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Digital twins in infrastructure: definitions, current practices, challenges and strategies

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Abstract

When combined with information and communication technologies and powerful data analytic algorithms such as artificial intelligence, digital twins enable organisations to conserve physical resources. This applies both during the design phase and when performing diagnostic and predictive analyses during operations. These abilities bring significant opportunities to the infrastructure industry to develop new ways of designing, constructing, operating and monitoring infrastructure at a time when much of the world's civil infrastructure is ageing and showing signs of deterioration. This study aims to find out how digital twins can help the infrastructure industry to deliver and operate sustainable and smart infrastructure assets. This paper presents an overview of digital twin definitions, current practices, benefits and challenges through a series of semi-structured expert interviews with executives from the UK infrastructure industry. Additionally, it suggests a series of strategies to aid digital transformation and digital twin adoption in the industry. Results from the interviews illustrated that the executives involved in digital transformation in the infrastructure industry are very well aware of the definitions, benefits and challenges of digital twins. In general, they understand the
ally digital twins. They know the reasons

behind the need for transforming the industry and adopting data-driven concepts such as digital twins. Moreover, the executives interviewed as part of this study mentioned common challenges across different infrastructure domains. The strategies presented are focused on addressing these three main challenges identified and agreed upon by the participants – culture, technology adoption and lack of a skilled workforce. The three main strategies, addressing digital transformation (1), cultural transformation (2) and bridging the skills gap (3), are explained later in this paper. The article concludes by underlining the importance of creating equal opportunities for the current workforce to improve their digital fluency and skillset by providing information about the benefits of digital twins throughout the sector and organisations to improve adoption and the realisation of benefits.

Keywords: Data digital twins infrastructure smart infrastructure resilience

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Facilitation of Digitalization in Construction Sector: Towards Digital Construction

Introduction

Since it was introduced by Michael Grieves in 2003, the term “digital twin” (Grieves and Vickers 2017) has experienced a growth in popularity and is now recognised as a key enabler for transformation to Industry 4.0. In the last two decades, many digital twin applications have been presented regarding space (Glaessgen and Stargel 2012) and manufacturing (Schleich et al. 2017; Qi and Tao 2018; Tao et al. 2018) industries. A digital twin in the built environment domain has been defined as a realistic digital representation of assets, processes or systems (Bolton et al. 2018). It mirrors physical, social and/or economic systems and the processes that are articulated alongside the system in question, and across its lifecycle, mimicking its operation in real-time (Batty 2018).

There are different approaches to implementing digital twins. While some (Rudrappa 2017) 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 (XMPRO, 2019). Furthermore, digital twins can consist of several components such as 3 D models, Internet of Things (IoT), sensors, data models, artificial intelligence and machine learning-enabled analytics and algorithms, and knowledge (Rudrappa 2017). When combined with information and communication technologies and powerful data analytic algorithms such as artificial intelligence, digital twins allow organisations to conserve physical resources during design and perform diagnostic and predictive analyses during operations (Grieves and Vickers 2017).

Much of the world's civil infrastructure is ageing and showing significant levels of deterioration (Hoult et al. 2009; Gürdür Broo and Schooling 2020). Ageing assets are not only a financial burden for society but also affect the environment and the overall sustainability of the planet (Van Breugel 2017). In addition, the delivery of major infrastructure projects has been slow and uncertain (National Infrastructure Commission, 2018). The delivery of infrastructure projects has major effects on sustainable development (Shen et al. 2011). There are some sustainability-focused approaches for building construction that supports life-cycle thinking across three sustainability dimensions – economic, environmental and societal. However, there are few integral approaches specifically designed for the sustainability assessment of infrastructures (Bocchini et al. 2014). This needs to change because infrastructure systems form the backbone of every society, providing essential services that include energy, water, waste management, transport and telecommunications (Thacker et al. 2019). 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.

Digital twins provide an opportunity to collect and integrate data for improving the design, construction, operation, and maintenance of physical infrastructure assets which, in turn, could improve sustainable development. This study approached executives leading digital transformation in the biggest infrastructure projects of the United Kingdom to answer one question:

> RQ 1: How can digital twins help the infrastructure industry to deliver and operate sustainable and smart infrastructure assets?

To answer this question, we have divided it into three sub-questions (SRQ):

- SRQ 1: How does the definition of digital twins differ for different infrastructure projects?
- SRQ 2: What are the main benefits of digital twins?
- SRQ 3: What are the challenges of implementing and operationalising digital twins?

The main objective of this study is to provide an overview of the current digital twin practices of the United Kingdom's infrastructure sector by summarizing the definitions, benefits, and challenges. While digital twin implementations, case studies and literature reviews from other domains exist; this particular focus on current practices and

e practitioners in the infrastructure sector has not been discussed in the literature prior to this study. Moreover, the study aims to present series of strategies that can be useful for not only the studied region but in a wider context when infrastructure digital twins are developed by other countries and regions.

The original contribution of this paper consists of an industrial overview of digital twin definitions, current practices, benefits, and challenges through a series of semi-structured expert interviews with executives from the UK infrastructure industry. Additionally, it delivers a series of strategies to aid digital transformation and digital twin adoption by the industry.

To this end, Section "Related work" presents the earlier work on the research topic. Section "Methodology" details the research methodology. Later in Section "Findings", the findings of the study are presented. Before concluding the article in Section "Conclusion", we discuss the findings and strategies in Section "Discussion".

Related work

Several researchers have studied the potential of using big data in smart infrastructure, specifically in a smart grid or city context. Some studies focused on socio-economic problems and suggested using data to form collective awareness for creating innovative solutions (Pitt et al. 2013). Other studies looked at infrastructure from an efficiency perspective and included data resources from surveying, communication, geospatial and network applications to manage power consumption and operational resources (Al-Hader and Rodzi 2016; Le et al. 2019; Akterujjaman et al. 2020). Recent literature is specifically rich when it comes to providing solutions to technical problems related to networking (Idwan et al. 2017; Ota et al. 2017; Das et al. 2019), monitoring (Alavi et al. 2019; Heaton et al. 2019; Chung et al. 2020), blockchain (Kiu et al. 2020) or in general emerging technologies (Li and Liu 2019; Noruwa et al. 2020). However, very few papers focus on the multidisciplinary aspects (Ogie et al. 2017), digital transformation (Zomer et al., 2019) and data challenges related to these systems (Bowers et al. 2018; Gürdür Broo and Schooling 2020). Several researchers looked at the construction and infrastructure industry from a management perspective considering smart decision making through data-driven approaches. While some focused on implications of industry 4.0 (García de Soto et al. 2019) or the effect of digitalisation (Aghimien et al. 2020), others focused more on the improving performance of the infrastructure industry (McDermot et al. 2020), proposed frameworks to assessing the sustainability of the infrastructures (Siew et al. 2016).

Early definitions of a digital twin, such as the one from Grieves and Vickers (2017), presented the concept with basic characteristics (Trauer et al. 2020) of a 'real space' and a 'virtual space' connected via data and information exchange (Grieves and Vickers 2017). 'Real' is also later referred to as 'physical' and 'virtual' as 'cyber'. This division of physical and cyber parts is also seen as an evolution from Gelernter's (1991) "mirror worlds" concept which can be expressed as, "software programs... about to be joined by vast public software works that will revolutionize computing and transform society as a whole".

The most widely used definition of a digital twin is from NASA which states that the digital twin is an "integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin" (Shafto et al. 2012). Some definitions such as the one from Deloitte (2017), "a near-real-time digital image of a physical object or process that helps optimize business performance", focus on the speed of updating the digital/cyber representation. A more current definition in manufacturing defines the term as "… a digital representation of an active unique product […] or unique product-service system […] that comprises its selected characteristics, properties, conditions, and behaviours by means of models, information, and data within a single or even across multiple life cycle phases" (Stark and Damerau 2019). Digital twins in infrastructure is a new concept and there is no commonly accepted definition of the term. The Centre for Digital Built Britain defines it as "a realistic digital representation of assets, processes or systems in the built or natural environment" (Bolton et al. 2018).

Barricelli et al. (2019) conducted an extensive survey on digital twin definitions, characteristics, applications and design implications where they have reviewed 75 papers from aviation, hospital management, manufacturing, precision medicine and manufacturing. There was no research article that specifically focused on infrastructure digital twins that were part of the survey. Trauer et al. (2020) also conducted a literature review on the digital twin definitions and examined 57 articles. Similarly, Jones et al. (2020) conducted a systematic literature review to characterise digital twins. In total, 92 publications are analysed and in addition to characteristics; important themes, benefits, research gap and similar topics are discussed. While the literature on digital twin definitions is discussed by these literature survey studies, the acceptance of these definitions in industry and specific to the infrastructure industry is not presented before this article.

The literature on digital twins in infrastructure is still nascent. However, important investments and efforts are on their way to build ecosystems of digital twins all around

lational Digital Twin Programme (Centre for

Digital Built Britain 2019) of Centre for Digital Built Britain was set up to deliver key recommendations of the National Infrastructure Commission’s 2017 'Data for the Public Good Report' (National Infrastructure Commission 2017).

Gürdür Broo and Schooling (2020, 2021) suggested that the industry should address the challenges related to availability, accessibility, quality, volume, variety, and longevity of data by considering user-centric approaches, blending methodologies (Gürdür and Törngren 2018), and identifying the organisational needs (Gürdür Broo et al. 2021). At the same time, Sacks et al. (2020) argue that in the academic and popular literature of the built environment, many authors use the term digital twin simply (and naively) as a synonym for Building Information Modelling (BIM). Azhar (2011) describes BIM as one of the most promising recent developments in the architecture, engineering, and construction industry. While BIM aims to present an accurate virtual model of a digitally constructed asset, it differs from the digital twin because digital twins are more than only a digital representation of the physical systems. In addition to having sensor updates, the digital twin has to mirror the current reality of the physical asset where the current BIM approach mainly focuses on providing a detailed information model to visualize what is to be built in a simulated environment (Azhar 2011). Jones et al. (2020) characterise the digital twin as the three-dimensional models with two-way data connections corresponding to BIM Level 3. Yet, they also argue that “from its foundations, BIM is a virtual representation of a physical entity albeit with a greater focus on the users of the system than the Digital Twin”.

Similarly, some researchers (Borrmann et al. 2018) agree that digital twins for operation and maintenance in infrastructure are based largely on the building information models produced through their design and construction. As a different way to approach digital twin implementation, Rausch et al. (2021) proposed 3 D scanning based approaches to create digital twins. The importance of differentiating 3 D models and building information models from the digital twins is also highlighted by Tchana et al. (2019). They stated that the industry should move from the idea of 3 D models (digital models) towards digital duplications (digital twins) of the infrastructure for effective lifecycle management.

Methodology

The main methodology that has been adopted for this study is semi-structured interviews with experts. In general, interviews represent a research data collection method that has been applied across a plethora of research disciplines for collating opinions and knowledge from research participants.

To understand the current digital twin practices of the UK infrastructure sector, a semi-structured survey methodology was adopted. Here, the term survey refers to the selection of a sample of people from a pre-determined population, followed by the collection of a relatively small amount of data from those individuals (Kelley et al. 2003). A semi-structured interview is formed with a selection of pre-determined open-ended questions that prompt discussion and allow the interviewer to explore emergent themes further (Mason 2017). This less structured interview strategy means that the person interviewed is more a participant in the meaning-making than a conduit from which information is retrieved (DiCicco-Bloom and Crabtree 2006). In general, these interviews are useful tools to provide a "snapshot of how things are at a specific time" (Denscombe 2014).

Although this stream of research offers great benefits for qualitative researchers, there is a danger of simplifying and idealising the interview situation based on the assumption that interviewees are competent (Qu and Dumay 2011) and moral truth-tellers "acting in the service of science and producing the data needed to reveal" their experiences (feelings, values) and/or the facts of the organisation under study (Alvesson 2003). Therefore, it is important when conducting interviews to address relevant biases in interview questions. Therefore, the investigators must understand and be able to prevent, or at least minimise, bias in the design of their questionnaires. Choi and Pak (2005), based on a review of the literature, identified 48 types of bias in questionnaires. During this study, these biases and the interview phases in which the biases may occur were identified (Choi and Pak 2005; Gürdür et al. 2019; 2019). Details of the phases and the considered biases are listed below:

- Question design phase
    - Problems with the wording: ambiguous question, complex question, double-barreled question (two questions in one), technical jargon, uncommon and vague word usage.
    - Missing or inadequate data for the intended purpose: belief vs. behaviour (hypothetical question, personalised question), starting time, data degradation, insensitive measure.
    - Faulty scale: forced-choice (insufficient category), missing interval, overlapping interval, scale format.
    - Inconsistency: case definition, change of scale, change of wording.
- Interview design phase

    - Formatting problem: horizontal response format, juxtaposed scale (questionnaire format), left alignment and right alignment.
    - Questionnaire too long: no-saying (nay-saying) and yes-saying (yea-saying), open question (open-ended question), response fatigue.
    - Flawed questionnaire structure: skipping a question.
- Interview administration phase
    - Interviewer, not objective: interviewer, non-blinding.
    - Respondent’s subconscious reaction: end aversion (central tendency).
    - Respondent’s conscious reaction: faking bad (hello-goodbye effect), faking good (social desirability, obsequiousness).

The interview survey that is used in this study was designed to be concise, easy to understand, and succinct. The final set of questions were discussed by different researchers, who all previously worked on similar research, before the interviews. Conducting research interviews requires not only the use of various skills, such as intensive listening and note-taking but also careful planning and sufficient preparation (Qu and Dumay 2011). Interviews are conducted online and recorded with the consent of the interviewees where the procedures for interviews are laid out in writing and are clearly explained to interviewees before interviews proceed. For the confidentiality of the participant, their names are taken out, anonymised, and coded names are used. The recording transcripted to text for easier analyses and coded names are integrated with this text. The transcripts are used when the answers to the interview questions are analysed. Before analysing the results, the yes-saying or no-saying issues (answering all of the questions as yes or no) were checked. Some questions sought to collect data about the respondents’ beliefs, and these questions were designed specifically for that purpose. The remaining questions were about the facts related to the respondents’ roles, projects, and workplaces. The interview questions did not aim to collect any data related to the behaviour of the respondents; therefore, the findings do not include any behaviour-related comments. The recordings are deleted after the anonymised transcripts are produced.

Participants consisted of senior management and C-suite executives from multinational and UK-based infrastructure clients and developers whose ages fall between 39-62. Two of the nine participants were women. The participants are chosen from different infrastructure companies which deliver and operates the biggest infrastructure projects in the country. In total, nine participants were interviewed from eight different

ɛir organisations varies from 40-40,000

people and their team sizes from 4-140 people. The domains of the infrastructure organisations interviewed are city, environment, water, transportation, natural gas and electricity. For the selection criteria, we have considered that each participant is involved in either mega or large-scale infrastructure project design and development. Furthermore, the participants are selected by considering that they have to manage digital twin implementations related to these projects in the UK or internationally in addition to driving digital transformation in their organisations. Executives have 10-30 years of experience in the infrastructure sector. Their job descriptions include chief technical officer, director, risk manager, head of digital engineering, programme manager, integrated systems manager, asset information manager and engineering information manager, This selected group of executives were not only leaders in their organisation, for instance, four of the participants also sit on different committees at a national level where they contribute to strategies, roadmaps and guidelines to transform the infrastructure industry such as national digital twin programme of the Centre for Digital Built Britain.

While the sample size for the interview is small, the real population size of executives in the infrastructure sector who has organisations that has digital maturity to develop digital twins and have experience in delivering digital twins is also small. Moreover, the findings of this study are not quantitative but rather qualitative where the objective of the study is not to deliver statistical results on questions but instead share the common and different views of infrastructure executives from the UK on digital twin developments. When the interview data is analysed and presented, we have considered this limitation and we did not for instance try to provide or generalize answers by dividing infrastructure into different subcategories or give percentages/numbers to support the analyses. The main implications of this work are, therefore, not statistical questionnaire results but quantitative interview findings and supporting strategies that may help the infrastructure industry to operationalize digital twins for the future.

Findings

Participants were asked to answer questions related to four main categories: the definition of a digital twin, current practices, benefits and challenges of implementing digital twins. The next four sections will summarise the findings related to these categories.

Definitions

The participants were aware of the early adoption stage of the term that we have

nmented on different aspects of the

definition of digital twins. Some participants specifically underlined that the definition of digital twin should include characteristics such as real-time data transfer or feedback loops between the virtual and real spaces. While all responses started with defining the digital representation aspects of the physical asset, some participants' views on further capabilities of digital twins were completely different. For instance, one participant defined the term as

- "when physical is influenced by the digital and vice versa".

On the other hand, another participant said just the opposite and stated that

- "digital twins do not need to have real-time performance nor feedback loops".

One participant highlighted that in infrastructure projects where the design and construction of the asset take years, the digital twin may mean different things at different lifecycle phases. While it may be only a static representation of the physical asset at the design phase, later construction telemetry, Geographic Information System (GIS) and sensor data might be integrated to make a digital twin a virtual simulation of a physical asset.

Some of the participants defined digital twins as more abstract such as

- "being able to access information when you need it" or
- "a digital representation of whatever it is that we are managing"

whereas others detailed and narrowed down the definition to

- "[a] digital twin is a separate computerised version of the physical infrastructure through which we can run scenario planning, live operational enquiries."

Nearly all of the participants (six out of seven) mentioned Building Information Modelling (BIM) and 3 D CAD models as models related to the digital twin concept. While some saw BIM and CAD as a first step to digital twin development, others mentioned difficulties related to turning these information points into dynamic models. All of the participants commented that data and information flow between the physical and cyber worlds is vital in the definition of the term 'digital twin'.

Current practices

The second part of the interview focused on the current practices of the participants and their organisations related to digital twins. The questions focused on whether they have any existing digital twin implementations and their details such as maturity level, technologies, and use cases.

Participants were reluctant to say that they have working digital twin implementations but mentioned that they have prototypes and implementations in development which reflect some characteristics of a digital twin. A few of the given examples of digital twin developments included: 3 D modelling of physical assets; integration of real-time weather forecasts; asset data and information projects; integration of different information systems coming from several organisations (in the construction phase); contract management systems throughout the supply chain (in the construction phase); procurement of a network management system and its integration with existing systems; sensor data collection; implementation of common data environments; and modelling of systems and control philosophies and similar.

While the participants connected the benefits with data and digital twins, they also mentioned that current practices are not yet mature enough to do that. For instance, one participant said that: “It’s fair to say that we’ve got a lot of data. A lot of it is pretty poor quality, it’s created by old infrastructure that’s that keeps failing and is stored in systems that nobody can get hold of it. So it has taken quite a lot of work to get to the point where we have, where we’re beginning to bring some of the key datasets that we want to work with into one place.”

Some of the technologies that the participants mentioned are cloud platforms; web-based technologies; real-time data collection and analytics; big data processing; common data structures and ontologies; human-readable rule implementations; data integration tools; 3 D CAD modelling tools; light detection and ranging; laser scanners; and supervisory control and data acquisition systems.

Most of the digital twin development projects in the UK mentioned by the participants were first projects and in their very early stages. A few international projects were focusing on using sensor data to develop information visualisations to inform citizens through web-based applications.

All of the example use cases were implementations in isolation, except one which is still in the construction phase. Integration with other digital twins or information systems, interoperability, standardisation and common data environments were discussed but none of the projects was at the integration stage and there were generally no plans to combine more than one digital twin in the near future. Most of the integration-related discussion focused on consolidating different heterogeneous data sets. One project which paid a lot of attention to integration was a partnership between public and private organisations. This led to the formation of different teams for asset information and engineering information management. These teams are working on collecting, integrating and analysing information throughout the design and construction phases and will transfer this information to other organisations and teams after asset delivery.

Addressing these requirements from the very beginning of the project encouraged the stakeholders to work together and set up mechanisms to structure and provide useful information between them.

Benefits

Participants were asked to state the benefits of digital twins. All of the participants talked about the importance of transforming raw data into information to support better decisions. Several participants underlined the importance of digital twins when delivering new assets, in operations, in maintenance or planning stages – throughout the lifecycle of the asset.

One participant mentioned that

- “It is about knowing what you have got and what condition it is in”.

Similarly, another participant stated that digital twins enable an organisation

- “to understand where and when to intervene”.

Even though their current digital twin prototypes were not designed for future integration with other digital twins from their partners, stakeholders, collaborators, when asked about the digital twin benefits, several participants mentioned integration with other assets as a key to deliver the most benefits.

A number of frequently-cited benefits listed by the participants include:

- better asset and resource management
- faster project delivery
- organisational transformation
- untapped resources utilisation
- bringing value from data
- lower cost through better information flows
- optimising operations
- decreasing risk and increasing safety

Another important benefit related to digital twins and mentioned by the participants was regarding the use of artificial intelligence, machine learning and predictive algorithms to forecast or predict future events. One participant described the need for this kind of predictive analysis to identify bottlenecks by looking at the historical data and predicting future events.

Challenges

When asked to list the barriers to the adoption of digital twins in infrastructure, all of the participants mentioned three main challenges: technology adoption; culture; and lack of skilled people. Many participants discussed digital twin development as a natural result of a digital transformation. While highlighting the interconnected relationships between these three challenges, participants specifically concentrated on the human factor of the transformation.

One participant stated that:

- "I think that the bigger issue, the thing which is harder, the human bit, is to get people to understand the value, to change their behaviour, to change the way they specify requirements and to change the commercial arrangements".

Another participant touched upon the organisational barriers,

- "a corporate organisation like ourselves has limits to the level of corporate capability and managing some of those types of applications i.e. bandwidth, and capability of the investments that you've made".

The participant highlighted the importance of building business cases and the difficulty of creating these cases when there are not enough skilled people around to run these activities. Similarly, another participant stated that:

- "Trying to get people to understand the value of data and what it means for them? We can talk about having better data, making better decisions, but actually, what does that mean at the end of the day? We are trying to sell the vision".

The same participant summarised the barriers as:

- "First barrier, ignorance. The second barrier, politics. The third barrier, apathy. Because the barriers to change around digital twins are no different from the barriers with a change of anything else. You can get any system to do anything you want if you've got enough time and money."

Most of the participants commented on data-related challenges such as data collection, governance, data standards and integration. They also underlined the importance of interoperability and commented on the difficulties of isolated, individual digital twin developments.

- “We need people to be more open to sharing their information and sharing it in a format that is machine-readable”.

Another participant shared their frustration as the biggest challenge is

- “The proprietary nature of everything. All our systems are different. It’s sometimes quite difficult to share data across the project because different people are using different versions, even different versions of the same software. Even when there are open standards, different companies’ implementations of those standards are quite often – I don’t want to say deliberately different – but sometimes it does feel that way”.

Several participants commented on the digital transformation maturity of the infrastructure industry as a barrier. One participant who also sits at national-level committees states that:

- “Too often people are producing lots and lots and lots of data but there is no structure, there’s no governance, there is no ownership, and that’s really why I talk about a digital strategy. So when we [sat in a specific committee] asked: ‘Do we have digital strategies?’ and we all went: ‘Well, we’re doing things digitally but what is a digital strategy? What’s digital transformation?’ We’re quite lucky, we are a relatively young, agile digital organisation, but others aren’t. There are many older and huge organisations with lots of legacy information.”

Participants talked about specifics in relation to the infrastructure. For instance, addressing the monitoring of infrastructure using sensors and integrating sensor data to digital twins, one participant said:

- “The deterioration in infrastructure is incredibly slow and the problem we’ve always had with that kind of infrastructure is if you’re going to put sensors on the infrastructure often the sensors require far more maintenance than the structures”.

Another participant identified infrastructure procurement methods and practices as a barrier to digital transformation. They underlined the importance of systems engineering or systems thinking and said:

- “It needs to be embedded into the client organisations. Currently, the contractors don’t have the capability to read various modelling languages around system modelling and that goes back to the cultural point. If the clients are not pushing the contractors and the industry, the capability and the competency will never change. There are a number of areas but certainly, I think the biggest one is around requirement setting and contractual arrangements”.

Yet another participant commented on the challenge related to the limitations of infrastructure projects:

- “For us, I think the reality is, as we stand here today, we’ve got assets that were built in Roman times. We’ve got a lot of assets that were built in Victorian times. The chance of creating a full digital twin for those, a perfect representation is impossible. However, that does not mean to say that we can’t recognise or identify the key aspects of those assets and represent them in a form so we can create a digital relationship. I see it as more of a framework”.

Future trends and expectations

As part of the interview process, participants are also asked about what future trends and technologies they follow and if they see the future of the infrastructure industry evolving towards more data-centric, digital twin-driven operations.

The participants cited a number of technological trends including Industrial Internet of Things; robotics; augmented/virtual reality; smart/live sensors; concrete 3 D printing; photogrammetry and defect detection; artificial intelligence and machine learning; interoperability; digitalisation of the current documentation; blockchain; and automation. They also referred to non-technical trends including the circular economy, resilience, carbon-free infrastructure, systems thinking, moving away from black-box solutions, cultural change, upskilling the workforce and acquiring talents.

When asked about their organisational practices related to considering the developments in other domains and identifying relevant trends, most of the participants talked about their efforts. Many of the respondents mentioned that they are attending conferences and following news outlets on technological development. Yet only one participant mentioned ongoing efforts on trend spotting activities as a company strategy.

Discussion

This study aimed to understand the current definitions, practices and challenges related to the development of digital twins in infrastructure and used semi-structured interviews with C-level executives as a methodology. In one of the sub research questions posed at the beginning of this article, we wanted to understand how the definition of digital twins differs for different infrastructure projects. The interview results show that the digital twin definition not only differs between sectors but that even within the same sector, such as infrastructure, organisations define the term differently. In the literature, digital

simulating, emulating, mirroring or

“twinning” the life of a physical entity, which may be an object, process, human or even human-related feature. For instance, Barricelli et al. (2019) argue that a digital twin is more than a simple model and simulation and refers to the works of Grieves (2014), Kritzinger et al. (2018), Negri et al. (2017) and Boschert and Rosen (2016). The definitions from the executives in the infrastructure industry did not always align with this view.

In contrast to other industries, infrastructure projects are lengthy in duration and the infrastructure assets are often in service over a long period. Compared to the automotive, manufacturing or aerospace industry, the assets are less data-driven, more static and are built to last for 50 to 100 years. In reality, some of these assets are in continued use for more than a century. This context could present an opportunity for digital twin implementations. For example, by monitoring the assets one can better understand the degradation or structural changes. That said, it is impossible to know an asset’s condition when it has been built because there is not enough existing information. This longevity dilemma (Gürdür Broo and Schooling 2020) differentiates infrastructure digital twins from others. Additionally, the construction of infrastructure assets takes a long time and there are currently no standard procedures for capturing data or developing digital assets followed by the industry and stakeholders. Large projects are rarely repeated, making application of lessons learned difficult and for most infrastructure projects new procedures, contractors, technologies and materials are used.

The executives who took part in the interviews were very well aware of the differences between different types of infrastructure projects. This awareness was key when it came to defining digital twins because they emphasized the goal behind developing particular digital twins rather than trying to fit in with a specific definition. This thinking is not new or only relevant to the infrastructure domain, the literature survey from Barricelli et al. (2019) shows that more than half of the reviewed articles on digital twins did not define the concept. The participants also underlined the role and implementation strategies of digital twins at different stages of the infrastructure projects and defined the maturity level of the digital twin differently. None of the participants was specifically emphatic about their definitions, instead, they came to the understanding that the digital twin for a tunnel in the design phase may be different from a digital twin of an energy grid or a railway during the operation phase. Furthermore, the difference between infrastructure assets and products from other disciplines are mentioned several times. This difference between digital twin usage, maturity, purpose and capabilities are not unique to the infrastructure industry. In the literature, digital twins have been discussed in relation to concepts such as product avatars – the digital counterpart or set of digital counterparts which comprise the ability to act intelligently (Hribernik et al. 2013) – or digital thread – delivering “the right information to the right place at the right time” (Hastings 2019).

Even though the executives did not exactly use similar terms like product avatars or digital thread their explanations were very similar to the definitions of these concepts. They have used these definitions to explain the different capabilities of a digital twin in different stages of the asset lifecycle.

When it comes to the second research question on the benefits of digital twins, participants were very well prepared and confidently explained why they believe that digital twins would benefit their organisations, their assets and society as a whole. There was a consensus that digital twins in infrastructure can only be realised as part of digital transformation. Discussions were around operationalising the existing data to create information to bring better insights for delivering, operating and maintaining the infrastructure assets. The participants also recognised the benefit of improved efficiency to optimise whole life value at different phases of their asset management. Sometimes the focus of the participants was on managing resources and assets better. At other times the focus was on bringing value to the organisation, stakeholders and customers by transforming data into knowledge. Reducing costs, optimising operations, utilising resources and similar topics were also discussed as benefits of digital twins. This shows similarities with the work done by Jones et al. (2020). In their study, Jones et al. (2020) reviewed the literature and identified the perceived benefits of the digital twin concept. Their findings include reducing costs (Grieves 2014; Ben Miled and French 2017; Hu et al. 2018), risk and design time (Damjanovic-Behrendt 2018), efficiency (Ayani et al. 2018), maintenance decision making (Macchi et al. 2018), and safety and reliability (Söderberg et al. 2017). The participants perceived digital twins as an opportunity to drive the digital transformation and data fluency of their organisations, similar to Grieves's (2014) view on digital twins potential to fostering innovation. Yet the executives were outspoken about the reality of a lack of industry awareness of the benefits or the importance of this transformation.

Even though the participants were following technological and social changes taking place outside of their organisations, there were no organisational mechanisms that required everyone to follow similar practices. The future trends and technological advancements were briefly mentioned by participants but the wider effect on the industry and infrastructure projects were not discussed in detail. This future perspective is characterised as one of the most important drivers behind digital transformation. As discussed by Deloitte Switzerland et al. (2018) in their digital future-readiness report, to remain competitive in the digital age of exponentially growing technologies – such as digital twins – companies need to have a future perspective and be prepared to adapt to the change. While the integration of digital twins was mentioned as an important future requirement from the digital twins and the system of digital twins identified as beneficial for the public good, the executives did not have any projects or plan to integrate their digital twins with other infrastructure assets. They reflected on the low adoption rate of digital twins and the non-existence of digital twin integration in the context of the slow transformation of the industry, citing the lack of skilled workforce, data standardisations and common data environments as overarching cultural barriers.

The third sub-question was specifically about these challenges and barriers. Participants critically reviewed the current situation and commented on individual, organisational and industry level challenges to adopting digital twins in infrastructure. Strong emphasis was given to human factors such as cultural acceptance, skills, overall understanding of benefits and business cases, and the difficulty of change-making and digital transformation. Another important challenge concerning data. They commented on both technical challenges related to collecting, storing, analysing and integrating data and also non-technical aspects such as understanding the value of data, providing mechanisms to operationalise data and so on. Some of the technical challenges such as data, enabling technologies and information technologies infrastructure are mentioned in the literature prior to this study by, for instance, Fuller et al. (2020) and Rasheed et al. (2019).

Strategies

The main research question that this article tries to answer is about how digital twins can help the infrastructure industry to deliver sustainable and smart infrastructure assets. To answer this question, the findings related to the three sub-questions are reviewed and a series of strategies are identified. These strategies are;

- digital transformation
- cultural transformation
- bridging the skills gap

Digital transformation

As we discussed in earlier sections, to be able to implement and use digital twins the infrastructure industry must drive digital transformation. The current practice shows that organisations are working to improve their digital capabilities by collecting more data, trying new technologies and bringing data-driven insights to life. However, the current transformation trend is vertical and isolated. For every organisation, there is at least one division or department that works on digital transformation. But these efforts are not then transferred to other parts of the organisations. Since most of these organisations are also big, it is difficult to integrate digital transformation across all areas of a business.

The real benefits of digital twins can only be possible when the organisations complete this digital transformation and improve their digital skills. The infrastructure industry should challenge the status quo and deliver the necessary environments to experiment with new technologies and even be prepared to fail. The current approach does not have enough flexibility to allow this learning process. Currently, projects are very competitive to win, delivery times are shrinking and profits are marginal. This pushes companies into a cycle to do the same things with the same people. Additionally, the infrastructure projects are big and generally, there is no room for risk or innovation. The digital transformation, therefore, is limited. Only by giving opportunities to infrastructure companies to experiment and learn without the time and cost constraints, can they acquire more productive and creative methods while driving digital transformation.

Cultural transformation

Similar to digital transformation, the infrastructure sector should have industrial cultural transformation strategies. Even though the executives interviewed in this study were aware of the importance and benefits of digital transformation, and specifically digital twins, they also mentioned several times that the culture of the industry is a key component towards adopting digital twins and similar concepts. From business to operations, from design to construction and maintenance, data and information technologies bring opportunities. To turn this opportunity into gains, the industry must have a workforce that is fluent in these technologies and which understands the value that data can bring. To speed up this process, the infrastructure industry should invest in its people. This would not only help to close the skills gap but also assist in aligning employee values and behaviours with digital transformation goals.

Identifying and clarifying goals of the transformation, communicating cultural attributes, paying attention to transparency and accountability, establishing culture risk management programmes and allowing the workforce to learn, experiment and fail would help the culture be more accepting of new concepts such as digital twins. This collaborative and comprehensive process can help shift the culture to embrace and advance digital transformation. In return, this understanding and acceptance from the infrastructure workforce will shift the culture and enable the implementation of future digital twins in infrastructure.

Bridging the skills gap

The interview results also showed that the skills gap in the infrastructure industry is one of the most important underlying factors in the adoption of digital twins. The existing skills gap in the industry may also be one of the reasons for issues of cultural acceptance of the new technologies. While the industry is aiming to grow by 33,000 jobs in the next

goal will be met (Walker 2019). A growing skills gap exacerbated by an ageing workforce and a limited supply of an appropriately trained new workforce is expected to persist or even get worse if the industry does not change its approach (ibid).

Organisational level or internal training and education programmes are one route to upskilling the current workforce. These programmes should be designed to give employees the skills they need for data and technology fluency, systems thinking and integration, simulation and data analyses, and even prediction and artificial intelligence. These training topics are vital to bridge the gap in knowledge because, without a fundamental understanding of technologies throughout the organisation, transformation and digital twin development cannot be achieved. Alternatively, collaborating with educational institutions for upskilling through certification programmes and providing continuous learning opportunities would not only improve the skills of the current workforce and increase productivity and quality but also increase the attractiveness of the industry and prepare it for the long-anticipated digital transformation.

The competitiveness of the industry in employing a talented and skilled workforce should be closely examined. Currently, it is difficult to employ and keep a skilled workforce in the infrastructure industry. A talented workforce chooses higher salaries in other industries. This can only be addressed by offering favourable labour market conditions, excellent work environments, wellness programmes and benefits.

Conclusion

This study aimed to understand how digital twins can help the infrastructure industry to deliver and operate sustainable and smart infrastructure assets. To that end, we conducted interviews with nine the UK infrastructure industry executives who have been part of different industrial committees on digitalisation and occupy roles to transform both their organisations and the industry to become more data-driven, smart and sustainable.

The interview results showed that each infrastructure domain and organisation approaches digital twin development from a different angle. Some defined digital twins as a concept and see it as the next step of the digital transformation, where some others define it as a real-time realistic representation of an asset. While they all understand the differences in defining digital twins, they all agree that digital transformation and digital twins would benefit the industry on different levels. In general, the main benefit of digital twins is defined as enabling value from integrated data sets to ultimately allow the industry to build, construct, deliver and operate infrastructure assets faster, better, The executives agreed there were common challenges across different infrastructure domains. These challenges were categorised under three heads – technology adoption, culture, and lack of skilled people. Later, three main strategies were set out to addresses these challenges – digital transformation (1), cultural transformation (2), and bridging the skills gap (3). These strategies focus on providing equal opportunities to the current workforce to improve their digital fluency and skillsets. They can be summarised as informing individuals within the sector and other organisations of the benefits of digital twins to improve their adoption and realisation; identifying and clarifying goals of the transformation; communicating cultural attributes; paying attention to transparency and accountability; establishing culture risk management programmes; and improving the attractiveness of the industry by offering favourable labour market conditions, excellent work environments, wellness programmes and benefits.

This study shows that the digital twin implementations in the smart infrastructure sector are still in their infancy. While real application and empirical studies on digital twin implementations are yet to be seen, the leaders in the sector agreed on common benefits and challenges to take the industry to this next level. More studies on experiences and learning on digital twin design and development would benefit the industry to build common knowledge to deal with not only the complexity of providing technical digital twin products but also to help the industry to transform.

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