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Digital twins in the asset life cycle: are we there yet?

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An academic–industry team present the results of research conducted into the current benefits being derived from the use of digital twins across the entire life cycle of an asset. The team reviewed the benefits being derived by the asset-management community, as it is through this that through life productivity and effectiveness benefits will be realised. The team conducted a review of relevant literature, surveyed 122 practitioners and worked with their industry partner and a UK professional body to validate their conclusions. Specifically, (*a*) the authors examined the current application of digital twins in three industry sectors: process industries, infrastructure (civil engineering) and manufacturing. (*b*) The authors grouped the data according to role types – namely, professionals working predominantly in design and build and professionals in the operation and maintenance part of the life cycle. As regards the sector results, the responses were found to be contradictory. When controlling by role type, the results are more cohesive. Individuals involved in the operation and maintenance stages consistently indicated that digital twins are not delivering on their promise. The authors present a series of problem statements to define the current state, together with some managerial recommendations, and the authors propose further work to establish detailed guidance for infrastructure sector projects.

Keywords: Building Information Modelling (BIM)/built environment/digital twin/information technology/productivity

1. Introduction

1.1 Background

In this paper, the authors examine the current perception that the adoption and use of digital twins (DTs) in design-and-build projects is not translating into beneficial new capabilities for the asset manager. One type of DT often promoted for use during the design-and-build stage of infrastructure projects is building information modelling (BIM). The International Organization for Standardization (ISO) standard for BIM, ISO 19650 (ISO, 2018), identifies a number of benefits for the asset manager (or facility manager) in adopting the BIM model for the asset-management stage of the life cycle. These include reduced costs, better operational and maintenance awareness, better decisions, identification of impending failures, better strategic planning and improved verification. However, research suggests that these benefits are not being realised in practice (Winfield, 2020). Key challenges of BIM in the operational phase include lack of interoperability between BIM and facility-management (FM) technologies, limited knowledge of requirements for the implementation of BIM in FM, lack of open systems and standardised data libraries, large current number of disparate operational systems managing the same building and lack of clear roles, responsibilities, contract and liability framework (Kassem *et al*., 2015). Asset managers are less convinced about the impact of BIM during the operation phase, as they have not seen any significant improvement in the performance of the asset in either reduced costs or increased value (RICS, 2019)

The authors' research team includes academic, consulting and industry partners, and their prime area of interest is the infrastructure sector, but the use of DTs is examined in three different industry sectors to see if the approach to DTs and maturity levels is different across sectors. This approach responds to voices calling for establishing a cross-sector approach in DTs (IET, 2022) The authors' ultimate objective is to develop a set of guiding principles for users in the infrastructure sector that will guide the development of DT strategies regarding the choice of software (and related DT models) at different life-cycle stages and will define the optimum relationship between the data lake, the software, the model and real-world data (e.g. from sensors).

In this paper, the authors discuss their first step in developing these guiding principles, which is to develop a clear problem statement for the current suboptimal state. The work of other learned bodies is reviewed to assess the current level of understanding of this problem. In particular, the authors collaborated with the Institute of Asset Management (IAM) to align the authors' research with the work that AIM are doing on the use of digital-asset-management techniques (IAM, 2020).

To provide a clear focus for the definition of the problem statement, the following research questions were defined.

- To what extent are DTs delivering life-cycle benefits across industry sectors –that is, infrastructure, manufacturing and process industries? (sector focus)
- How do the different user groups involved throughout the asset life cycle (capital expenditure (Capex), operating expenditure (Opex) and digital user groups) view the success of DTs in their sectors? (role type focus)

1.2 DT definition

DTs are realistic digital representations of physical assets (Bolton *et al*., 2018). For the purposes of this study, a DT is considered to have three 'layers':

- data layer: a unique and comprehensive set of data that enables the physical asset to be modelled in the solution layer for the intended purposes of the users
- solution layer: the modelling and analytical tools (e.g. software, VR) that virtually represent the actual and potential characteristics of the physical asset that is of interest to the user (e.g. geometry, maintenance information, flow rate, temperatures)
- sensor layer: the automated devices or manual processes that capture the data of interest from the physical asset and feed this into the data layer.

In this study, the authors are principally interested in how the modelling and analytical tools in the solution layer support the interests of the users through the asset life cycle.

2. Literature review

2.1 DTs: what are they?

The term 'digital twin' is used to describe a digital replication of a physical asset and, in addition, the process of seamlessly transmitting data between the physical twin and the DT (El Saddik, 2018). In theory, DTs can update data in real time, so that virtual models can undergo continuous improvement by comparing the virtual asset with the physical asset (Tuegel *et al*., 2011).

DTs bring together the data from all aspects of the asset or product life cycle, laying the data foundation and enabling quality traceability. DTs should shorten the product development cycle, improve the build efficiency and guarantee accuracy, stability and quality. Furthermore, the use of DTs promotes efficient synergies between the different stages of a product life cycle (Qi and Tao, 2018). Asset owners are increasingly requiring the handover of DTs that can be used to support the operations and maintenance processes of their physical assets, be it buildings or production lines (Krystallis *et al*., 2015, 2016; Love and Matthews, 2019).

2.2 Types of DT technologies

In a review of the benefits of DTs (Love and Matthews, 2019), it was found that DTs were linked to a suite of technologies such as BIM, geographic information systems (GISs) and supervisory control and data acquisition systems to create a DT for operations and maintenance. This study compared a variety of digital technologies for asset management across different settings, including rail, process plant and oil and gas. It was found that there are three main types of DT technologies. First, these include input technologies, for sending data from the physical world to the DT. Key input devices such as sensors and the Internet of things (IoT) are embedded or installed on assets to capture their performance, operation and changes over time. The second type includes processing technologies, for analysing the data demonstrating the impact of changes, evaluating scenarios and external conditions by incorporating multi-physics simulations, data analytics and artificial intelligence (AI), including machine learning (ML) data analytic approaches. This data-intensive stage eliminates the need for physical prototypes and reduces modelling and simulation time. The third are output technologies, for sending information from the DT back to users and/or to the physical world. In this phase, DTs are continuously updated to reflect changes to their physical twins across their life cycle, feeding back through output technologies such as actuators and into a virtual environment, through augmented reality (AR) and virtual reality (VR), that enables users to monitor and optimise continuously the asset by combining data and insights.

2.3 Product life cycle and DTs across sectors

2.3.1 Infrastructure and buildings (the built environment)

A recent study in digital technologies in the built environment (BE) found that the main technologies discussed in the literature were BIM, AR, VR, IoT, cloud computing and big data (Papadonikolaki *et al*., 2022). The authors also point out that, that unlike other sectors where big data are available, the BE is behind the curve in terms of asset digitisation, usage and labour (Agarwal *et al*., 2021). However, the BE sector is slowly picking up (Whitmore *et al*., 2021).

DTs – an 'output technology' – are often conflated, and there has been some misconception about how DTs differ from BIM. In a review of the relationship between BIM and DTs (Radzi *et al*., 2023), four types of relationship were identified: (*a*) BIM is a subset of a DT; (*b*) the DT is a subset of BIM; (*c*) BIM is the DT; and (*d*) there is no relationship between BIM and the DT. In addition, a review of DTs in the construction sector (Sacks *et al*., 2020) builds on existing concepts of BIM, lean project production systems, automated data acquisition from construction sites and supply chains, and AI to propose how DTs can achieve closed-loop control systems in construction across the project life cycle. It also proposes different types of DTs across the physical twin and DT. In a 2019 report, the Institution of Engineering and Technology and Atkins offered their DT maturity spectrum defining principles and outline usage, where BIM is at level 2 on a 0–5 DT maturity scale (Evans *et al*., 2019).

2.3.2 Manufacturing

The concept of DTs originates in manufacturing when it was part of systems engineering, in particular model-based systems engineering (MBSE) (Madni *et al*., 2019). Initiatives in the aerospace and defence industries formed the basis of the National Aeronautics and Space Administration (Nasa) technology road map (Shafto *et al*., 2012) and the Nasa Apollo project that created two identical space vehicles to allow mirroring the conditions of the space vehicle during the mission (Rosen *et al*., 2015).

The automotive industry leads DT developments from manually operated cars to fully autonomous vehicles leveraging automated control. DTs in automotive manufacturing range from simple DTs simulating vehicle braking systems and how they would perform across various scenarios and weather conditions (Madni *et al*., 2019) to how Tesla advances car automation, through IoT, AI and ML developing a DT for every car, enabling real-time data exchange between the car and the factory (Schleich *et al*., 2017).

2.3.3 Process industries

Apart from DTs of assets and products, applications of DTs are also relevant across processes, emphasising less on product and more on the production life cycle, supporting real-time and dynamic cyber-physical connectivity across all stages of the production life cycle. MBSE has also been applied in plant manufacturing, not only during design but also during the back end of the life cycle for diagnosis and optimised operations (Rosen *et al*., 2015). In MBSE, the roles of modelling, simulation and optimisation are interconnected, as only after accurate data are fed into the system to produce robust simulations can optimisation take place to increase the competitiveness of the process as to energy and resource efficiency, shorten production time to market and enhance process control. DT developments in logistics and warehousing are being revolutionised by Amazon for real-world simulations of digital shop floor management (Brenner and Hummel, 2017). However, the available literature on implementing DTs in the process industries is scattered across various topics and industry types. As a result, there is a lack of a comprehensive overview regarding the main factors that enable or hinder DT implementation (Perno *et al*., 2023). The literature is still developing, and coupled with the inherent complexity of production processes (Kockmann, 2019), it becomes difficult for companies in this sector to determine the most suitable approach for implementing DTs to enhance their assets and operations.

2.4 Research gap

Table 1 summarises the main aspects of DTs in infrastructure, manufacturing and process industries, according to DT concept definition, key asset manager, dominant technologies and DT implementation approach according to the reviewed literature.

The review of the literature has shown the potential of DTs for designing and operating assets in a more efficient manner across the product or the project life cycle. However, the literature takes a normative approach to DT – namely, technologies, software and complex mathematical simulations are dominating this body of knowledge. Undoubtedly, this body of work is important in advancing productivity across all sectors. However, these innovations are merely tools and techniques; the human element is missing from this literature. Specifically, one of the key elements missing relates to the lack of perspectives from the asset managers and owners, who are the key drivers of realisation of DT benefits. For instance, key recent industry initiatives such as the Apollo Protocol (IET, 2022) have been successful in bringing different industries together to transfer lessons and break the disciplinary boundaries of DTs, but the perspective of the asset managers is largely missing.

The authors also find from the literature that there is limited cross-fertilisation of experience between their industry sectors of interest. For example, although the DTs for maintenance seem to be more mature in the manufacturing sector, the literature concludes that, use of DTs in the process industry is fragmented and immature (Perno *et al*., 2022).

Therefore, this study builds on two gaps. First, the study will offer the much-needed perspective of professionals working in different parts of the asset life cycle, specifically asset managers

Table 1. DTs – summary analysis across different sectors

	Infrastructure	Manufacturing	Process industries
DTs	Final product asset (e.g. bridge) Enabling system twin (twin during the design-and-build phase)	Product, process or facility twin	Production model simulation
Asset manager	Those who operate and maintain the asset	Asset manager of the staff, plant machinery, spare parts, equipment and facilities	Plant manager
Technology for delivering DTs	BIM, GIS, AR, VR, IoT	IoT, AI, ML, PLM	ERP, PLM
Approach	Data are produced during the design and construction phases; only a fraction of data is relevant in terms of asset management	Highly sophisticated data produced for product (e.g. car), with links to factory operations	Emphasis less on the product and more on the production life cycle, supporting real-time and dynamic cyber-physical connectivity across all stages of production life cycle

ERP, enterprise resource planning; PLM, product life-cycle management and owners, and second, it will investigate the realisation of the perceived benefits of DTs across the three sectors.

3. Methodology

3.1 Rationale and questionnaire design

This study employed the following steps to answer the two research questions. Initially, the literature was reviewed to explore the current application of DTs in three industry sectors: process industries, infrastructure (civil engineering) and manufacturing.

Second, referring to the project-management literature, the authors followed a project life-cycle view of DTs to identify stakeholders that engage in the development and use of DTs in the Capex and Opex phases of the asset lifecycle. Third, the research team developed a questionnaire based on the objectives of the research and issued it directly to professionals with experience in DTs and through relevant industry bodies – for example, the IAM 'Digital Hot Topic' team and the Nuclear Institute Digital Special Interest Group. The questionnaire investigated the experiences of respondents with DTs and gauged their satisfaction with current approaches and solutions using a Likert scale – a well-documented approach in survey research. Collecting a large number of responses allows for regression to the mean, which provides insight into the current perception of the target group (Joshi *et al*., 2015)).

The objectives of the questionnaire were to understand

- to what extent developers and users of DTs consider the relationship between the data lake, the operational data (e.g. from sensors) and the choice of software for the DT at the different stages of the project life cycle
- the overall satisfaction levels with the current performance of DTs across the asset life cycle by sector
- the extent to which users adopt different software solutions at different stages of the life cycle.

The complete list of questions is provided in the online supplementary material to this paper.

3.2 Sampling strategy

The recruitment strategy was to contact professional bodies and user groups to ensure that actual users and relevant industry professionals were addressed. The authors also directly asked known experts and users to comment.

Initially, 91 people responded to the survey from a wide range of backgrounds and business sectors. The research team analysed the background of the respondents and concluded that there were not enough respondents with an asset-management background to ensure that the results were valid. At this stage, the team contacted the IAM in the UK, who agreed to help with access to asset managers and owners. This resulted in a total of 122 responses, with a final spread of respondents as summarised in Table 2.

3.3 Research validation

To strengthen the rigour of the research and evaluate the relevance and accuracy of the conclusions, research validation methods were employed to triangulate the results and strengthen the shortcoming of mono-method studies (Sarantakos, 2017). There are different types of research validation, such as construct validation (whether the study explores what it claims to explore), internal validation (whether the data analysis was accurate, involving the research subjects) and external validation (involving new subjects external to the research) (Boudreau *et al*., 2001). Here the authors focused on external validation aimed at gaining the reflections of industry experts on the research results. The authors hosted a workshop with their industry partner, Sellafield Limited, and the IAM to review the conclusions of the survey and the authors' interpretation of it.

4. Results

4.1 Sector analysis

Of the three sectors surveyed (infrastructure, manufacturing and process industries), none was satisfied with how well the benefits of DTs have been delivered (Table 3). The authors found, perhaps surprisingly, that there was no real difference between sectors on this question. This is inconsistent with the literature review, which identifies best practice in these sectors. Surprisingly, although DTs have been used for many years in the manufacturing sector, where they were originated and one would expect that their implementation would be mature enough to show clear benefits, this was not evident in the data.

The next question related directly to how well the DT developed during the design stage is optimised for use by the asset manager.

Table 2. Roles and business sectors of the respondents to the survey (total number of respondents in parentheses)

Number of respondents				
Role	Engineering	IT/digital	Asset management	Project management
Total: 122 (110 valid)	29	46	20	15
Sector	Infrastructure	Manufacturing	Process industries	Multiple/others
Total: 122	58	16	23	25

Note: of the 122 'role' responses, 12 people quoted roles not included above. These were four students, three academics and five business managers. In the 'sector' responses, among the 25 'multiple/others' responses, 23 people said that they worked across industry sectors and two stated non-industrial sectors – namely, financial services and science. IT, information technology

Table 3. Delivery of benefits against sector (92 respondents)

Sector	How well have the benefits been delivered (percentage of respondents from each sector)?			
	Very well	Well	Not well	Poorly
Infrastructure	10.2%	26.5%	44.9%	18.4%
Manufacturing	9.1%	27.3%	45.5%	18.2%
Process industries	13.3%	26.7%	46.7%	13.3%
All sectors	9.8%	26.1%	48.9%	15.2%

The authors found that none of the sectors indicated strongly that the DT handed over was optimised (Table 4). A small majority of process industries respondents felt that the DT was optimised or highly optimised (53.4%), albeit with some modification required. However, most of the respondents in the infrastructure (53.2%) and manufacturing sectors (60%) indicated the DT was suboptimal or worse. Of particular concern was that, despite the significant benefits promoted for BIM in the infrastructure sector, less than 9% of the respondents in that sector stated that the DT handed over was highly optimised for use by the asset manager. This showed that the DT technologies were still evolving and they were not yet fit for purpose in the Opex life-cycle stage.

4.2 Role type analysis

Looking at the results from the perspective of the professionals involved, the authors grouped them together into role types. This was to assess the views of professionals working in different parts of the asset life cycle. Project managers and engineers were grouped together as the 'Capex' role type – that is, professionals working predominantly in the Capex (design-and-build) part of the life cycle. Asset owners, asset managers and asset-management consultants were grouped together in the Opex role type – that is, professionals working predominantly in the Opex (operation and maintenance) part of the life cycle. Professionals working across the life cycle supplying digital technology or management consultancy were grouped together in the 'digital' role type.

The authors found that no group was content with the benefits delivered and all groups agreed that the benefits of DTs had not been realised, but crucially, the Opex group was particularly dissatisfied, with 73.3% of this group classifying the delivered benefits as poor or not well delivered (Table 5). This result aligned with the literature on DTs used for maintenance tasks across sectors.

The next question related directly to how well the DT developed during the design stage was optimised for use by the asset manager (Table 6).

The Capex (51.7%) and digital (55.3%) role types had a slight majority view that the DT handed over was optimised. However, the Opex group indicated the DT handed over was unsuitable, with 60% of asset managers, asset owners and asset-management consultants scoring this as suboptimal or worse. Furthermore, one-third of the respondents of this group said that no DT was handed over. When the authors looked at the breakdown of the Opex group to focus on the 'hands-on' users, the asset managers, this became worse (Table 7).

It can be seen in this analysis that none of the hands-on user group indicated that the DT handed over was highly optimised for their use. It was also seen that 40% of the asset owner or manager community received no DT from the design-and-build phase of the project life cycle. It would appear that the potential

Table 4. How well the DT is optimised for use by the asset manager (88 respondents)

Sector	Is the DT handed over optimised for asset management (percentage of respondents from each sector)?				
	Highly optimised	Optimised (reconfigured)	Suboptimal	Unsuitable	No DT is handed over
Infrastructure	8.5%	38.3%	27.7%	10.6%	14.9%
Manufacturing	30.0%	10.0%	20.0%	30.0%	10.0%
Process industries	26.7%	26.7%	20.0%	6.7%	20.0%
All sectors	19.3%	30.7%	26.1%	10.2%	13.6%

Table 5. Delivery of benefits against role type (92 respondents)

Role type	How well have the benefits been delivered (percentage of respondents from each sector)?			
	Very well	Well	Not well	Poorly
Capex	12.5%	28.1%	46.9%	12.5%
Opex	6.7%	20.0%	40.0%	33.3%
Digital	10.3%	28.2%	53.8%	7.7%
All roles	9.8%	26.1%	48.9%	15.2%

Table 6. How well the DT is optimised for use by the asset manager (88 respondents)

Role type	Is the DT handed over optimised for asset management (percentage of respondents from each role type)?				
	Highly optimised	Optimised (reconfigured)	Suboptimal	Unsuitable	No DT is handed over
Capex	17.2%	34.5%	37.9%	6.9%	3.4%
Opex	6.7%	33.3%	20.0%	6.7%	33.3%
Digital	26.3%	28.9%	18.4%	13.2%	13.2%
All roles	19.3%	30.7%	26.1%	10.2%	13.6%

Table 7. Subdivision of the asset-management group (15 respondents)

Role	Is the DT handed over optimised for asset management (percentage of respondents from each role type)?				
	Highly optimised	Optimised (reconfigured)	Suboptimal	Unsuitable	No DT is handed over
Asset owner or manager	0.0%	30.0%	20.0%	10.0%	40.0%
Asset-management consultant (supplier)	20.0%	40.0%	20.0%	0.0%	20.0%

productivity gains and other benefits claimed for an optimised DT developed in the design stage (e.g. BIM) were not being seen in the Opex phase of projects.

Lastly, respondents were asked to answer which type of model they used for the DT (Table 8). The asset-management community (Opex) predominantly did not use a geometric model as their DT, with 63% using an asset database. However, the Capex role types considered that the DT often comprised a geometric model (44.4%), with digital role types agreeing (58.3%). This would seem to underpin a view that the software used to comprise the DT would change through the asset life cycle and the concept of a single piece of software representing the DT throughout the life cycle was flawed.

5. Discussion

5.1 Sector results

As regards the sector results, the responses were found to be contradictory. The responses across the questionnaire were mixed, and it was found that on average, half of the respondents were neither satisfied nor agreeing that DTs delivered to their promise, whereas the other half of the responses said the opposite was true.

Perhaps unexpectedly, given the long-standing integration of DTs in the process industries and manufacturing sectors (Kockmann, 2019; Neto *et al*., 2020; Pfeiffer *et al*., 2019; Uhlemann *et al*., 2017), respondents from these sectors were equally dissatisfied as the respondents in the infrastructure sector. This means that despite the assumed technological maturity of DTs in these two sectors (Alcácer and Cruz-Machado, 2019; Perno *et al*., 2022), operationally, all three sectors believe that more work needs to be done for their DTs to reach operational maturity.

However, the role model companies most quoted by the respondents (in a free-field question) were Rolls-Royce (manufacturing sector) and a range of water sector companies (process industry sector). The sector-based results provided strong indication that there was general dissatisfaction across all three sectors but with islands of best practice in some subsectors.

5.2 Role type results

When controlling by role type, the results were more cohesive. Individuals involved in the Opex stages consistently indicated that DTs were not delivering on their promise. This result was in stark contrast to the views shared by the individuals involved in the Capex stages and digital specialists.

It is therefore essential that the benefits of DTs are better delivered, particularly to the asset-management community, very few of whom feel that they are currently realising these benefits. The principal added value of the asset is delivered during

Table 8. Type of DT used (65 respondents)

	Type of DT used by the respondent (percentage of respondents for each role type)			
	Physical model of the asset	Geometric model (e.g. BIM)	Mathematical model (e.g. Matlab)	Asset database (e.g. Maximo)
Capex	22.2%	44.4%	22.2%	11.1%
Opex	0.0%	25.0%	12.5%	62.5%
Digital	8.3%	58.3%	12.5%	20.8%
Other	16.7%	50.0%	0.0%	33.3%
Grand total	13.8%	47.7%	15.4%	23.1%

operations (Krystallis *et al*., 2015; Liu *et al*., 2019; Love and Matthews, 2019), and this is where productivity gains can be made if the predictive qualities of DTs can be used to ensure that the asset is maintained efficiently and asset availability and process throughput is maximised.

A range of types of DT are used, and it is generally accepted that the type of software used in the DT solution layer will change during the asset/product/project life cycle. However, the usefulness of the DT to the asset manager is generally considered to be suboptimal or worse, suggesting that the requirements for the DT in the design phase have not been well validated and the delivery of the DT solution has not been verified by the asset manager.

A significant majority of the respondents indicated that further guidance would be useful to enable them to select the right type of DT strategy for through-life applications. In the BIM domain, ISO 19650 (ISO, 2018) provides relevant guidance and requires the upfront definition of the information requirements for the data layer of the DT. However, this only relates to the BIM element of the solution layer and does not address the full solution space. This is an important conclusion and partly explains why the full requirements of the asset manager are not captured when BIM is the only information model used. The guidance that the authors propose needs to cover the entire DT.

5.3 Managerial recommendations

Based on the results of this research, the authors have developed a series of problem statements and propositions.

Problem 1. The adoption of DTs is not delivering the expected benefits in the operational stage of the asset life cycle.

Proposition 1. Project managers should review the asset manager's data requirements early in the project and ensure that design features are built into the asset to capture these data and software solutions are developed during the design stage to expose these data to the asset manager in the operational phase. Specifically, in the infrastructure sector, the proponents of BIM would argue that BIM serves this purpose, but the authors have seen that it is not delivering this value to the asset managers, and this needs to be reviewed.

Problem 2. The need for a bespoke software solution to aid the asset manager in the operational stage of the asset life cycle is often not identified early in the project, and the design-and-build software is falsely assumed to be optimised for extended use in the operational phase.

Proposition 2. Project managers should ensure that the through-life DT strategy is defined before the design stage of the project. Specifically in the infrastructure sector, they should avoid assuming that BIM will deliver all the asset manager's DT needs and define the asset DT strategy before any solutions have been selected.

Problem 3. The multiplicity of producers of DTs leads to multiple sources of truth, leading to poor asset integration.

Proposition 3. Asset managers need to engage more with their internal and external suppliers, both those involved in the Capex phases and those who are engaged in their operations – to understand what data are being collected and produced. Potential risks could be mitigated such that there could be several data sources, leading to multiple handling, and if not controlled, several 'sources of truth may coexist' (Love *et al*., 2020; Whyte *et al*., 2016). Thus, asset managers should invest in understanding better what systems their suppliers are using and how these could interface with both the suppliers and the asset owner organisation.

Proposition 4. Another risk mitigation related to this problem statement is to understand how asset data should be represented to meet the demands of the asset owner organisation – for example, project units have demands different from those of asset-management units in an asset owner organisation. Stronger links and collaborating as equal partners between project-based units – that upgrade, refurbish and extend the asset base – and operation-based units – that operate and maintain the assets – of the same asset owner organisation should help avoid commissioning of additional data capture regimes with their associated data-management challenges (Krystallis, Locatelli and Papadonikolaki, in press). Krystallis, Locatelli and Papadonikolaki (in press) suggest that the two units, by jointly developing structured routines to negotiate and disseminate adoption of DT process and technologies, can successfully reconfigure their processes to achieve asset integration.

6. Conclusions and future research

This study examined the current perceptions regarding the adoption of DTs across the asset life cycle. Whereas the literature takes a technology advancement and normative view of DTs, the authors took a critical view related to operational maturity and examined the adoption of DTs across three sectors: process industries, manufacturing and infrastructure. The authors also categorised the responses by taking a life-cycle view of DTs.

The responses across the three sectors were mixed, indicating that all three sectors are polarised as regards the benefits resulting from the adoption of DTs.

When controlling by role type, the results are clearer and may explain the sector-level polarisation. It was found that the opinions of professionals involved in the Capex (design-and-build) stages, information technology (IT) specialists and professionals involved in the Opex (operation and maintenance) stages are not aligned. Whereas Capex and IT professionals believe that adoption of DTs delivers on their promise, Opex professionals have a very different view. The findings of this study suggest that organisations need to pay more attention to the Opex stage of DTs, identifying and involving Opex stakeholders in the development of DTs from the outset. The authors define several problem statements and propositions to address these findings.

The authors have identified several ways forward. First, future work could develop a guide to decision making, in terms of the type of solutions used in the solution layer of the DT appropriate for the different stages of the life cycle and for different asset types – for example, BIM during the construction phase of an infrastructure asset and a physics model during the operation phase of a process plant. The survey found that such a guide would be almost universally helpful to all participants.

Second, future research could also develop guiding principles for the design of the solution layer of the DT, appropriate for the type of asset, most suited to the different life-cycle stages.

Finally, more research is needed with asset owner organisations, to examine their DT strategies to ascertain whether the principles would result in a change to those strategies. Case studies, ethnographies and other type of studies that afford deep direct qualitative observations would yield promising results and shed light on the group dynamics (between Capex professionals, IT specialists and Opex professionals) and cultural/professional differences between these groups.

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