IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 20, 2021, accepted January 27, 2021, date of publication January 29, 2021, date of current version February 9, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3055652

A Framework for Using Data as an Engineering Tool for Sustainable Cyber-Physical Systems

DIDEM GURDUR BROO[1,2], (Senior Member, IEEE), AND JENNIFER SCHOOLING[1]

[1]Centre for Smart Infrastructure and Construction, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, U.K.
[2]Laing O'Rourke Centre for Construction Engineering and Technology, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, U.K.

Corresponding author: Didem Gurdur Broo (dg580@cam.ac.uk)

This work was supported in part by the Centre for Digital Built Britain through the Government's Modern Industrial Strategy by Innovate U.K., part of the U.K. Research and Innovation, and in part by the Engineering and Physical Sciences Research Council (EPSRC)/Innovate U.K. Centre for Smart Infrastructure and Construction under Grant EP/N021614/1 and Grant 920035.

ABSTRACT Smart infrastructure has the potential to revolutionise how infrastructure is delivered, managed and automatically controlled. Data and digital twins offer an opportunity to enable this revolution and secure sustainable future smart infrastructure. In this article, we discuss data as an engineering tool and propose to use data throughout the asset's whole life cycle from identifying the need, planning and designing to construction, operation, integration and maintenance. This requires systems thinking where focus is not limited to the problems but rather constructs a systemic perspective to understand the interrelationships between components and systems. Future infrastructure is connected, intelligent and data-driven. To enable more sustainable decision-making, we should not only consider how to integrate different infrastructure elements but also use data to monitor, learn from and inform decisions. To this end, we present a case study where several assets, such as bridges, railways and transport systems are integrated, and data are curated for the purpose of aiding climate-conscious, sustainable decision-making. An example systems architecture for integration of different digital twins is explained and benefits of this data-driven, systemic perspective are discussed.

INDEX TERMS Data science, cyber-physical system, information systems, sustainability, systems thinking.

I. INTRODUCTION

Much of the world's civil infrastructure is ageing and suffers from significant levels of deterioration [1]. Ageing assets are not only a financial burden for society but also affect the environment and the overall sustainability of the planet [2]. In addition, the delivery of major infrastructure projects has been slow and uncertain [3]. Infrastructure projects have major effects on sustainable development [4]. While there are some sustainability-focused approaches, which support life-cycle thinking across three sustainability dimensions – economic, environmental and societal – for the building construction, few integral approaches specifically designed for the sustainability assessment of infrastructures are available compared to those for building construction [5]. However, infrastructure systems form the backbone of every society, providing essential services that include energy, water, waste management, transport and telecommunications [6]. Therefore, more attention should be brought to developing new ways of designing, constructing, operating and monitoring infrastructure to better understand current and future needs and the relationship with sustainability.

This study brings light to a new perspective on infrastructure where data are used as an engineering tool for sustainable cyber-physical systems (CPS) and defines smart infrastructure as a form of CPS. CPS are defined as the integrations of computation and physical processes [7]. CPS include software systems, communications technology, sensors/actuators, and embedded technologies. These technologies are accepted as a driving force behind digital transformation [8]. Today, CPS exist across sectors in different sizes, with different functionalities and capabilities [9]–[11]. Some examples of CPS include smart cities, collaborative robots, autonomous vehicles and intelligent transport systems. CPS often support critical missions that have significant economic and societal importance [12].

CPS are data-driven systems and the cyber (software) aspects of these systems promise new and innovative ways to design, build, operate and maintain our future smart infrastructure. One example of this is the digital twin. A digital twin is "a realistic digital representation of assets, processes or systems in the built or natural environment" [13]. They mirror physical, social and/or economic systems and the

The associate editor coordinating the review of this manuscript and approving it for publication was Farhana Jabeen.

processes that are articulated alongside the system in question, and across its lifecycle, matching its operation, which takes place in real-time [14]. There are different approaches to implementing digital twins. While some [15] provide classifications such as digital twin prototypes, digital twin instances, digital twin aggregates and digital twin environments, others divide the digital twins as status twin, operational twin or simulation twin [16]. Furthermore, digital twins can consist of several components such as 3D models, Internet of Things (IoT), sensors, data models, artificial intelligence and machine learning-enabled analytics and algorithms, and knowledge [15].

Regardless of how CPS are classified, what technologies they have been implemented with and what systems they try to mimic in a digital form, digital twins provide an opportunity to collect and integrate data for improving the design, construction, operation and maintenance of physical assets. For instance, connected digital twins can analyse and optimise energy and material usage through a network of smart IoT. Or they can enable monitoring of usage, efficiency, safety and similar parameters of different infrastructure and suggest more sustainable practices. This study focuses on understanding how data can be used as an engineering tool to enable sustainable decision-making for future smart infrastructure. The original contribution of this paper consists of an exemplification of systems architecture to integrate different digital twins for the purpose of assessing the sustainability of civil infrastructure and to support different stakeholders in their decision-making.

The second section provides a summary of the literature on data-centric approaches for sustainability. This features a hypothetical case study, and data as an enabler for sustainable decision-making is presented with an example data model to support stakeholders. Consideration of data as an engineering tool and its role for sustainability is discussed in detail. Finally, the most relevant conclusions are drawn.

II. BACKGROUND

This study builds on the idea of infrastructure as a system of systems with its main purpose to enable human flourishing [17]. Therefore, this section will focus on the earlier studies that see infrastructure as an integrated system of systems and underline its value to improve sustainability across the economy, the environment and society and provide a platform for human flourishing.

One of the first studies that considers infrastructure as an integrated system of systems is published by Lemer (1993). In this study, the author describes the challenges and the promise that integrated infrastructure may provide as ‘‘decisions influencing infrastructure development and use—asset management—undertaken and executed without fully recognizing the complexity, diversity, and social and technological evolution of the system almost inevitably squander economic, environmental, social, and cultural resources’’ [18]. More than a quarter of a century later, this statement is still true. Although the literature on integrated infrastructure discusses the tools and theory for taking an integrated approach to infrastructure systems, the relationship between interoperability and sustainability, and example systems architectures to enable climate aware decision-making are still limited if not lacking. In addition, while the term ‘integration’ is used throughout the existing literature, further clarifications on the level and detail of the integrations are lacking and existing works and tools do not examine long-term impacts [19].

An extensive literature review conducted by Saidi *et al.* (2018) highlights the importance of understanding the nature of infrastructure interdependencies and complex networks and concludes by underlining the need for a holistic view. The authors state that, ‘‘there is a clear need for long-term focus in order to examine the impacts and assessment of future policies and scenarios and their impact on general environmental, social, economic, and suitability is crucial especially with the increased interdependence of these infrastructures with more information and communication technologies instrumentation and their rapid change. Future smart cities and the Internet of Things will facilitate the integration of the infrastructure systems by providing informational dependencies among nearly all components within and between each infrastructure.’’

While the literature on digital twins for the CPS is rich from the manufacturing sector [20]–[22], very few exist for cities [23], [24] and they are generally focused on technological decisions, and very few are present for infrastructure. At the time this article was written we could not identify any article on digital twins for CPS focusing on infrastructure systems.

This article, discusses sustainable development goals as one of the examples of a common purpose for digital twin development as part of the case study. Stafford-Smith *et al.* [25] states that now the agenda moves from agreeing the goals to implementing and ultimately achieving them. The authors argues that the integration is the key to implementing sustainable development goals. Moreover, they suggest that the efforts should focus interlinkages across sectors, across actors and across countries. At the same time, Wu *et al.* [26] looked at the correlations among sustainable development goals and information and communications technologies. In this study, after an extensive literature review, the authors found that the majority of contributions to sustainable development goals have mainly focused on the technical aspects while there are lack of the holistic social good perspectives. Sachs *et al.* [27] discusses six transformations to achine sustainable development goals. One of these transformation is on the building, construction and infrastructure industry where decarbonization of the industry is in focus. One of the other transformation suggestion is for science, technology and telecommunications and the interventions on this perspective focuses on universal information-technology infrastructure, digital inclusion, privacy protection and mobilizing digital technologies to achieve sustainable development goals. In next sections we will introduce a case study and a framework to illustrate how purposeful digital twin implementation and integration through data-oriented approaches may help to improve the implementations of the sustainable development goals, specific to cyber-physical systems in infrastructure industry.

III. CASE STUDY

This study uses a hypothetical integrated smart infrastructure case study to showcase the importance of the systemic view and applicability of data architectures and models to improve the sustainability of future cities and infrastructure. The next two subsections, therefore, focus on the description of the case study and an example systems architecture to support sustainable decision-making related to this system.

A. CASE STUDY DESCRIPTION

The National League of Cities' report on trends in smart city development considered five cities intending to provide recommendations to help local governments to consider and plan smart city projects. The report lists important abilities such as transport congestion sensors, water and wastewater monitoring, parking and kiosks, bridge inspection systems, self-driving cars, waste management sensors, lighting, fire detection, energy monitoring, solar panels, smart logistics/freight, vehicle fleet communication, drones, surveillance cameras, body cameras, wearable detection, and broadband infrastructure [28]. Similarly, other reports mention the integration of information and communication technology, Internet of Things, sensors, geospatial technology, data and artificial intelligence as technologies to enable these abilities for the built environment.

The hypothetical smart infrastructure that we would like the reader to imagine is no different to what has been described before. It is an ecosystem of grids, buildings, roads, railways, bridges and industries. In this case study, the integration of different systems of systems – to support both the functionalities of the city and the needs of infrastructure – is at the core. Yet it is sustainable and human-centered. The goals of this cyber-physical system are to provide improved city services and a higher quality of life including wealth, health, opportunities, safety, inclusivity, independence, and overall sustainability. To make this possible, we support the idea of using a series of federated digital twins [29]. This requires different stakeholders to collaborate to identify common needs, data sharing requirements and common purpose to support human flourishing, defined by Schooling *et al.* (2020) as the purpose of infrastructure.

B. SYSTEM ARCHITECTURE

To be able to improve infrastructure services and the quality of life of the citizens, we should design an intelligent, connected ecosystem built on a data-driven physical infrastructure and cyber-physical systems. In this study, we do not aim to provide a well-defined data architecture as a solution because, today, we are facing rapidly changing and advancing systems of systems as part of our cities and infrastructure. Having a fixed data architecture with any particular technology or platform would be a short-sighted solution. This is true especially when we look at sustainable decision-making for infrastructure, where we not only aim to provide a sustainable built environment but also to protect the natural environment while also considering social implications. Instead, we present a modular, flexible and scalable systems architecture which may be applicable to accommodate changing needs of infrastructure stakeholders, citizens and built environment providers. To this end, we want to start with the purpose, aims and goals of infrastructure before considering the importance of collaboration through multi-stakeholder participation, and using data and digital twins as an approach to operationalise data for supporting the implementation and assessment of the goals. And finally, we show how this type of interoperable and collaborative approach can enable different services to support sustainable smart infrastructure.

As many stated before [17], [30], infrastructure and cities should focus on citizens and include better quality of life, economic stability, environmentally-conscious sustainability, inclusivity, transparency, engagement and more. The aim here is to create an ecosystem that responds to the needs of citizens, aids better resource management, connects different stakeholders for better interoperability and decision-making while considering both the needs of today and of generations to come. Figure 1 summarises the systems architecture to support sustainability for this smart and integrated infrastructure system.

The four layers of this architecture include goals, stakeholders, smart infrastructure system-of-systems (SoS) including digital twins of different entities and interoperable data layer, and services. The architecture is intentionally designed to be technology-agnostic and does not aim to suggest any particular technological solutions for different layers. Still, several technologies are mentioned as examples from the current literature. Furthermore, the architecture does not belong to any particular phase of the asset life cycle such as design, construct, integrate, operate and maintain, but addresses them all. The description of the architecture is as follows:

- *Goals:* These can be specific goals that are identified and agreed by the stakeholders or the general sustainability goals that are defined by the government [31] or other institutions such as the United Nation's Sustainable Development Goals [32].
- *Stakeholders:* Some examples of stakeholders can be listed as asset owners, contractors, partners, collaborators, sponsors, government initiatives, citizens and service providers.
- *Smart Infrastructure SoS:* Smart infrastructure can only be possible if we integrate different components, entities, or systems and use these integrations towards smarter decision-making. This can later be automated by using artificial intelligence approaches such as deep learning and machine learning.
    - *Digital Twins/Entities:* Some examples of these entities include grids, buildings, roads, railways, bridges or components related to these entities such as digital signage, traffic sensors and cameras and fibre optic sensing for health monitoring.

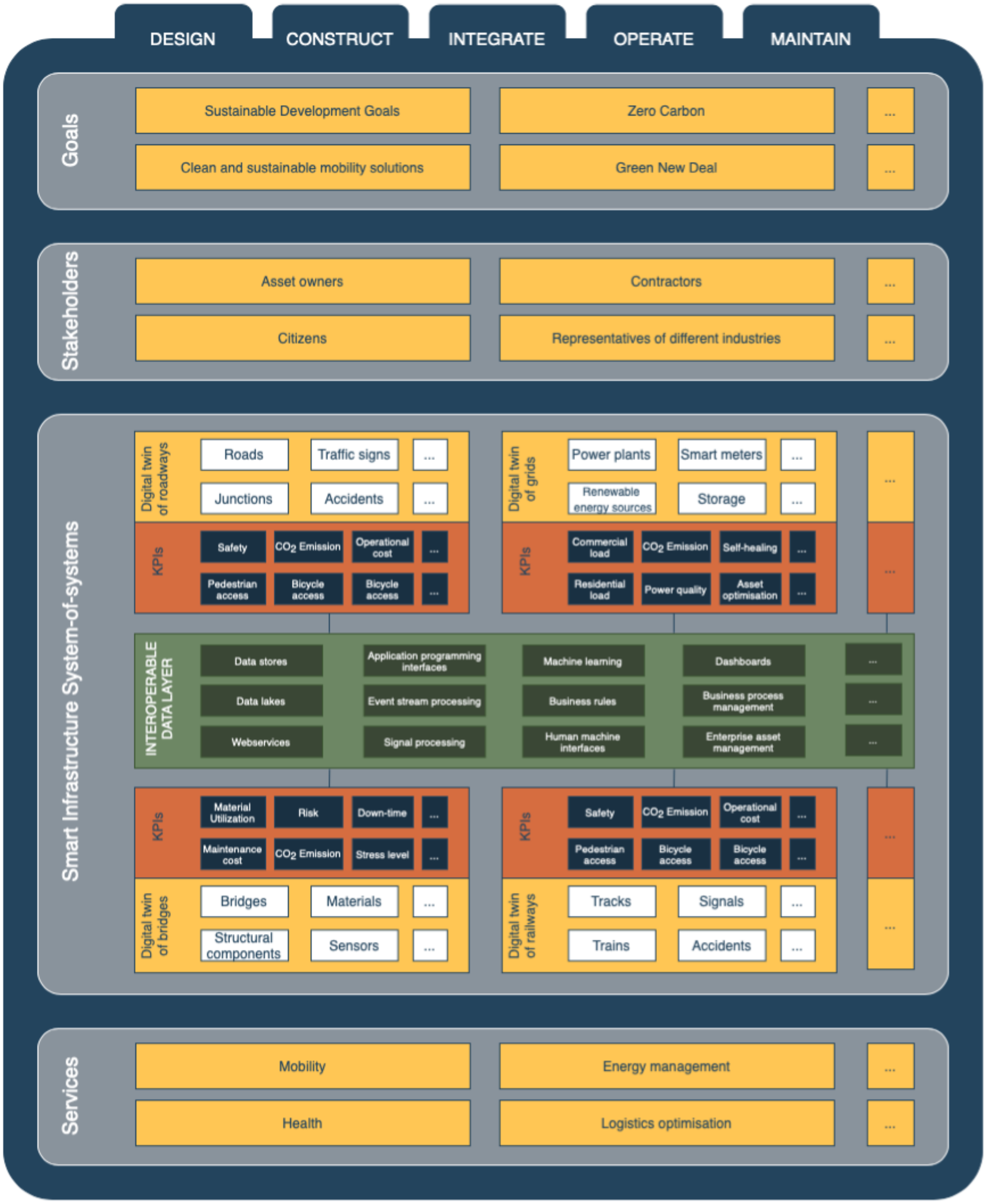

FIGURE 1. Systems architecture for the integrated smart infrastructure hypothetical case as the example of a cyber-physical system.

- *Key Performance Indicators (KPIs):* These indicators are going to be identified by the stakeholders as important metrics that then can be calculated or assessed with the help of an interoperable data layer.
- *Interoperability Data Layer:* The interoperable data layer is a layer that allows different digital twins to share information. This can be one common data lake, linked data repository, cloud platforms or any other database technologies. Interoperability related literature is rich and showcases many applications of successful implementations with different technologies [22], [23], [33]–[39]. The interoperable data layer enables data integration, abstraction, analytics, artificial intelligence applications, visualisation and similar functions, which is vital to the success of the cyber-physical systems.

- *Services:* The services can be related to transport, health, culture, economy, city/infrastructure/asset management, social care, public safety, and more. Some examples include mobility, smart grid, energy management, connected fleet, logistics optimisation and automated supply chain.

C. PROVIDING MORE THAN TECHNOLOGY

The data integration efforts which follow the suggested architecture are driven by sustainability-oriented goals that have been guided by government/institution agendas on climate change and agreed by stakeholders. The architecture can be extended to include different goals for interoperability between digital twins, trustworthy communication between digital twins, performance management and orchestration of digital twin networks and similar. Furthermore, the level of digital twin details can vary. For instance, it is possible to extend the abilities of the digital twins by focusing on condition monitoring at the component level, or asset performance management at the systems level, or predictive maintenance at the discrete level. These details related to the digital twin design, modelling and implementation can be specified by the stakeholder who owns the digital twin.

Implementing digital twins with modular, extendable, and flexible architecture, which allows developers to use multi-platform approaches where different application programming interfaces are provided to enable the integration between different digital twins, is seen as a reasonable approach towards enabling cyber-physical systems for infrastructure. This approach goes beyond choosing the right technology solution for integrating infrastructure systems, and understands the multi-stakeholder, goal-oriented, collaborative and more importantly, the sustainability-focused methodology for interoperable cyber-physical systems for the future built environment.

IV. DISCUSSION

This study aims to provide a methodological and systemic way to use data as an engineering tool through digital twins for the purpose of improving sustainability in cyber-physical systems. Several important discussions are beyond the scope of this particular article, including: the different types of digital twins [16]; challenges related to the data [40]; the role of cyber-physical systems and smart infrastructure [17] for society; and various technologies to enable digital twin implementation and integration [41]–[45].

In general, cyber-physical systems in smart infrastructure bring opportunities to improve sustainability in all three dimensions (economic, environmental, social) – and data is one of the most important enablers of this. However, some challenges related to the projects for these future systems – such as multi-stakeholder involvement, heterogeneous data sources, and purpose misalignment – are currently slowing down the implementation and integration of these systems.

Multi-stakeholder Involvement: Cyber-physical systems projects require several stakeholders to work together. These stakeholders include designers, developers, product/asset owners, contractors, partners, collaborators, sponsors, government initiatives, citizens, service providers and so on. Even though in the different phases (design, construct, integrate, operate, maintain) of these projects several stakeholders are working collaboratively, there are rare occasions where they all come together. To be able to make sustainable decisions, these occasions should be more frequent, enabling stakeholders to discuss and identify key performance indicators, processes, procedures and similar details related to these projects. However diverse and unrelated they may seem, the interactions and discussions between these stakeholders form a collective intelligence that cannot be replaced with any other way of working towards sustainable decision-making.

Several researchers [46]–[49] studied multi-stakeholder involvements' benefits on sustainability-related decision making processes. For instance, Li *et al.* [49] suggest developing multi-stakeholder multi-objective decision making model which focuses on both consensus building and also conflict analyses. The authors of the study stated that ''the decision rule approach offers the closest to a human rational approach to decision analysis and thus performs well in encouraging different interest groups with diverse educational backgrounds and intelligence levels to contribute to decision process/outcomes''. Similarly, Azadi *et al.* [48] focuses on green urban spaces and the role of multi-stakeholder involvement. This study underlines the influential role of the state, society, implementation and regulation on multi-stakeholder involvement. To initiate multi-stakeholder involvement and to integrate the efforts of the stakeholder these types of methods can be used.

Heterogeneous Data Sources: The key identifier of cyber-physical systems is the ability to use networking abilities to connect different components, entities or systems and allow computations to affect physical processes and vice versa. The data that is shared between these systems is the enabler of better decision-making. However, different data are of interest and value for different stakeholders, domains, disciplines at different phases of the systems' life cycle. Some examples of this heterogeneity are: physics-based models (e.g. FEM, thermodynamic, geological); analytical models (e.g. predictive maintenance); time-series data and histories, transactional data (e.g. ERP, EAM); master data (e.g. EAM, AF, BPM); and visual models (CAD, AR, VR, BPM, BIM, GIS, and GEO).

Purpose Misalignment: Since the cyber-physical systems projects are multi-stakeholder, the purpose and goals of each stakeholder differ. In well-defined business models, organisational hierarchies, business processes – which are traditionally driven by performance, profit and similar mainly quantitative metrics – it is very difficult to create an overarching purpose, which is common for all of the stakeholders, and even includes future generations. Unfortunately, this purpose misalignment leads to short-term, individual, organisation-oriented decision-making. Sustainability-related decisions cannot be solved with these types of limited practices.

These three points may appear challenging, but they can also present opportunities by understanding, acknowledging and working on them. For example, the heterogeneity of data is on one hand a challenge, yet it is what makes the cyber-physical systems a driving force behind digital transformation. The multi-stakeholder collaboration in cyber-physical systems is the only way to make cyber-physical systems not only functional but also sustainable. And none of this would be possible without providing an ecosystem where the stakeholders align their expectations and purposes.

To deal with these three points, we suggest starting with providing environments to align sustainability-oriented goals where stakeholders listen, discuss, and agree. This will require different approaches to collaboration, where - in addition to the project requirements, deliverables and goals - the common purpose and different sustainability goals, deliverables, and requirements must also be identified.

In addition, organisations need to reconsider their organisational structures. Data, being at the core of the digital twin development, integration and operations, necessitate new structures, skill sets, procedures, and literacies. While the new ways of working will be aligned with the sustainability-focused project implementations and deliveries, new skill sets, data and technology fluencies within organisations will help to adopt the right technological solutions to enable interoperable digital twin communications. These points have been discussed in systems thinking, design thinking and innovation-related literature prior to this article. Due to the limited length of this article, we suggest interested readers look at the literature to gather different tools to enable thinking creatively (e.g. [50], [51]), service design (e.g. [45], [46]), designing sustainable manner (e.g. [54], [55]), and building a collective intelligence (e.g. [56], [57]).

Limitations: It is important to mention limitations and possible threats of the proposed approach. Each one of the three challenges that we have discussed in this section – multi-stakeholder involvement, heterogeneous data sources, and purpose misalignment – has their own challenges when they are decided to be addressed. For instance, multi-stakeholder involvements incorporate ambiguity, uncertainty, and complexity. Considering the different interests, stakeholders will likely have different perspectives on optimal outcomes where objectives may need to be revised periodically, based on evolving understanding of the landscape situation and processes of negotiation [58]. Related with the data and integration of heterogeneous data sets there are many important concepts that needs to be considered. In general, any data-oriented approaches should consider privacy, security, safety, ethics and social implications of the data usage. Specific to cyber-physical systems data availability, accessibility, quality, longevity and variety [40] should be considered and necessary precautions should be taken into account. Lastly; for purpose alignment; close relationship between purposes and strategies, structures and implementations should be studied, and common purpose or goals should be identified by multi-stakeholder engagements. This is closely related with the rate of change and the scope of the purpose. Therefore, the purpose, the existing structures that may or may not contribute to the purpose and the implementation of the solutions needs to be considered by evaluating stakeholders, processes and technologies. Furthermore, the current, short-term and long-term affects related to these purpose and goals should be examined.

V. CONCLUSION

This work treated the future infrastructure systems as cyber-physical systems and exemplified how these connected, intelligent and data-driven systems can be designed, constructed, integrated, operated and maintained in a collaborative, purpose-driven and sustainable way. To this end, a case study is described and a systems architecture, including the process to enable the implementation of the smart infrastructure, is presented. This architecture suggests multi-stakeholder contributions towards the identification of common goals, digital twin integration and ecosystem development for continuous assessment of sustainability indicators.

The success of this approach is very much linked with three important considerations, namely: multi-stakeholder involvement; heterogeneous data source integration; and purpose alignment. These considerations require organisations to find new ways of collaboration, reconsider current organisational structures, and acquire new skills including technology and data fluencies. Ultimately, the goal is to start a conversation on not only data integration and interoperability related technical considerations (related to the future smart infrastructure systems), but also to provide an example architecture that gives guidance on how to combine these technical decisions with collaborative, human-centered, innovative but more importantly sustainable practices.

REFERENCES

[1] N. Hoult, P. J. Bennett, I. Stoianov, P. Fidler, Č. Maksimović, C. Middleton, N. Graham, and K. Soga, "Wireless sensor networks: Creating 'smart infrastructure,'" *Proc. Inst. Civil Eng. Civil Eng.*, vol. 162, no. 3, pp. 136–143, Aug. 2009, doi: 10.1680/cien.2009.162.3.136.

[2] K. van Breugel, "Societal burden and engineering challenges of ageing infrastructure," *Procedia Eng.*, vol. 171, pp. 53–63, Jan. 2017, doi: 10.1016/j.proeng.2017.01.309.

[3] *National Infrastructure Assessment*, National Infrastructure Commission, London, U.K., 2018.

[4] L. Shen, Y. Wu, and X. Zhang, "Key assessment indicators for the sustainability of infrastructure projects," *J. Constr. Eng. Manag.*, vol. 137, no. 6, pp. 441–451, 2011, doi: 10.1061/(ASCE)CO.1943-7862.0000315.

[5] P. Bocchini, D. M. Frangopol, T. Ummenhofer, and T. Zinke, "Resilience and sustainability of civil infrastructure: Toward a unified approach," *J. Infrastruct. Syst.*, vol. 20, no. 2, pp. 1–16, 2014, doi: 10.1061/(ASCE)IS.1943-555X.0000177.

[6] S. Thacker, D. Adshead, M. Fay, S. Hallegatte, M. Harvey, H. Meller, N. O'Regan, J. Rozenberg, G. Watkins, and J. W. Hall, "Infrastructure for sustainable development," *Nature Sustainability*, vol. 2, no. 4, pp. 324–331, Apr. 2019, doi: 10.1038/s41893-019-0256-8.

[7] E. A. Lee, "Cyber-physical systems—Are computing foundations adequate," in *Position Paper for NSF Workshop on Cyber-Physical Systems: Research Motivation, Techniques and Roadmap*, vol. 2, 2006, pp. 1–9.

[8] C. Klotzer, J. WeiBenborn, and A. Pflaum, "The evolution of cyber-physical systems as a driving force behind digital transformation," in *Proc. IEEE 19th Conf. Bus. Informat. (CBI)*, Jul. 2017, pp. 5–14, doi: 10.1109/CBI.2017.8.

[9] D. Gürdür, *Making Interoperability Visible: A Novel Approach to Understand Interoperability in Cyber-Physical Systems Toolchains*. Stockholm, Sweden: KTH Royal Institute of Technology, 2017.

[10] D. Gürdür, J. El-Khoury, T. Seceleanu, and L. Lednicki, "Making interoperability visible: Data visualization of cyber-physical systems development tool chains," *J. Ind. Inf. Integr.*, vol. 4, pp. 26–34, Dec. 2016, doi: 10.1016/j.jii.2016.09.002.

[11] D. Gürdür, J. El-khoury, and M. Nyberg, "Methodology for linked enterprise data quality assessment through information visualizations," *J. Ind. Inf. Integr.*, vol. 15, pp. 191–200, Sep. 2019, doi: 10.1016/j.jii.2018.11.002.

[12] *A 21st Century Cyber-Physical Systems Education*, National Academies of Sciences Engineering and Medicine, Washington, DC, USA, 2016.

[13] R. N. Bolton, J. R. McColl-Kennedy, L. Cheung, A. Gallan, C. Orsingher, L. Witell, and M. Zaki, "Customer experience challenges: Bringing together digital, physical and social realms," *J. Service Manage.*, vol. 29, no. 5, pp. 776–808, Oct. 2018.

[14] M. Batty, "Digital twins," *Environ. Planning B, Urban Analytics City Sci.*, vol. 45, no. 5, pp. 817–820, Sep. 2018, doi: 10.1177/2399808318796416.

[15] S. G. Rudrappa. (2017). *Architecture To Bridge Physical world to Virtual Digital World*. Medium. Accessed: Sep. 2, 2020. [Online]. Available: https://medium.com/@shivakumar.goniwada/architecture-to-bridge-physical-world-to-virtual-digital-world-d55ecbe93b85

[16] P. van Schalkwyk, *Digital Twins: The Ultimate Guide*, XMPro, 2019. [Online]. Available: https://xmpro.com/digital-twins-the-ultimate-guide/
[17] J. Schooling, G. Burgess, and M. Enzer, "Flourishing systems: Re-envisioning infrastructure as a platform for human flourishing," Centre Digit. Built Britain, Cambridge, U.K., Tech. Rep. 2020, 2020.
[18] A. C. Lemer, "Progress toward integrated infrastructure-assets-management systems: GIS and beyond," *Management*, vol. 410, pp. 7–24, 1993.
[19] S. Saidi, L. Kattan, P. Jayasinghe, P. Hettiaratchi, and J. Taron, "Integrated infrastructure systems—A review," *Sustain. Cities Soc.*, vol. 36, pp. 1–11, Jan. 2018, doi: 10.1016/j.scs.2017.09.022.
[20] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 9–12, pp. 3563–3576, Feb. 2018, doi: 10.1007/s00170-017-0233-1.
[21] J. Leng, H. Zhang, D. Yan, Q. Liu, X. Chen, and D. Zhang, "Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop," *J. Ambient Intell. Humanized Comput.*, vol. 10, no. 3, pp. 1155–1166, Mar. 2019, doi: 10.1007/s12652-018-0881-5.
[22] Y. Lu, C. Liu, K. I.-K. Wang, H. Huang, and X. Xu, "Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues," *Robot. Comput.-Integr. Manuf.*, vol. 61, Feb. 2020, Art. no. 101837, doi: 10.1016/j.rcim.2019.101837.
[23] K. M. Alam and A. El Saddik, "C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems," *IEEE Access*, vol. 5, pp. 2050–2062, 2017, doi: 10.1109/ACCESS.2017.2657006.
[24] J. Jin, J. Gubbi, S. Marusic, and M. Palaniswami, "An information framework for creating a smart city through Internet of Things," *IEEE Internet Things J.*, vol. 1, no. 2, pp. 112–121, Apr. 2014, doi: 10.1109/JIOT.2013.2296516.
[25] M. Stafford-Smith, D. Griggs, O. Gaffney, F. Ullah, B. Reyers, N. Kanie, B. Stigson, P. Shrivastava, M. Leach, and D. O'Connell, "Integration: The key to implementing the sustainable development goals," *Sustainability Sci.*, vol. 12, no. 6, pp. 911–919, Nov. 2017, doi: 10.1007/s11625-016-0383-3.
[26] J. Wu, S. Guo, H. Huang, W. Liu, and Y. Xiang, "Information and communications technologies for sustainable development goals: State-of-the-art, needs and perspectives," 2018, *arXiv:1802.09345*. [Online]. Available: http://arxiv.org/abs/1802.09345
[27] J. D. Sachs, G. Schmidt-Traub, M. Mazzucato, D. Messner, N. Nakicenovic, and J. Rockström, "Six transformations to achieve the sustainable development goals," *Nature Sustainability*, vol. 2, no. 9, pp. 805–814, Sep. 2019, doi: 10.1038/s41893-019-0352-9.
[28] N. L. O. Cities, "Trends in smart city development," in *National League of Cities' Center for City Solutions Applied Research*. Washington, DC, USA: National League of Cities, 2016, pp. 1–23.
[29] Centre for Digital Built Britain. (2019). *National Digital Twin Programme*. [Online]. Available: www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme
[30] W. D. Eggers and J. Skowron, "Forces of change: Smart cities," Deloitte Insights, Tech. Rep., Mar. 2018, pp. 1–16.
[31] UK Green Building Council. (2019). *Climate Change: UKGBC's Vision for a Sustainable Built Environment is One That Mitigates and Adapts to Climate Change*. Accessed: May 10, 2020. [Online]. Available: https://www.ukgbc.org/climate-change/
[32] *Transforming Our World: The 2030 Agenda for Sustainable Development*, United Nations, New York, NY, USA, 2015.
[33] J. El-khoury, D. Gürdür, and M. Nyberg, "A model-driven engineering approach to software tool interoperability based on linked data," *Int. J. Adv. Softw.*, vol. 9, no. 3, pp. 248–259, 2016.
[34] J. Posada, C. Toro, I. Barandiaran, D. Oyarzun, and P. Eisert, "Visual computing as key enabling technology for Industrie 4.0 and industrial Internet," *IEEE Comput. Graph. Appl.*, vol. 35, no. 2, pp. 26–40, 2015.
[35] Q. Qi and F. Tao, "Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison," *IEEE Access*, vol. 6, pp. 3585–3593, 2018, doi: 10.1109/ACCESS.2018.2793265.
[36] M. Derakhshannia, C. Gervet, H. Hajj-Hassan, A. Laurent, and A. Martin, "Data lake governance: Towards a systemic and natural ecosystem analogy," *Futur. Internet*, vol. 12, no. 8, pp. 1–16, 2020, doi: 10.3390/FI12080126.
[37] B. Ahlgren, M. Hidell, and E. C.-H. Ngai, "Internet of Things for smart cities: Interoperability and open data," *IEEE Internet Comput.*, vol. 20, no. 6, pp. 52–56, Nov. 2016, doi: 10.1109/MIC.2016.124.
[38] A. Broring, S. Schmid, C.-K. Schindhelm, A. Khelil, S. Kabisch, D. Kramer, D. Le Phuoc, J. Mitic, D. Anicic, and E. Teniente, "Enabling IoT ecosystems through platform interoperability," *IEEE Softw.*, vol. 34, no. 1, pp. 54–61, Jan. 2017, doi: 10.1109/MS.2017.2.
[39] G. Aloi, G. Caliciuri, G. Fortino, R. Gravina, P. Pace, W. Russo, and C. Savaglio, "Enabling IoT interoperability through opportunistic smartphone-based mobile gateways," *J. Netw. Comput. Appl.*, vol. 81, pp. 74–84, Mar. 2017, doi: 10.1016/j.jnca.2016.10.013.
[40] D. Gürdür Broo and J. Schooling, "Towards data-centric decision making for smart infrastructure: Data and its challenges," in *Proc. 4th IFAC Workshop Adv. Maintenance Eng., Services Technol.*, 2020, pp. 90–94.
[41] F. Tao and M. Zhang, "Digital twin shop-floor: A new shop-floor paradigm towards smart manufacturing," *IEEE Access*, vol. 5, pp. 20418–20427, 2017, doi: 10.1109/ACCESS.2017.2756069.
[42] S. Haag and R. Anderl, "Digital twin—Proof of concept," *Manuf. Lett.*, vol. 15, pp. 64–66, Jan. 2018, doi: 10.1016/j.mfglet.2018.02.006.
[43] P. D. U. Coronado, R. Lynn, W. Louhichi, M. Parto, E. Wescoat, and T. Kurfess, "Part data integration in the shop floor digital twin: Mobile and cloud technologies to enable a manufacturing execution system," *J. Manuf. Syst.*, vol. 48, pp. 25–33, Jul. 2018, doi: 10.1016/j.jmsy.2018.02.002.
[44] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 1016–1022, 2018, doi: 10.1016/j.ifacol.2018.08.474.
[45] D. Gürdür, A. V. Feljan, J. El-khoury, S. K. Mohalik, R. Badrinath, A. P. Mujumdar, and E. Fersman, "Knowledge representation of cyber-physical systems for monitoring purpose," in *Proc. 51th CIRP Int. Conf. Manuf. Syst. (CIRP CMS)*, 2018, pp. 468–473.
[46] L. Thabrew, A. Wiek, and R. Ries, "Environmental decision making in multi-stakeholder contexts: Applicability of life cycle thinking in development planning and implementation," *J. Cleaner Prod.*, vol. 17, no. 1, pp. 67–76, Jan. 2009, doi: 10.1016/j.jclepro.2008.03.008.
[47] V. M. Waligo, J. Clarke, and R. Hawkins, "Implementing sustainable tourism: A multi-stakeholder involvement management framework," *Tourism Manage.*, vol. 36, pp. 342–353, Jun. 2013, doi: 10.1016/j.tourman.2012.10.008.
[48] H. Azadi, P. Ho, E. Hafni, K. Zarafshani, and F. Witlox, "Multi-stakeholder involvement and urban green space performance," *J. Environ. Planning Manage.*, vol. 54, no. 6, pp. 785–811, Jul. 2011, doi: 10.1080/09640568.2010.530513.
[49] T. H. Y. Li, S. T. Ng, and M. Skitmore, "Modeling multi-stakeholder multi-objective decisions during public participation in major infrastructure and construction projects: A decision rule approach," *J. Constr. Eng. Manag.*, vol. 142, no. 3, 2016, Art. no. 04015087, doi: 10.1061/(asce)co.1943-7862.0001066.
[50] L. Leifer and C. Meinel, "Looking further: Design thinking beyond solution-fixation," in *Design Thinking Research*. 2019, pp. 1–12, doi: 10.1007/978-3-319-97082-0_1.
[51] J. Kolko, "Design thinking comes of age," *Harv. Bus. Rev.*, vol. 2015, pp. 66–71, Sep. 2015.
[52] M. Stickdorn, M. E. Hormess, A. Lawrence, and J. Schneider, *This is Service Design Doing: Applying Service Design Thinking in the Real World*. Newton, MA, USA: O'Reilly Media, 2018.
[53] P. Jittrapirom, V. Caiati, A.-M. Feneri, S. Ebrahimigharehbaghi, M. J. A. González, and J. Narayan, "Mobility as a service: A critical review of definitions, assessments of schemes, and key challenges," *Urban Plan.*, vol. 2, no. 2, p. 13, 2017, doi: 10.17645/up.v2i2.931.
[54] F. Ceschin and I. Gaziulusoy, "Evolution of design for sustainability: From product design to design for system innovations and transitions," *Design Stud.*, vol. 47, pp. 118–163, Nov. 2016, doi: 10.1016/j.destud.2016.09.002.
[55] F. C. Rios and D. Grau, "Circular economy in the built environment: Designing, deconstructing, and leasing reusable products," *Encycl. Renew. Sustain. Mater.*, vol. 5, pp. 338–343, Jan. 2020, doi: 10.1016/b978-0-12-803581-8.11494-8.
[56] A. Boder, "Collective intelligence: A keystone in knowledge management," *J. Knowl. Manage.*, vol. 10, no. 1, pp. 81–93, Jan. 2006, doi: 10.1108/13673270610650120.
[57] T. W. Malone, R. Laubacher, and C. N. Dellarocas, "Harnessing crowds: Mapping the genome of collective intelligence," *SSRN Electron. J.*, vol. 132, no. 2, pp. 327–335, 2009, doi: 10.2139/ssrn.1381502.
[58] K. Kusters, L. Buck, M. de Graaf, P. Minang, C. van Oosten, and R. Zagt, "Participatory planning, monitoring and evaluation of multi-stakeholder platforms in integrated landscape initiatives," *Environ. Manage.*, vol. 62, no. 1, pp. 170–181, Jul. 2018, doi: 10.1007/s00267-017-0847-y.