically, the research seeks to address two pivotal questions: 1) What are the prospective additional functions that can be integrated into infrastructures? and 2) What are the reasons behind incorporating these functions? Through this investigation, the objective is to develop theories that elucidate the intricate relationship between context, infrastructure, its functions, and the derived additional value and resilience.

The remainder of this paper is organized as follows. First, we conduct a detailed literature review on value and resilience in the context of the lifecycle of infrastructure projects, following which gaps in the literature are highlighted (Section 2). We then describe the research methodology of choosing multiple case-study-based approaches focusing on the European context (Section 3). We highlight the findings (Section 4) and discuss the additional functions and rationales for adding these functions (Section 5). The implications of moving from single to multifunctional infrastructure are then discussed from a value and resilience perspective (Section 6). Finally, we summarize the findings, theoretical and practical contributions, limitations, and future scope of work in the conclusion section (Section 7).

2. Literature review

Projects are vehicles for defining, creating, and delivering values [32], which benefits their stakeholders [57]. Value in projects is a multidimensional concept related to project implementation, sustainability, social value, and systemic value [33]. Project management discipline has primarily focused on delivering project outputs rather than on organizations' broader strategic and operational issues [11]. In that sense, the value in project is determined by the objective asset characteristics, whether the asset provides its intended value to the society such as roads transporting people and goods [5]. However, stakeholders such as sponsors, users, service providers, commercial firms and public organizations consider project outcomes in the operations phase as a measure of value rather than project completion metrics such as performance on time, cost, quality, and safety [38]. Additionally, infrastructure projects not only serve practical functions but also embody significant conceptual value tied to broader global goals, such as sustainability, social equity, and urban resilience [43]. Whyte and Mottee [53] advocate for a shift in mindset regarding projects, moving away from viewing them solely as social or technological endeavors, where success is primarily measured in terms of cost, quality, and schedule. Instead, they propose adopting a more comprehensive outcome-focused approach. This approach considers not only the efficient use of natural resources but also the broader impacts, both positive and negative, on various places and people over time. This means the value in projects is seen with the overall goals of supra system (e.g., sustainability, climate change adaptation, etc.). Thus, from a value perspective, there is an increasing focus on the expanded value of infrastructure projects.

In many infrastructure projects, the planning phase typically spans four to five years, followed by a similar duration dedicated to construction. Subsequently, the remaining period constitutes the operation phase, which often occupies the most substantial portion of the project's lifecycle [30]. When an infrastructure project reaches a lifecycle of 60 – 80 years, the projects become increasingly expensive in terms of maintenance, although the project was initially designed to last more than 100 years. Focusing on a single function of such infrastructure is costly and dismisses an opportunity to exploit the infrastructure's value to its whole lifecycle. In that sense, a system lifecycle view considering the expanded value of an infrastructure project enables a broader view of the project's temporary dimension to a multi-organizational system with integration between multiple organizations [2]. Projects must expand from their existing function to include other functions in the surroundings, moving from single to multifunctional infrastructure to increase value across the lifecycle [28].

Multifunctionality describes the capacity of an infrastructure to provide multiple functions in society [29]. It entails a meticulous balancing act among various functions and their spatial arrangement to enhance overall value [51]. It is related to practical functionality such as a road connecting region A and B or a solar panel generating electricity [27]. For example, a recreational park can incorporate supplementary functions like a football pitch, a cherry grove, and a parking lot designed to act as spaces for water retention during severe rainstorms (Hansen, 2019). In the process, multifunctional infrastructure addresses multiple issues in society simultaneously and has the potential to provide multiple benefits concurrently [54]. Multifunctionality can be also understood as creating multiple values without altering its original function. For example, according to Tadaki et al., [48], infrastructure can offer historical relation value that is tied to local environment. In this case, the function adapts to new demand while keeping infrastructure's conceptual value. However, multifunctionality is an elusive concept, with little information on how and why it is employed in infrastructure projects. There is a need to encourage multifunctionality in infrastructure projects, expanding their lifespan, to encourage flexibility, adaptability and, therefore, more sustainable projects (Hansen, 2019). To understand multifunctionality in the operations phase, a Systems of Systems (SOS) approach is well suited since it considers learning, adaptation, and navigation instead of control and prediction, which are critical capabilities for operating in high-uncertainty contexts such as in the case of the long lifecycle of infrastructure projects.

The literature on complex systems recognizes various system types, including monolithic, complex adaptive, and Systems of Systems (SoS) with each type possessing distinct characteristics [37]. In a monolithic system, all components are interconnected. While they can be straightforward to develop and initially maintain, they can become challenging to scale and modify as they grow in size and complexity. A complex adaptive system is comprised of multiple interacting elements that adapt and self-organize in response to changes and stimuli in their environment [4]. In contrast to these, SoS are typically larger, more complex entities that require coordination and interoperability among their constituent systems as these systems evolve [14]. A Systems of Systems (SoS) is delineated as a metasystem consisting of numerous interlinked and embedded autonomous complex subsystems. These subsystems may vary in technology, context, operation, geographical location, and conceptual framework. However, their integration is pivotal within the metasystem, collectively striving to yield desirable performance outcomes and achieve higher-level missions while adhering to constraints [26]. The goal of SoS is not prediction but rather understanding the essence of the problem because of which it has been used in many research studies that examine domains with ambiguity, complexity and change [17], such as multifunctionality in this study.

Bourne et al. [58] record five paradigms of an SoS framework – learning and adaptation, localization and orchestration, loose coupling, heterogeneity, and navigation and improvement. The first paradigm can be considered as autonomy [41] and focuses on learning and adaptation because SoS considers parts of the system to have independent purposes, and configuring them would require greater devolvement, delegation of authority, and autonomy. In the second paradigm, the emphasis lies on localization and orchestration within Systems of Systems (SoS). Leaders might pivot towards orchestrating the SoS's operations by coordinating interactions among its subsystems, rather than attempting to enforce a predetermined solution through centralized control and alignment. In the third paradigm, there's an emphasis on loose coupling within Systems of Systems (SoS). Here, the structure evolves as individual autonomous systems opt to join or depart from it. Consequently, the relationships among these systems cannot be pre-designed or predetermined [45]. The fourth paradigm focuses on heterogeneity, as units may contribute to the objectives differently, even in the presence of common goals and objectives. The fifth paradigm centers on navigation and improvement within Systems of Systems (SoS). It recognizes that the properties and functions of the SoS are qualitatively new, arising from a continually evolving complex configuration of its individual components [6]. The SoS paradigm theory [58], comprehensively integrates both technical and social aspects of the system. Its core objective is to aid decision-makers in navigating through uncertainties and effectively responding to the varied needs of multiple stakeholders.

The gaps in the management of infrastructure research, both in terms of how value creation and resilience can be achieved across the lifecycle of infrastructure projects and how multifunctionality may be integrated into the lifecycle, call for an examination of current practice from an SoS perspective. Through this research, we take the first step in this direction by investigating the type of additional functions included in multifunctionality and why these functions are added.

3. Research setting and method

To address our research inquiries, we adopted a multiple qualitative case study approach, which allows us to examine various cases pivotal for theory formulation [55]. This qualitative case study design permits in-depth exploration of real-world participation and the dynamics and processes inherent within each case [13]. This methodology is well-suited for examining complex phenomena such as multifunctionality, as it allows for in-depth understanding and interpretation of nuances and patterns inherent in various cases for exploration of the concept. The choice of multiple cases allows the identification of common themes across distinct contexts, enhancing the generalizability of the findings [12]. The methodological approach followed in this research is depicted in Fig. 1.

The European context was selected for this study due to several compelling reasons. Firstly, much of the infrastructure in the region, predominantly constructed after the Second World War, is approaching the end of its operational life. Secondly, within the European context, there's a pronounced emphasis on upgrading existing infrastructure to optimize its societal value, rather than exclusively focusing on building new structures [23]. Additionally, Europe is undergoing various transitions, such as in energy and sustainability, which entail both renewing existing infrastructure and implementing new projects. Hence, this research delved into several critical case studies of infrastructure projects in Europe that transitioned from single to multifunctional systems [16].

We compiled multiple mini-cases in Europe that offer rich, detailed information and varying perspectives on the phenomenon being studied. The case selection criteria involve purposive sampling based on relevance to the research focus and diversity in organizations, countries, and sectors such as airports, ports, dikes, railway stations, etc. Data was collected through news articles, reports, documented case studies, academic papers, etc., based on the local knowledge of the involved researchers. Our careful collection of data sources based on the experience of locally involved researchers allowed us to build a rich case study that describes the dynamics of the multifunctionality of the particular infrastructure. We found these data sources adequate for our exploratory research. We did not require too much information on the entire infrastructure project, such as the processes or micro-practices; instead, we were focusing on the additional functions and why those functions were essential to be added. Thus, we opted for a broad scan, covering multiple critical European cases rather than an in-depth analysis of a single case. We created short cases of 500 words on each project and its multifunctionality.

The data collection and analysis steps were conducted together to develop theoretical explanations inductively. We conducted a cross-case analysis, scrutinizing each case to identify the additional functions incorporated and the rationale behind their inclusion. Open coding and categorization were conducted to capture critical themes, patterns, and unique aspects across the cases [7]. Here, the focus was on finding consistency in issues, relationships, and other themes. Cross-case analysis was conducted to synthesize findings and develop a comprehensive understanding of the phenomenon. Constant comparison techniques are utilized to ensure rigor and reliability in identifying patterns and trends. Triangulation of data sources, investigator triangulation, and member checking are used to enhance the credibility and confirmability of the findings [35]. We, thus, discuss multiple cases in different countries, tabulate the key findings, theorize the type of additional functions and the rationale for adding these functions and suggest implications for future research in the following sections.

4. Findings

In the Netherlands, the Port of Rotterdam, located in the province of South Holland, is the largest seaport in Europe. Its primary function was as a port facilitating the transport of goods by water. However, the port has the vision to facilitate multiple regional transitions and be well-integrated with society. During the recent energy crisis in Europe, the project provided residual heat from the port to households in Hague. This pilot case was expanded to WarmtelinQ project which will supply residual heat from the Port of Rotterdam to nearby municipalities including Vlaardingen, Schiedam, Midden-Delfland, Delft, Rijswijk and the Hague[1]: "*WarmtelinQ ensures that residual heat can be put to good use. This residual heat comes from industry in the Port of Rotterdam and - because it is a waste product - it is CO 2 -free heat.*"

Another project in the Netherlands, the Gouda Dike, protects the city and surrounding areas from floods while functioning as a Westen Ring Road. In 2012, the Water Board of Schieland concluded that the dike no longer meets their safety standards and has to be renewed. At the same time, there was a proposal for a new ring road beside the dike. Instead of developing a separate dike and road, South Holland Province and the Water Board decided to work together to create an integrated one. Combining two functions – road and dyke – yields saving costs and extra returns. An article summarized the multifunctionality in the Gouda dike, *"In Gouda, [...] costs are saved by building a road that also serves as a dyke; a saving of 84%. At the same time, the road, which is also a dyke, yields extra returns: access to the area is better than without the road cum dyke, so existing and new homes are more easily accessible (*[22]*; p.29)."* The Rotterdam the Hague Airport is a minor international airport serving two adjacent cities, Rotterdam, the second largest city in the Netherlands, and the Hague, the administrative and royal capital of the country. Rotterdam the Hague Airport claims to ensure *"a balance between public interests such as economy, welfare, health, and climate. Various surveys show that a large majority of the population in the region supports the airport. We are all aware of the fact that an airport has an impact on our environment. Not only in terms of employment, connectivity, and incoming passenger flows but also because of the effects on noise pollution and air quality*[2]*."* Large numbers of noise-related complaints were registered by the people living close to the airport, as the noise from aircraft breached their private lives. Along with taking steps to reduce the noise level, the

[1] https://www.warmtelinq.nl/over-warmtelinq

[2] https://www.rotterdamthehagueairport.nl/en/airport-and-me/airport-as-neighbour/a-new-balance/

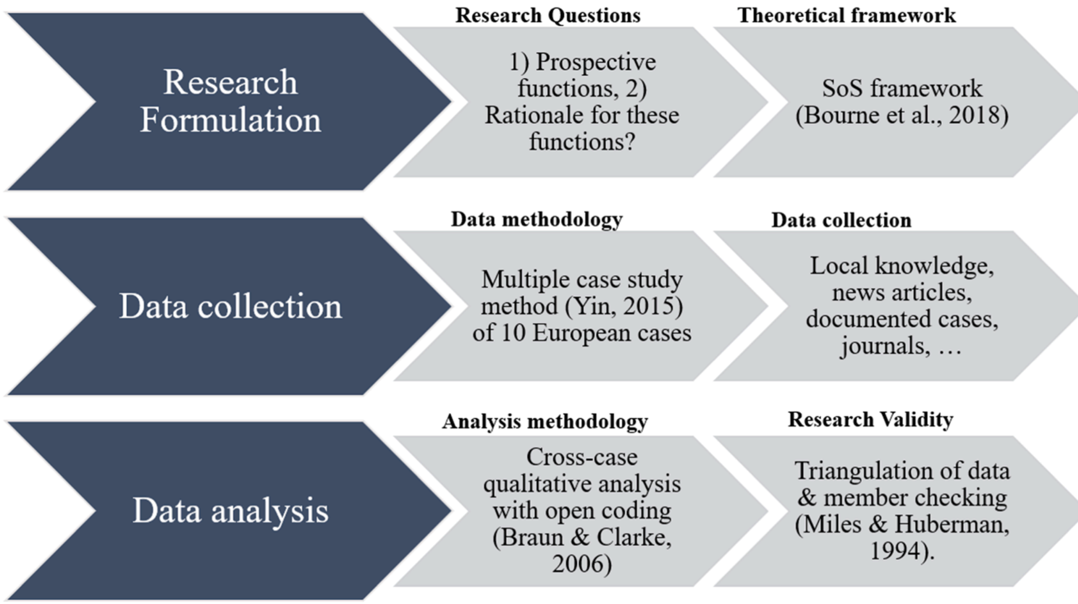

Fig. 1. Methodological approach in this research.

airport authorities started a business park in the airport premises to support entrepreneurs and bring economic activity and benefits to the people living close to the airport.

In Austria, the redesign of the public square in front of U6 station Josefstädter Straße and Yppenheim is another example of creating additional value from obsolete infrastructure. Josefstädter Straße, a station on the U6 line of the Vienna Gürtel and part of Vienna's rapid transit network, was opened in 1898 as part of the Stadtbahn. In 2015, all the square areas around the station were redesigned, removing a neighboring gas station. *"The aim of this wholescale renovation project is also to ensure that the costs of maintenance work in the coming years are kept as low as possible*[3]*."* Attractive passages and recreation areas transformed the square into a more open and accessible public space. Similarly, in the case of the High Line in New York, the abandoned railway was transformed into a green space through a collaboration between architects, landscape designers, city planners, and local communities, revitalizing the area and fostering community engagement [15]. In the instance of the Katschberg Tunnel in Salzburg, the Austrian road authority ASFiNAG has implemented solar panels across various areas: on road embankments, atop the tunnels, and integrated into noise barriers along the highway. The new system in the state capital will generate an annual yield of up to 305,000-kilowatt hours, which will be used directly on-site, primarily for the energy-intensive entrance lighting of the tunnel [3]. Adding solar panels to existing infrastructure is one of the easy ways to add functions to enhance the value of infrastructure. Thus, the project and the tunnels within are made completely self-sufficient by utilizing solar panels.

The Oresund Bridge is a combined railway and motorway bridge across the Oresund strait connecting Sweden to Denmark. The bridge was commissioned in July 2000; however, it fell short of the revenue forecast during the initial years of operation. The authorities started the Oresund Science Collaboration, facilitating close collaboration between universities on either side of the bridge to drive economic activity. One study revealed that *"the removal of physical barriers in a cross-border region can have a substantial positive effect on knowledge flows if a targeted policy effort is made (*[20]*; p. 35)"*. These collaborations are also a means to build skills to identify new opportunities in the project. Another example from Sweden is the Swedish rail, which has a network of over 15,000 km of tracks across the country. The railways used this network to deliver high-speed communication systems to support the Swedish government's initiative to develop 'Fiber to the X' (FTTX) networks throughout the country. *"And as the rail market in Sweden is in the throes of a huge FTTX expansion, we are joining forces with Emtelle to help the Swedish operators cover huge swathes of their national networks rapidly and cost-effectively with our cutting-edge solutions*[4]*"* expressed the Head of Telecom Sales for Nordic countries at Nexans.

In Belgium, there were several attempts to convert less-used underground public car parks into something more useful. One example is in Antwerp, where a water company, Water-link converted part of the underground car park in Groenplaats into rainwater storage. This project is part of Water-link's efforts to improve the city's water management and reduce the reliance on drinking water for non-drinking purposes. The rainwater is used for various purposes, including irrigating public spaces, flushing toilets in public buildings, and cleaning streets. The car park also had a purifying facility to supply drinking water to the local community [25]. Also, the first floor of the underground car park is converted into a bicycle park, providing more green transport options[5].

The multiple European infrastructure projects considered in this research, along with their primary function, additional functions, and rationale for additional functions, are summarized in Table 1.

5. Discussion

In this section, we theorize the additional functions and the rationale for adding these functions from the empirical data on multiple critical cases in Europe.

5.1 Additional functions

From the empirical data, we noted that different additional functions, such as energy generation, regional and economic development,

[3] https://www.intelligenttransport.com/transport-articles/17370/vienna-juggling-much-needed-renovation-with-no-service-interruption/

[4] https://www.railwaypro.com/wp/nexans-to-upgrade-communication-systems-of-swedens-rail-network/

[5] https://tripbytrip.org/2022/05/20/antwerp-groenplaats-to-become-green-again/

Table 1
Multifunctionality in European infrastructure projects.

Project	Primary function	Additional functions	Rationale for additional functions
Rotterdam port (Netherlands)	Water goods transport	Functions for energy supply (heat)	Changing demands of society, opportunity
Gouda dike (Netherlands)	Water management	Functions for optimizing space and resources (road with dike)	Renewal of infrastructure (renovation of dike)
Rotterdam-Hague airport (Netherlands)	Air transport	Functions for economic development (business parks)	Community resistance
Josefstädter Straße (Austria)	Station area	Functions for revitalizing space (Aesthetics)	Declining primary function; Redesigning for cost reduction
Katschberg tunnel project (Austria)	Road transport	Functions for energy generation (solar energy)	Changing demands of society (operational sustainability), opportunity
Oresund bridge (Sweden-Denmark)	Road/rail transport	Functions for regional and economic development (university collaboration)	Changing demands of society (increase value from the project); adding new skills
Swedish rail network (Sweden)	Rail transport	Functions for network effect (communication systems)	Need for new infrastructure
Underground car park in Groenplaats (Belgium)	Underground car parking	Water storage, bicycle parking	Changing demands of society, opportunity

network effect, and revitalizing space, were added to an infrastructure's primary function. These are discussed below.

1. *Functions for energy generation and supply:* The port of Rotterdam in the Netherlands provided residual heat to the city of the Hague, and the Katschberg Tunnel in Austria installed solar panels to become energy self-sufficient. Energy generation by installing solar panels is an easy function for all infrastructure as it can serve the energy needs of the infrastructure and has the potential to supply energy to the grid. Additionally, energy supply with residual energy from the infrastructure can transfer to nearby areas, optimizing energy generation and use.
2. *Functions for economic development:* The Oresund Bridge in Sweden facilitated the Oresund science collaboration to increase the bridge's demand and revenue. The collaboration led to the region's economic development and increased revenue for the bridge's construction. The Rotterdam the Hague Airport in the Netherlands also started a business park for the area's economic development. The economic development aimed to generate benefits for the community (e.g., jobs and amenities) who are inconvenienced due to the noise from aircraft.
3. *Functions for network effect:* An infrastructure can expand its functions to integrate with other infrastructure and create a network effect, creating more value from increased users. The infrastructure bed of one technology is used to embed others. This way, multifunctional infrastructure corridors emerge, and minimal impact on the surrounding landscape is guaranteed. For example, the Gouda dike expanded its function to include a highway, maximizing value. Similarly, the Swedish rail used its 15,000 km track to deliver high-speed communication systems nationwide. This adds to the systems of systems alignment thinking [19].
4. *Functions for revitalizing space:* The redesign of the Josefstädter Straße station area demonstrates how the former industrial use of the traffic infrastructure became obsolete and was replaced by a social infrastructure through the redesign and embellishment of its adjacent public spaces. Instead of obsolete infrastructure (gas station), the area became an open and accessible recreation area, attracting more people.

Thus, throughout the lifecycle of an infrastructure project, strategic consideration of multiple ecological, social, and economic functions can be integrated. This comprehensive approach ensures a more holistic and balanced outcome that accounts for various aspects across different stages of the project (Madureira & Andresen, 2013). The next section discusses the context and rationale for adding these functions.

5.2 Rationale for adding functions

From the empirical data, we note that additional functions were added for diverse rationales, such as changing demands of society and opportunity, community resistance, declining primary function, renewal of infrastructure, and need for new infrastructure.

1. *Changing demands of society and opportunity:* An infrastructure project has a long technical single-purpose lifecycle but is exposed to changing demands of society over the period. Infrastructure projects in Europe added functions to supply energy to people, such as in the case of the Port of Rotterdam, and functions to become energy neutral, such as in the case of the Katschberg Tunnel. Adding functions allows infrastructure projects to be future-proof and maximize value for society throughout the lifecycle.
2. *Community resistance:* Infrastructure projects such as airports, high-speed rails, and sewage treatment plants seldom benefit people living nearby who are constantly inconvenienced due to the primary function of the infrastructure [46]. In such cases, there is a need to get societal acceptance for the project. Social sustainability emphasizes the importance of considering the well-being and quality of life of the affected communities [52]. In the case of the Rotterdam the Hague Airport adding additional functions helped address the social impacts, engaging local stakeholders, and ensuring equitable access to resources and opportunities by making the project beneficial to the nearby people. The multifunctionality of infrastructure can ensure that the different needs of the population, particularly those living nearby, are met [21], thereby generating more value.
3. *Need for new infrastructure:* Existing infrastructure responds to the region's need for new infrastructure by adding the function of the new infrastructure. For instance, the Gouda dike responded to the need for a new highway infrastructure by expanding its function to include a highway on top of the dike. In a similar vein, the Swedish rail network responded to the government's 'Fiber to the X' (FTTX) initiative by integrating a high-speed communication system into its network. Burton [9] suggests repurposing existing infrastructure and reutilizing brownfields to maximize urban space efficiency. Our study expands on this literature by elucidating which functions can be incorporated into existing infrastructure and the reasons driving these additions.
4. *Renewal of infrastructure:* An infrastructure adopts new functions during its renewal, such as with the Gouda dike adopting new functions on renewal. Thus, the project optimizes space and resources during renewal, and the advantages for both parties on reduced costs and more benefits are clear from the beginning [31].
5. *Declining primary function:* The declining primary function was why the Vienna Ring Road planted vegetation and added an aesthetic function. Even during COVID-19, city administrations let restaurants set up tables in streets and parking lots, giving a new function to city roads with a declining primary function of fewer cars on the road

[47]. Here, additional functions are added to minimize damage due to declining primary function.

Fig. 2 shows how infrastructure projects respond to different events in their operation phase by adding functions.

The additional functions created more value for society due to the multifunctionality of infrastructure projects. Thus, infrastructure project adds value to society by being resilient throughout their lifecycle.

6. Implications

This research on the multifunctionality of infrastructure projects has several implications for research and practice for infrastructure projects anchored on the paradigms of an SoS system theory by Bourne et al. [58].

1. *Relation between the added function and its rationale:* We found that the functions added to an infrastructure project were not random instead it had a strong rationale. Functions depended on the changing demands of society, as was in the case of the European energy transition and the need for projects to be self-sufficient and provide heat to nearby areas. We also saw that functions that benefit the people living nearby were preferred for projects that cause inconvenience to the stakeholders adjacent to the project. In some cases, the added function was complementary to the primary function, as in the road over the dike case. Van der Heijden and de Blok [50] highlight that one function depends on another for proper integration. The implication aligns with the Systems of Systems (SoS) paradigm of 'localization and orchestration'. This perspective underscores the importance of orchestrating functions based on interactions between subsystems, rather than trying to enforce a predetermined solution through centralized control. It emphasizes a more adaptive and coordinated approach within the system [58]. Thus, multifunctionality in infrastructure is much more than adding many functions in the same space; instead, these functions should reinforce and complement one another to maximize value for society.
2. *Integration with the environment:* Infrastructure projects must be dynamic and adopt multiple functions to integrate with the environment over the long operation phase. Projects respond to the environment through changing demands of society and opportunity, community resistance, declining primary function, renewal of infrastructure, and the need for new infrastructure by adding additional functions. Infrastructure projects should improve the integration with the environment, i.e., with civil society or actor dimension, with area or scope dimension, or with the operating network or time dimension to create more inclusive projects [28]. Value creation in infrastructure projects depends on the interaction between organizations within the networked system [2]. Multifunctionality is a way for projects to think beyond the traditional view of a project as producing a physical facility to a project as delivering value for society. There is a need for a better understanding of a project and its relationship with the environment to bring into view alternative forms of future making [53]. Besides, adding functions can make the construction industry sustainable by reducing consumption and emissions in the sector. Thereby, multifunctionality answers a call for the construction industry to work what is already there in the form of existing infrastructure. Adapting existing infrastructure to suit changes through multifunctionality is similar to the 'loose coupling' SoS paradigm, where autonomous systems can choose to belong to a system or leave it depending on the environment [58]. Thus, infrastructure projects must be flexible enough to add new scope and functionalities throughout their long cycle for better integration with the environment. With multifunctionality, projects are planned to match systems of systems across a myriad of complex stakeholder relationships [19].
3. *Seeking opportunities to increase value:* Infrastructure projects actively seek opportunities to add functions and increase value during operation. This was seen in the case of the Oresund bridge, which enabled the Oresund science collaboration to increase its revenue. We highlight the potential of multifunctionality to generate additional value for society through a multi-level conceptualization of value enabled by different functions such as energy generation, economic development, network effect, and optimizing space and resources. The value created through multifunctional infrastructure is through an incremental transformation in contrast to megaprojects, which bring about radical transformations in the region. Adding new functions in

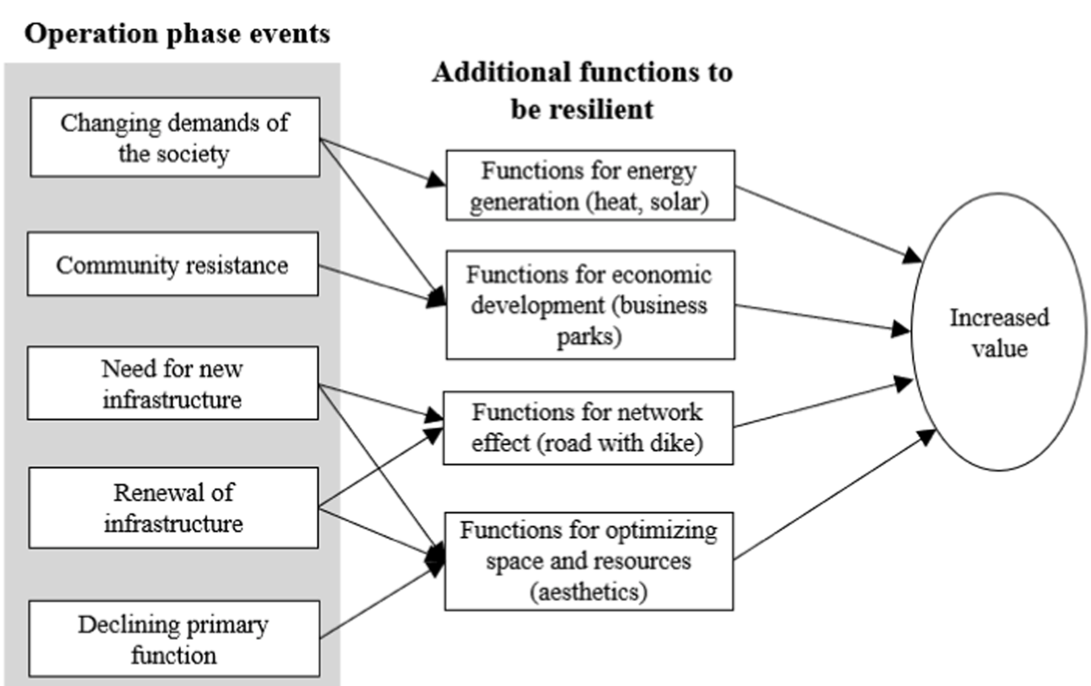

Fig. 2. Relation between events and additional functions

the decommissioning and conversion examples of Antwerp project was to increase the value and extend the lifespan. Through multi-functionality, infrastructure projects seek organizational alignment and autonomy through increasingly frequent loops of learning and adaptation of functions as in the SoS framework [42]. The primary objectives would revolve around continuous performance enhancement and refining the structure and operation of the system which would help navigate the complexities inherent in various environments, ensuring adaptability and improved functionality over time [58]. We thus extend the literature stating that the poorly managed operational phase of an infrastructure project undermines the project objectives and erodes value for money [40] to highlight how not tapping the value potential of multifunctionality during the operation phase also erodes value for money. Value is lost regarding an unoptimized infrastructure asset and the resource requirement to construct a new single infrastructure project for the particular function. Thus, we suggest a system lifecycle view to study existing infrastructure, considering the project's ability to continue operations and add value, creating functions even decades after the project phase has ended [2]. Along with city-wide planning, standards, and guidelines to promote multifunctionality within the city during the early stages of a project [21], asset owners must constantly seek opportunities to add functions and increase value.

4. *Role of infrastructure in resilience:* Resilience entails adaptive capacity, anticipatory capacity, and absorptive capacity [8] and building these capacities are essential to improve resilience of a system. We saw in this research how society was able to cope with changing scenarios due to the multifunctional nature of infrastructure, as in the case of the Port of Rotterdam providing heat to be resilient to the energy transition. In addition, infrastructure also became resilient by adding additional functions, as in the case of the Oresund Bridge. There is a need for increased resilience in society with frequent economic and climate changes. multifunctional infrastructures play a significant role in enhancing resilience due to their inherent qualities such as flexibility, adaptability, diversity, and interconnectedness with the larger urban environment [34]. These attributes empower them to better withstand and respond to various challenges and changes within their surroundings. Multifunctional infrastructures can contribute to resilience as they are flexible, adaptive, diverse, and connected to the broader urban fabric [34]. The ability of infrastructure to adapt to diverse functions is similar to the 'heterogeneity' SoS paradigm, where units may contribute to resilience differently even in the presence of common goals and objectives [58]. By drawing upon the theoretical concept of resilience, multi-functional infrastructure serves as a bridge, linking geographical nodes through renewal, complementation, or the addition of new components to existing infrastructure. This approach allows infrastructure projects to continually reinvent themselves, staying relevant and responsive to evolving needs and changing times by integrating new functions.
5. *Considering multiple perspectives in infrastructure:* To operationalize multifunctionality in infrastructure, there is a need to consider new scales of intervention [1]. Synergies are created when multiple functions are added, considering the local natural resources, impact on people living nearby, efficient use of space, collaboration between different agencies, integration of goals, etc., all of which have implications for the skills needed by infrastructure practitioners. Multifunctional infrastructure is more complex than single functional infrastructure as they are a multi-organizational system with separate financial streams and disruptions in adding a new function. To navigate this, infrastructure professionals must be T-shaped professionals with the ability to consider and understand multiple disciplines along with in-depth knowledge of their discipline of expertise [39]. In the case of the Oresund bridge, it can be argued that the science collaboration are also a means to build skills to identify new opportunities in the project. Within the Systems of Systems (SoS) paradigm, there's an emphasis on professions acquiring the requisite skills as and when needed. This enables them to effectively navigate through the multitude of changes they consistently encounter [10]. This adaptability and skill acquisition are crucial for managing the complexities inherent in dynamic systems. Thus, to operationalize multifunctionality, professions would require immense coordinating skills, multiple sets of capabilities and a greater involvement in the day-to-day operations of the infrastructure project.

Fig. 3 highlights how infrastructure projects can embrace multi-functionality through an improved understanding of multifunctionality and through improved practices of multifunctionality, both anchored on the paradigms of an SoS system theory by Bourne et al. [58].

7. Conclusion

This research underscores the significance of prioritizing the operations phase within infrastructure projects. This phase serves as a crucial period for adaptation, renewal, and the generation of increased value for society. It highlights the ongoing relevance and evolution of infrastructure beyond its construction phase, emphasizing its continuous contribution to societal progress and development. We argue that novel and practically relevant implications on the multifunctionality of infrastructure can be developed by employing a 'system of systems' (SoS) perspective previously used to study complex systems. We use multiple case studies in Europe to explore how and why infrastructure projects move from single to multiple functions. The case studies strongly indicate the imperative for infrastructure projects to continually evolve and maintain relevance amid changing times by incorporating additional functions. This research underscores that transitioning from single to multifunctional infrastructure enables asset owners to explore potential new avenues, fostering flexibility through a more decentralized approach. This approach is better equipped to adapt and respond to environmental turbulence effectively.

We make multiple contributions. Firstly, we record how infrastructure projects continuously evolve beyond its initial construction to remain relevant and beneficial in a rapidly changing environment by embracing multifunctionality. We highlight why certain functions are added to infrastructure projects. Functions were sometimes dependent on the changing demands of society, sometimes were for the benefit of inconvenienced people living nearby, and sometimes were complementary to existing functions. Secondly, we emphasize the vital link between resilience and value creation. We saw that value was created through multi-functionalities in the process of projects being resilient to changes. Thirdly, we extend the literature stating that an infrastructure project's poorly managed operational phase erodes value for money to highlight how not tapping the value potential of multifunctionality during the operation phase erodes value for money. We note that multifunctionality is required to create incremental transformation or constantly improve value in society in contrast to megaprojects, which bring about radical transformation. Fourthly, while highlighting the importance of enhancing multifunctionality in the planning stage, we also stress its importance as an operational goal for asset owners. Adding new functions to existing infrastructure according to the changing needs of the society can prevent the production of waste, while increasing efficiencies in the uses of energy, water, resources, and human capital. Finally, we show the significance of the operations phase of infrastructure projects and call for research on new project management approaches to add value and capacity beyond the construction phase, thus seeing constructed infrastructure assets managed by agencies optimized for value creation along with the current optimization for operations and maintenance.

The work has some limitations which offer some scope for future research. The case studies included in this research span across Europe. Future research can consider in-depth case studies across the world to

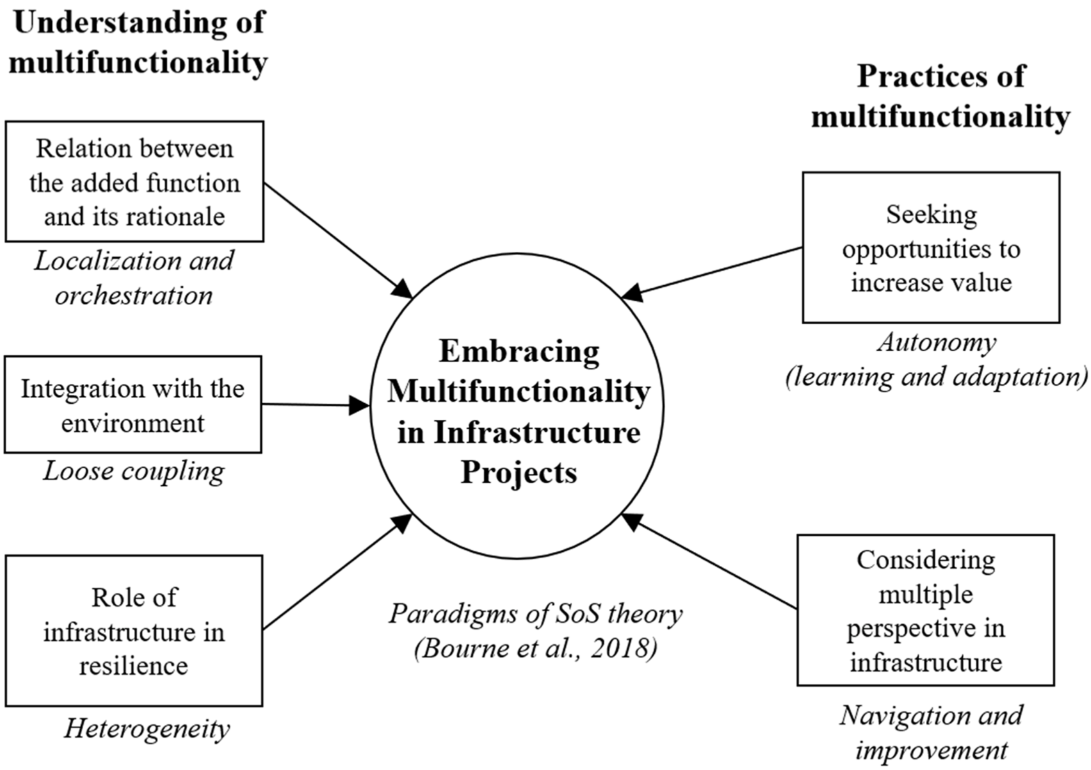

Fig. 3. Embracing multifunctionality in infrastructure projects from a SoS perspective

study the micro-practices of multifunctionality, such as how collaboration between partners happens. While macro-level analysis allowed us to uncover relevant System of Systems (SoS) dynamics of cooperation, synergy, and decentralized control, a future longitudinal analysis can provide a detailed analysis of the role of different stakeholders such as municipalities, NGOs, and community groups. Future research can consider the role of infrastructure and the rationale in adding other functions such as user safety and environmental protection. Additional research is needed to promote multifunctional infrastructures, enhance synergies, and manage potential conflicts between different functions. We also call for more research to study the use of space, the complementarity of functions, and resilience from a multifunctional infrastructure perspective.

CRediT authorship contribution statement

Johan Ninan: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yirang Lim:** Writing – review & editing, Methodology. **Hans de Boer:** Writing – review & editing, Conceptualization. **Ossi Pesamaa:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Maarten Van Acker:** Writing – review & editing, Writing – original draft, Conceptualization. **Eva Schwab:** Writing – review & editing, Conceptualization. **Johannes Bernsteiner:** Writing – review & editing. **Peter Soderholm:** Writing – review & editing. **Marcel Hertogh:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] P. Allmendinger, G. Haughton, Soft spaces, fuzzy boundaries, and meta-governance: the new spatial planning in the Thames Gateway, Environ. Plann. A 41 (3) (2009) 617–633.
[2] K. Artto, T. Ahola, V. Vartiainen, From the front end of projects to the back end of operations: managing projects for value creation throughout the system lifecycle, Int. J. Project Manag. 34 (2) (2016) 258–270.
[3] ASFiNAG, Road Tunnels Energy Generation and Storage Opportunities: Highly available, sustainable and efficient operation of road tunnels, ASFiNAG, 2020. Retrieved at, https://www.tunnel-graz.at/assets/files/tagungsbaende/2020-presentations/10_List_Tunnel2020_presentation.pdf.
[4] J.J. Assumpção, L.M. Campos, D.A. Vazquez-Brust, M. Carvalho, The orchestration of green supply chain management practices to enable performance measurement and evaluation, Product. Plann. Control (2023) 1–20.
[5] A. Babaei, G. Locatelli, T. Sainati, Local community engagement as a practice: an investigation of local community engagement issues and their impact on transport megaprojects' social value, Int. J. Manag. Projects Business 16 (3) (2023) 448–474.
[6] W.C. Baldwin, J.T. Boardman, B.J. Sauser, Expanding a system of systems model with the Schelling segregation model, Syst. Res. Behav. Sci. 30 (1) (2013) 65–75.
[7] V. Braun, V. Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2) (2006) 77–101.
[8] C. Brown, R.R. Shaker, R. Das, A review of approaches for monitoring and evaluation of urban climate resilience initiatives, Environ. Dev. Sustain. 20 (2018) 23–40.
[9] E. Burton, The compact city: just or just compact? A preliminary analysis, Urban studies 37 (11) (2000) 1969–2006.
[10] D. DeLaurentis, R.K.C. Callaway, A system-of-systems perspective for public policy decisions, Rev. Policy Res. 21 (6) (2004) 829–837.
[11] A. Edkins, J. Geraldi, P. Morris, A. Smith, Exploring the front-end of project management, Eng. Project Organization J. 3 (2) (2013) 71–85.
[12] K.M. Eisenhardt, Building theories from case study research, Acad. Manag. Rev. 14 (4) (1989) 532–550.
[13] K.M. Eisenhardt, M.E. Graebner, Theory building from cases: opportunities and challenges, Acad. Manag. J. 50 (1) (2007) 25–32.
[14] I. Eusgeld, C. Nan, S. Dietz, System-of-systems" approach for interdependent critical infrastructures, Reliab. Eng. Syst. Saf. 96 (6) (2011) 679–686.
[15] J. Foster, Off track, in nature: construction ecology on old rail lines in Paris and New York, Nature Culture 5 (3) (2010) 316–337.

[16] B. Flyvbjerg, Five misunderstandings about case-study research, Qual. Inquiry 12 (2) (2006) 219–245.
[17] A. Gorod, S.J. Gandhi, B. Sauser, J. Boardman, Flexibility of system of systems, Global J. Flexible Syst. Manag. 9 (2008) 21–31.
[18] C. Gürsan, V. de Gooyert, M. de Bruijne, E.A.J.A. Rouwette, Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands, Cities. 140 (2023) 104397.
[19] Y.Y. Haimes, Strategic preparedness for recovery from catastrophic risks to communities and infrastructure systems of systems, Risk Anal.: Int. J. 32 (11) (2012) 1834–1845.
[20] T. Hansen, Bridging regional innovation: cross-border collaboration in the Øresund Region, Geografisk Tidsskrift-Danish J. Geography 113 (1) (2013) 25–38.
[21] R. Hansen, A.S. Olafsson, A.P. Van Der Jagt, E. Rall, S Pauleit, Planning multifunctional green infrastructure for compact cities: What is the state of practice? Ecol. Indic. 96 (2019) 99–110.
[22] J.V.D. Heijden, M. Bakker, Reinventing Multifunctionality Combining Goals, Sharing Means, Linking Interests. Reinventing Multifunctionality Combining Goals, Sharing Means, Linking Interests, Netherlands Enterprise Agency, 2016.
[23] M.J. Hertogh, J.D. Bakker, M.J. van der Vlist, A.S. Barneveld, Life cycle management in upgrade and renewal of civil infrastructures, Org., Technol. Manag. Construct.: Int. J. 10 (1) (2018) 1735–1746.
[24] M.A. Höllerer, T. van Leeuwen, D. Jancsary, R.E. Meyer, T.H. Andersen, E. Vaara, Visual and Multimodal Research in Organization and Management Studies, Routledge, London, 2019.
[25] R. Ilsbroekx, M. Van Acker, Automotive urban landscapes: exploring public programmes for adaptive reuse of underground car parks, J. Landscape Architect. 16 (3) (2021) 24–39.
[26] C.B. Keating, J.J. Padilla, K. Adams, System of systems engineering requirements: challenges and guidelines, Engineering Management Journal 20 (4) (2008) 24–31.
[27] L. Kuitert, J. Willems, L. Volker, Value integration in multi-functional urban projects: a value driven perspective on sustainability transitions, Const. Manag. Econ. 42 (2) (2024) 182–198.
[28] S. Lenferink, T. Tillema, J. Arts, Towards sustainable infrastructure development through integrated contracts: experiences with inclusiveness in Dutch infrastructure projects, Int. J. Project Manag. 31 (4) (2013) 615–627.
[29] C. Liquete, S. Kleeschulte, G. Dige, J. Maes, B. Grizzetti, B. Olah, G. Zulian, Mapping green infrastructure based on ecosystem services and ecological networks: a Pan-European case study, Environ. Sci. Policy. 54 (2015) 268–280.
[30] J. Liu, P.E. Love, J. Smith, M. Regan, P.R. Davis, Life cycle critical success factors for public-private partnership infrastructure projects, J. Manag. Eng. 31 (5) (2014) 401–407.
[31] Y. Liu, Z. Wang, Z. Huang, J.Y.L. Forrest, Resource conflicts resolution of sophisticated production lines during the process of product renewal, IEEe Trans. Eng. Manage 71 (2024) 5965–5981.
[32] M.M. Martinsuo, L. Vuorinen, C. Killen, Lifecycle-oriented framing of value at the front end of infrastructure projects, Int. J. Manag. Projects Bus. 12 (3) (2019) 617–643.
[33] S. Mathur, J. Ninan, L. Vuorinen, Y. Ke, S. Sankaran, An exploratory study of the use of social media to assess benefits realization in transport infrastructure projects, Project Leadership Soc. 2 (2021) 100010.
[34] S. Meerow, J.P. Newell, Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit, Landsc. Urban. Plan. 159 (2017) 62–75.
[35] M.B. Miles, A.M. Huberman, Qualitative Data Analysis: An Expanded Sourcebook, 2nd ed., Sage Publications, 1994.
[36] V. Mishra, A. Sadhu, Towards the effect of climate change in structural loads of urban infrastructure: a review, Sustain. Cities. Soc. 89 (2023) 104352.
[37] A. Mostafavi, D.M. Abraham, D. DeLaurentis, J. Sinfield, Exploring the dimensions of systems of innovation analysis: a system of systems framework, IEEe Syst. J. 5 (2) (2011) 256–265.
[38] P.W.G. Morris, Reconstructing Project Management, John Wiley & Sons, Chichester, UK, 2013.
[39] J. Ninan, M. Hertogh, Y. Liu, Educating engineers of the future: T-shaped professionals for managing infrastructure projects, in: Project Leadership Soc., 3, 2022 100071.
[40] R. Osei-Kyei, A.P. Chan, E.E. Ameyaw, A fuzzy synthetic evaluation analysis of operational management critical success factors for public-private partnership infrastructure projects, Benchmarking: Int. J. 24 (7) (2017) 2092–2112.
[41] C. Pardo, R. Wei, B.S. Ivens, Integrating the business networks and internet of things perspectives: a system of systems (SoS) approach for industrial markets, Ind. Mark. Manag. 104 (2022) 258–275.
[42] A. Pavlov, P. Micheli, Rethinking organizational performance management: a complexity theory perspective, Int. J. Operat. Prod. Manag. 43 (6) (2022) 899–915.
[43] A. Ramaswami, C. Weible, D. Main, T. Heikkila, S. Siddiki, A. Duvall, A. Pattison, M. Bernard, A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems: An integrative curriculum across seven major disciplines, J. Ind. Ecol. 16 (6) (2012) 801–813.
[44] A. Sardi, E. Sorano, V. Cantino, P. Garengo, Big data and performance measurement research: trends, evolution and future opportunities, Measur. Bus. Excellence 27 (4) (2023) 531–548.
[45] B. Sauser, J. Boardman, D. Verma, Systomics: toward a biology of system of systems, IEEE Trans. Syst., Man, Cybernet.-Part A: Syst. Humans 40 (4) (2010) 803–814.
[46] N. Sergeeva, J. Ninan, Narratives in Megaprojects, Routledge, UK, 2023.
[47] K. Stankiewicz, Cities are Letting Restaurants Set Up Tables in Streets and Parking Lots to Ease Virus Restrictions, CNBC, 2020, 22 May 2020, https://www.cnbc.com/2020/05/22/cities-let-restaurants-set-up-in-streets-to-ease-covid-19-restrictions.html. accessed on 25 Feb 2023.
[48] M. Tadaki, J. Sinner, K.M. Chan, Making sense of environmental values: a typology of concepts, Ecol. Soc. 22 (1) (2017) 1–12.
[49] I. Todorović, Construction of Europe's First Hydrogen Pipeline System Underway in Netherlands, Balkan Green Energy News, 2023. https://balkangreenenergynews.com/construction-of-europes-first-hydrogen-pipeline-system-underway-in-netherlands/. accessed on 19 Dec 2023.
[50] J. van der Heijden, D. de Blok, Reinventing Multifunctionality: Innovation Through Integration, Netherlands Enterprise Agency, Utrecht, 2020.
[51] C. von Haaren, M. Reich, The German way to greenways and habitat networks, Landsc. Urban. Plan. 76 (1-4) (2006) 7–22.
[52] F. Wagner, R.W. Caves, Community Livability: Issues and Approaches to Sustaining the Well-Being of People and Communities, Routledge, 2012.
[53] J. Whyte, L. Mottee, Projects as interventions, Int. J. Project Manag. 40 (8) (2022) 934–940.
[54] J.J. Willems, L. Kuitert, A. Van Buuren, Policy integration in urban living labs: delivering multi-functional blue-green infrastructure in Antwerp, Dordrecht, and Gothenburg, Environ. Policy Governance (2022), https://doi.org/10.1002/eet.2028. In press.
[55] R. Yin, Case Study Research: Design and Methods, Sage, New York, 2015.
[56] V. Zerjav, A. Edkins, A. Davies, Project capabilities for operational outcomes in inter-organisational settings: the case of London Heathrow Terminal 2, Int. J. Project Manag. 36 (3) (2018) 444–459.
[57] O. Zwikael, J. Smyrk, A general framework for gauging the performance of initiatives to enhance organizational value, Br. J. Manag. 23 (2012) S6–S22.
[58] M. Bourne, M. Franco-Santos, P. Micheli, A. Pavlov, Performance measurement and management: a system of systems perspective, Int. J. Prod. Res. 56 (8) (2018) 2788–2799.