Centre for Digital Built Britain

Principle-based digital twins: a scoping review

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Summary

The Construction Innovation Hub and the Centre for Digital Built Britain's National Digital Twin Programme are calling on leaders involved in creating and managing the built environment to build the Gemini Principles into their digital strategies, especially for work on digital twins. The principles will enable a values-based approach to the development of digital twins and pave the way for secure, resilient data sharing, which is at the heart of the National Digital Twin.

Published by the Centre for Digital Built Britain in 2018, the Gemini Principles introduce a novel approach to digital twins by setting out generic principles for – rather than specific technological solutions to or outcomes from – the implementation of digital twins. This paper provides an answer to the question of whether principle-based digital twins have been explored before in published literature. Existing applications of digital twins have been motivated in a variety of ways based on their contexts and intended outcomes. These motivations tend to vary by sector and by academic discipline. Whether or not these motivations qualify as principles is debatable. Similarly, digital twins may be intrinsically linked to organisational principles or strategies without this fact being evident in the literature. Therefore, a definitive assessment of how many principle-based digital twins exist would be exceedingly difficult.

What is evident from a scoping review of the literature are different levels of strategy and motivation underlying the use of digital twins, from national and regional digital strategies, to organisational strategies, to the motivations driving individual academic or industrial case studies. In this paper, these have been loosely mapped to the Gemini Principles in order to draw some broad conclusions about their frequency in the literature. The most prevalent motivations are simulation, control, efficiency and structural health monitoring, with relatively few papers discussing digital twins in terms of public good, security, sustainability or collaboration.

The most notable exception is the literature around smart cities. Due to their complexity and citizen-centric focus, digital twins for smart cities are more often based on principles that parallel the Gemini Principles. Additionally, a small number of maturity frameworks and strategic road maps capture elements of the Gemini Principles and wider work toward a National Digital Twin (NDT).

Many of the papers focus on technical aspects of digital twins and also cite remaining technical barriers. However, many of these technical barriers intersect with social and organisational solutions. The gap around principles and service- or citizen-centric digital twins indicates that developing frameworks for principle-based digital twins is a challenge that very few academics or sectors are attempting to address.

Introduction

This report presents an overview of academic and non-academic (grey) literature in order to answer the question of whether any existing digital twins are grounded in underlying principles. It is based on a brief overview of the literature, known as a scoping review, and therefore the results should be taken as indicative rather than exhaustive[1]. It outlines the motivations and purposes for existing digital twins in the interest of establishing the gap between the current state and an eventual National Digital Twin (NDT) based on the Gemini Principles [1]. Section 1 introduces digital twins and the concept of the Gemini Principles, while section 2 discusses the motivations, principles and frameworks that are used to underpin digital twins according to the academic literature. Section 3 covers some of the most common technological and organisational barriers identified within this literature.

1 For an overview of the methods used, see Annex 1 to this paper.

Section 1

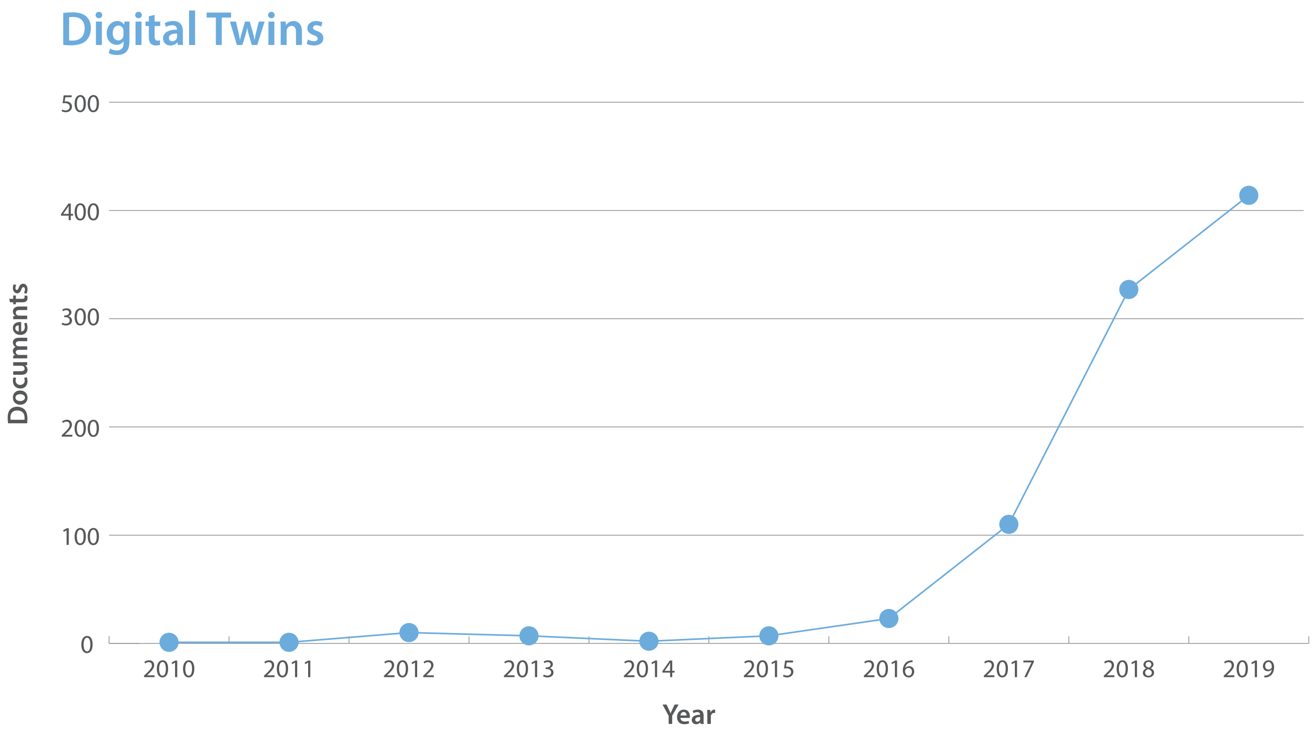


Fig. 1: Documents by year, based on a search of the Scopus database on 09/09/2019.

Digital twins have seen a surge of research interest over the past few years, with 96% of the over 850 academic papers on the topic having been published since 2016 (Fig. 1). This rapid increase marks a trend in which the term is wielded in a variety of ways. For example, it is often used to refer to any digital model or simulation of an asset whether or not that asset exists in reality. For the purposes of clarity, this paper uses the definition laid out in The Gemini Principles[2] :

> *"What distinguishes a digital twin from any other digital model is its connection to the physical twin. Based on data from the physical asset or system, a digital twin unlocks value principally by supporting improved decision making, which creates the opportunity for positive feedback into the physical twin."* [1]

The paper goes on to describe two different types of digital twin:

1. A **dynamic digital model**, fed by live data flows from a physical asset, for example a building, or one of its components, like a lift motor. Insights and programmed instructions from the digital twin can then impact the physical twin using real-time control mechanisms, for example shutting down a faulty lift or adjusting the temperature of a room.
2. A **static digital model** that changes periodically as long-term data about a physical asset are added in. This type of digital twin is used for strategic planning, and feedback into the physical twin is achieved through the capital investment process. This type is also sometimes referred to as a "digital shadow" to differentiate it from the first type of digital twin. [2]

2 For clarity, where this review is referring to the published paper, The Gemini Principles, it will use italics. Otherwise, the principles themselves will be referenced without italics.

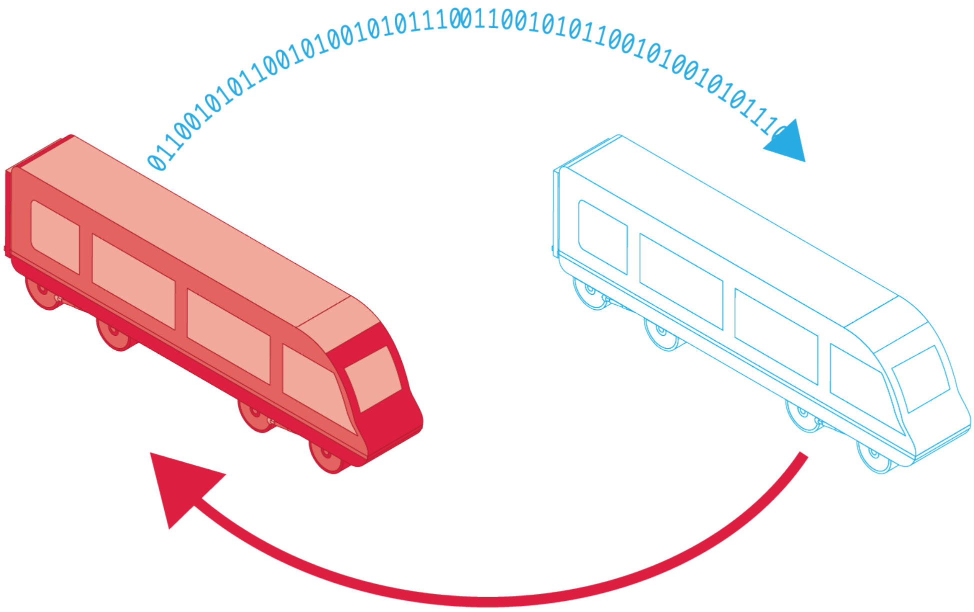


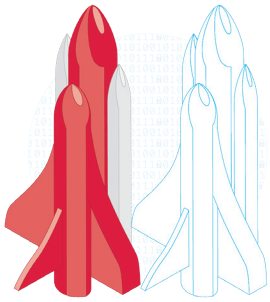
Fig 2: A digital twin has a reciprocal relationship with its physical twin. For example, a train car may send data to a digital model of itself, while the digital twin will analyse the temperature, occupancy or performance of the car and may make positive interventions, like changing the climate controls or sending a maintenance request.

Useful histories of the term are prevalent throughout the literature (for example [3], [4]). To clarify usage, [5] attempts also to disambiguate definitions of digital twins. That paper, produced in 2017, aimed to streamline and clarify the use of the term going forward. However, since then the literature has further diverged, and disparate uses of the term have persisted. Indeed, authors have continued to define, disambiguate, diagram and establish the core technologies for digital twins through various lenses and in diverse sectors[3].

Digital twins are also often discussed as an enabling or defining technology for Cyber-Physical Systems (CPS), the Internet of Things (IoT) or the Industrial Internet of Things (IIoT), accounting for a large proportion of their mentions in the published literature.

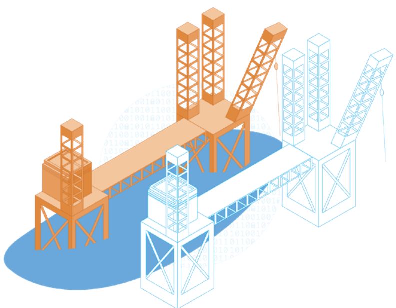
For this review, no distinction was drawn between these two types of digital twin invoked in The Gemini Principles. Research that described digital twin implementations of either type were in scope, even if they had not yet been created. The point of interest was the motivation, not the digital twin itself.

3 For further discussion of the state of the art in digital twins, see Annex 2.



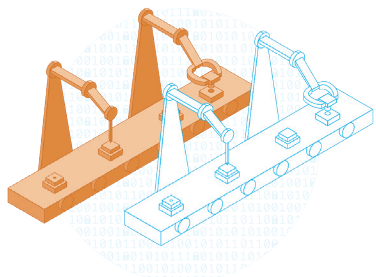
While the concept of accurately modelling the physical world dates back to the first attempts at accurate mapping, NASA were pioneers of digital twins for remote monitoring, controlling and running simulations of their spacecraft from Earth.

The aerospace and defence sectors are frequently cited as the next most advanced in digital twin use, using them to manage highly complex assets, though data sharing between organisational silos remains a barrier.



Offshore oil & gas use digital twins to monitor and predict maintenance schedules for their structures in the interest of safety and efficiency. Data security is a major concern in this sector.

Digital twins are prevalent in manufacturing literature and practice at various scales – from component to factory to wider logistics level – in order to manage efficiency, control, safety and logistics. Interoperability along the supply chain is one of the chief barriers in this sector.



In the built environment, the use of digital twins is just beginning to take off. Fully realised examples are rare, even at the level of individual assets. A great deal more technological and organisational maturity is needed for a National Digital Twin of built assets and services.

Maturity

Fig. 3 – Development and spread of digital twins over time.

National Digital Twin

A National Digital Twin (NDT) differs from existing digital twins in scale, complexity, data diversity and stakeholder base. An NDT may be created to support security, but there is a broader motivation of the integrated functionality of the built environment and the services that rely on it, and the resulting value for UK. The NDT would become increasingly complex, diverse and interconnected as it evolves over decades. "However, the NDT would never become 'fully federated' because there would be limited value in connecting every digital twin to every other digital twin. Nor would it ever be 'completed', just as the built environment will never be completed." [1]

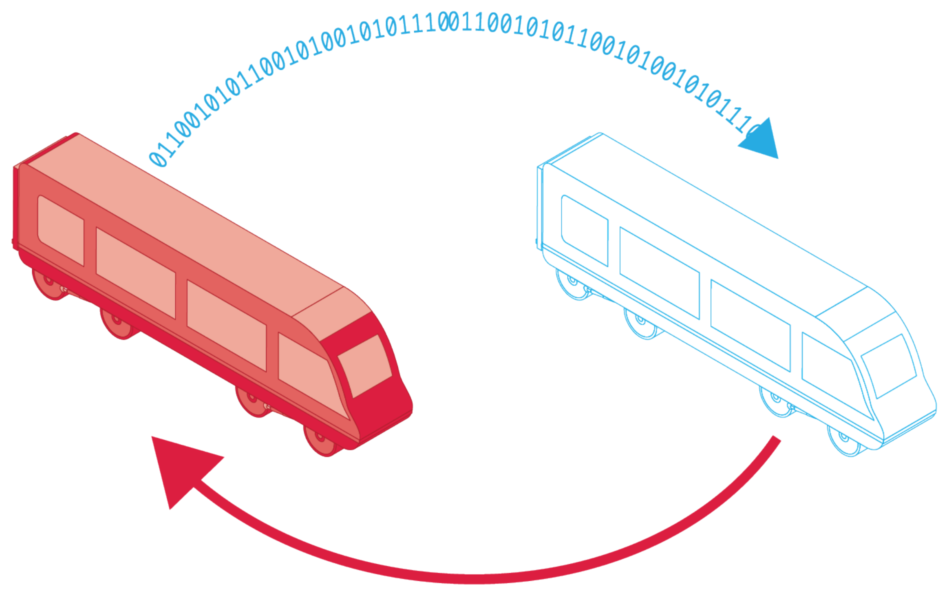
The evolution of digital twins from their current for to an NDT hinges on the ability to make them:

- Multi-scale, existing at various levels of complexity, from small components or discrete assets to whole systems.
- Multi-component, modelling distinct but interconnected assets or phenomena.
- Composite, including federated models from different sources.

This would enable queries and insights to be drawn from a rich and diverse data set, such as predicting the impact of extreme weather and global warming on buildings and the services that rely on them, or how changes to transport infrastructure might impact the ability of people with mobility issues to access GP surgeries.

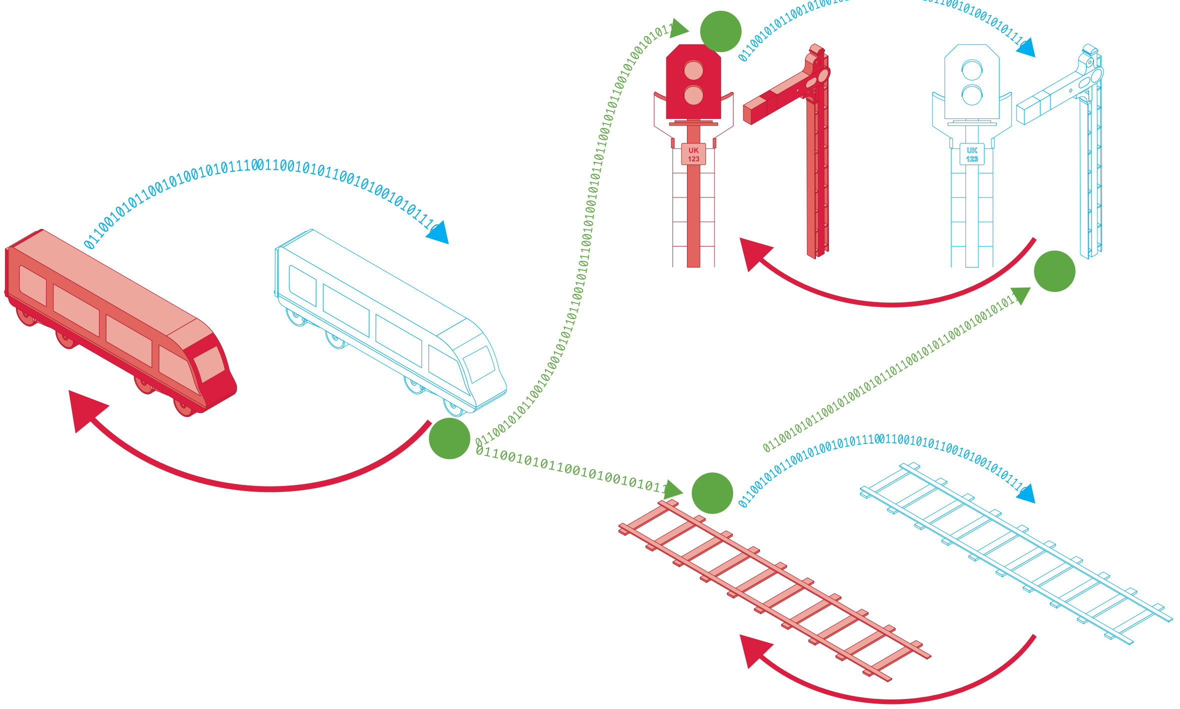
Digital twins can exist at many scales of complexity

1: Digital twin of a single asset or component



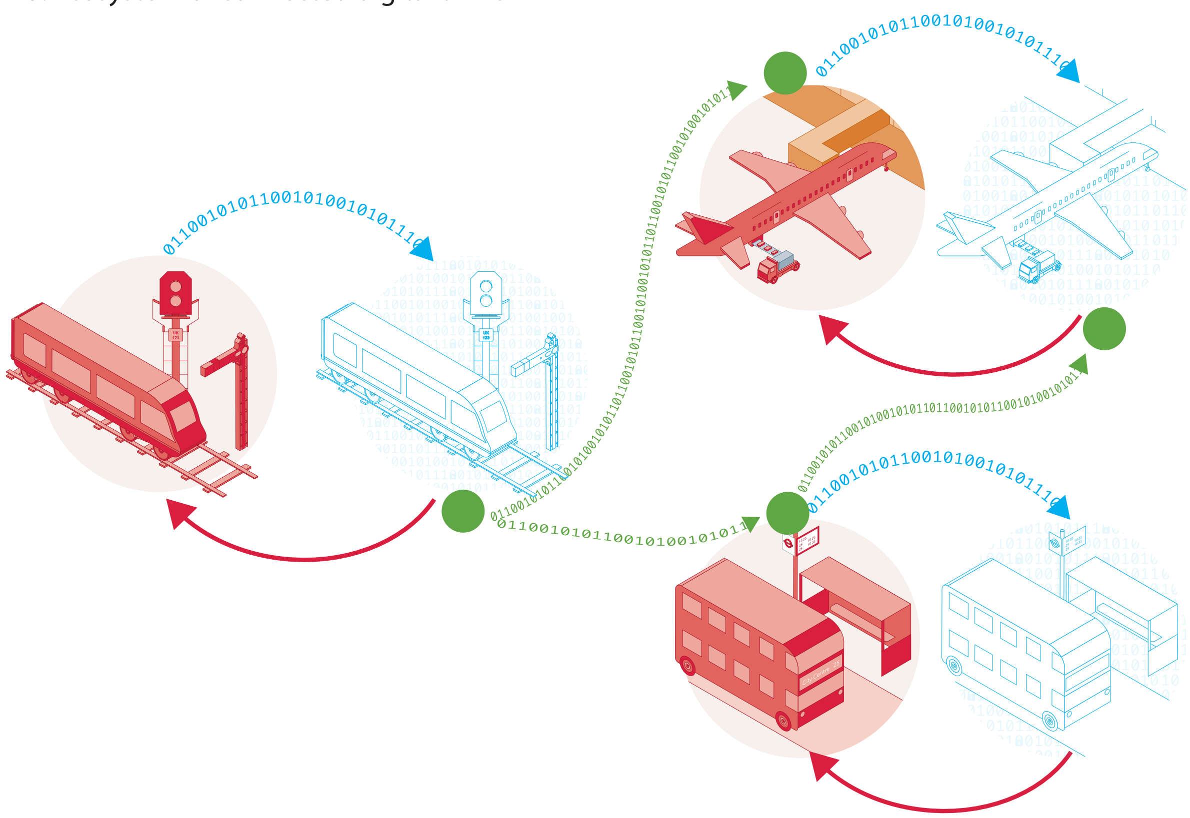
The simplest digital twins with two-way connections to assets, like a train car, are already in use, feeding the digital model with data, communicating back to the physical twin and making positive interventions.

2: Connected digital twins



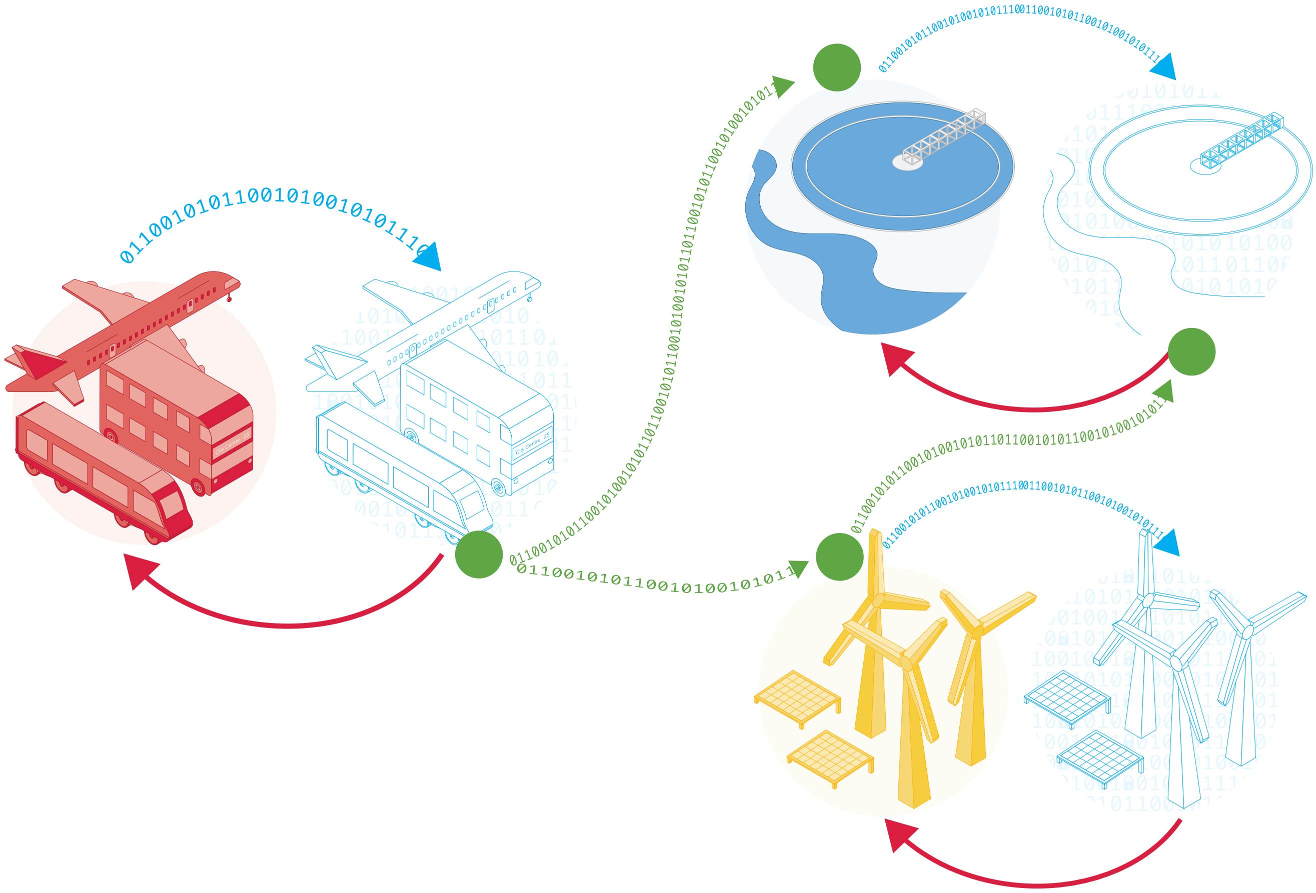
Digital twins may also be connected in order for assets to "talk to" each other within a (rail) system, like a train's digital twin sending messages to a control signal's digital twin to change the physical signal. The use of these more complex connected digital twins is less common than for stand-alone digital twins.

3: Ecosystem of connected digital twins



While there are scale and complexity barriers to overcome, ecosystems of digital twins could be created within networks of service-based assets, such as healthcare facilities or transport, in order to coordinate services across the network.

4: Ecosystem of connected digital twins



A National Digital Twin (NDT) would be an ecosystem of connected digital twins where different transport modes, utilities, services, bridges, tunnels and so on would securely "talk to" each other as needed in order to provide better services and better value.

Creating a multi-scale, multi-component, composite digital twin for the UK would require tremendous technical and semantic interoperability, managing data in ways that are fit for purpose and lead to better decisions. While different assets will be managed to achieve different outcomes, achieving insights like the ones described above require a common ground for information management. Therefore, establishing security, resilience, interoperability, public good and other fundamental requirements should happen early on in the development of digital twins.
The Gemini Principles were established in order to describe the possibilities and minimise the risk or adverse outcomes.

The Gemini Principles

Organisations currently using digital twins vary widely in their desired outcomes. Therefore, the groundwork for an NDT is to establish a set of outcome-agnostic principles that will underpin its component digital twins: the data and information ethics, interoperability and security that must be enshrined within them and what value they will create for society. While academic research on digital twins up to this point has undoubtedly advanced the surrounding technologies and information architecture, it has tended to focus on solving individual technical problems and optimising processes as its primary motivations. For a national network of digital twins to provide value on the scale set out by the National Infrastructure Commission [6], a common language and set of benchmarks are needed. These are outlined in *The Gemini Principles* as "foundational definitions and values for effective information management in the built environment." [1]

The principles laid out in Fig. 5 are necessarily broad, as an NDT will be made up of huge numbers of digital twins of individual assets at diverse scales and for diverse purposes. The Gemini Principles provide a consistent vision that will unite the component digital twins for the built assets – buildings and infrastructure – that make up digital built Britain.

Purpose: Must have clear purpose	**Public good** Must be used to deliver genuine public benefit in perpetuity	**Value creation** Must enable value creation and performance improvement	**Insight** Must provide determinable insight into the built environment
Trust: Must be trustworthy	**Security** Must enable security and be secure itself	**Openness** Must be as open as possible	**Quality** Must be built on data of an appropriate quality
Function: Must function effectively	**Federation** Must be based on a standard connected environment	**Curation** Must have clear ownership, governance and regulation	**Evolution** Must be able to adapt as technology and society evolve

Fig. 5: The Gemini Principles

Section 2

Motivations

Out of the hundreds of papers identified in the search, the majority cite some motivation for implementing digital twins, highlighting ways in which they might provide benefits or represent an opportunity. Many of the papers primarily describe technical solutions and the ensuing quantitative improvements, though some discuss more qualitative benefits. Cited motivations include:

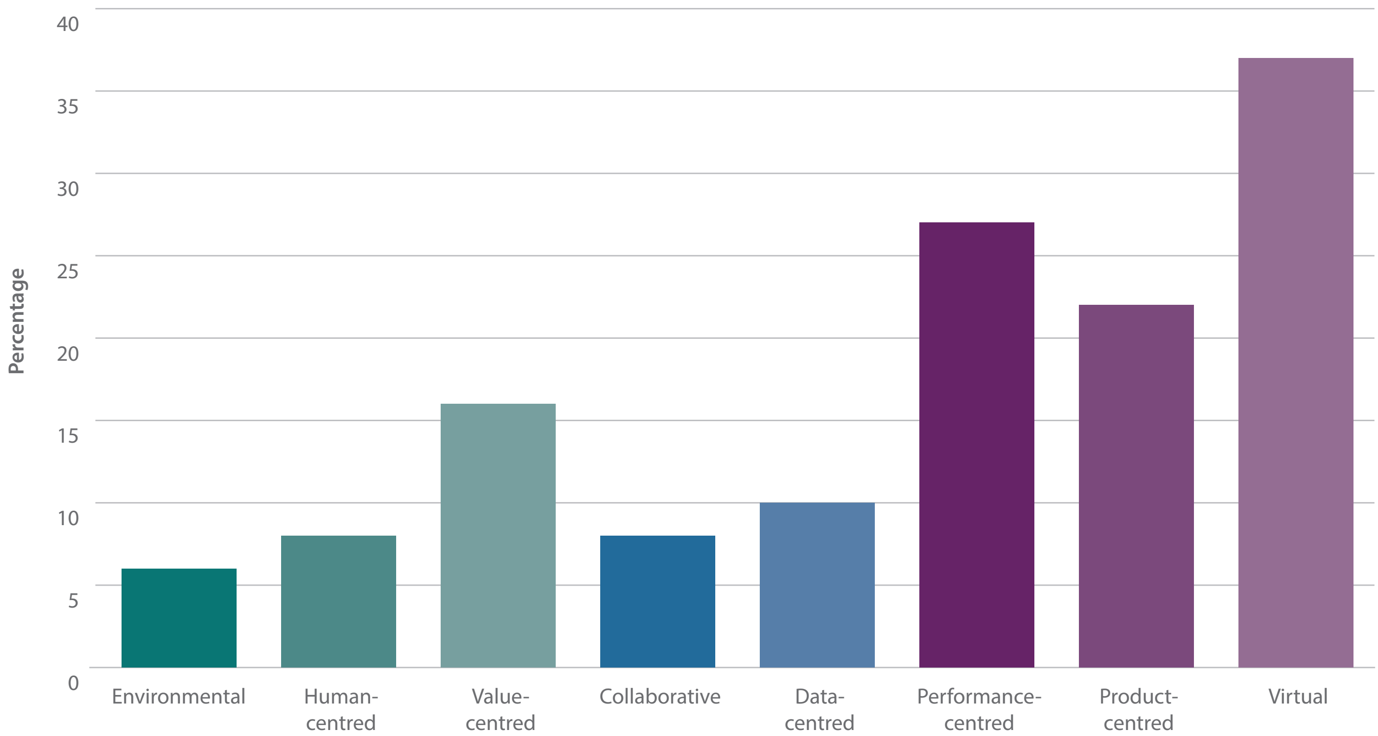
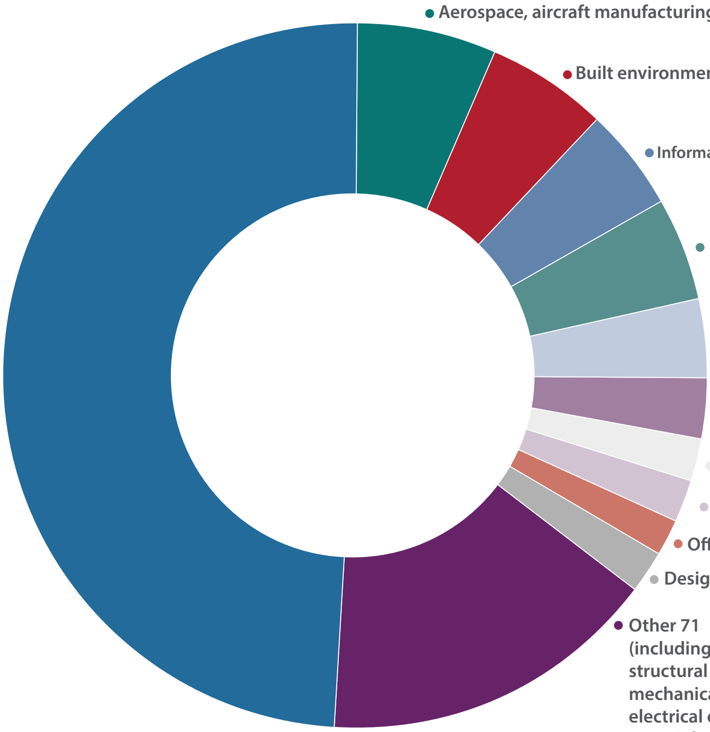


Fig 6: Breakdown of cited motivations for digital twins in the reviewed literature[4]

The method used to derive these figures is described in the Annex to this document. It was not exhaustive or systematic, so these results should be taken as indicative.

4 Motivations in the 'Virtual' category included using digital twins for design, simulation, remote control, flexible working, rapid prototyping, and other uses that had less to do with the performance of a physical asset and more with attributes unique to the virtuality of digital twins.



Articles by sector. To compare with the maturity of the sectors, see Fig. 3. The method used to derive these figures is described in the Annex to this document. It was not exhaustive or systematic, so these results should be taken as indicative.

The motivations for using digital twins tend to be similar within sectors.[5] For example, in the offshore oil and gas sector, safety, security, and predictive maintenance are the most commonly cited reasons. Manufacturing papers, on the other hand, tend to discuss virtual prototyping, efficiency and control capabilities. This reflects the ways in which digital twins fulfil different information needs in these respective sectors.

Organisational strategies, objectives and business models may be part of the motivation behind using digital twins, but these are less frequently cited. The "X-as-a-Service"[6] paradigm is present throughout several of the papers, sometimes highlighting motivations such as sharing information and customisation, for example [7]. However, a 2019 literature review found that only two of the 59 identified papers discussed how digital twins could enhance service systems. The rest of the papers focused on maintenance and production efficiency, largely ignoring the potential value that digital twins could generate in the rest of the lifecycle [8].

Through interviews with employees of various companies, [9] determined that the use of digital twins and other manufacturing execution systems had organisational drivers such as, "the need to use enterprise systems to achieve Industrial IoT ecosystem in the company", "the need to improve competitiveness through streamlining processes", and "the demand from manufacturing projects to obtain manufacturing intelligence". These organisational objectives do not seem to be principles in and of themselves, though they may be linked to deeper strategic drivers that were not explicitly cited in those interviews.

Some of the papers reviewed list a wide variety of motivating outcomes: for example, one paper discusses general performance optimisation, accuracy, energy efficiency, support for complex decisions and whole-life monitoring as motivations for using a digital twin for railway turnout systems. [10] The quantity or variety of motivations do not necessarily elevate them to the status of principles. Indeed, without a clear definition of what constitutes a principle-based digital twin it is difficult to say whether many of the written cases fit that description.

5 This is based on observation, not numerical analysis.
6 For example, Software-as-a-Service, Platform-as-a-Service and Mobility-as-a-Service.

Principles

As mentioned above, determining whether a digital twin is based on principles is difficult, even assuming there is an agreed definition of a principle in this context.[7] A few papers explicitly mention principles but do not use the word to denote foundational reasoning or purpose. For example, "Design Principles Behind the Construction of an Autonomous Laboratory-Scale Drilling Rig" focuses on what role a digital twin plays in making an offshore rig safer and more efficient. [11] Similarly, "Formation principles of digital twins of Cyber-Physical Systems in the smart factories of Industry 4.0" gives a back-to-basics overview of how to implement a CPS. [12] Neither of these papers are describing principle-based digital twins, so relying on the word "principle" as an indicator is ineffective.

Digital twins in other papers may be based on principles without this fact being made explicit. For example, while NASA's core values include safety as the "cornerstone upon which we build mission success" [13], this driver is not invoked in a paper that introduces NASA's digital twins as a means of safety assurance [14]. Other organisational strategies similarly may be the driving force behind digital twin demonstrators without this being acknowledged in the resulting academic papers. Given the technical emphasis of much of the literature, this omission may be a common occurrence.

A few papers do present principles for digital twins or systems that employ digital twins. In the context of decision support for asset management, [15] lays out the following principles:

- **Life-cycle orientation,** which leads asset managers to "incorporate long-term objectives and performances to drive decision-making"
- **System orientation,** which encourages "consideration of asset systems in their entirety"
- **Risk orientation,** which is a reminder of the risks arising from uncertainty, and the need to manage against them
- **Asset-centric orientation,** which leads to a focus on the data and information associated with an asset, in the interest of better decision-making about the life of that asset.

Each of these orientations is intended to encourage information management good practice throughout the lifecycle of assets. These relate to the "purpose" and "trust" facets of the Gemini Principles.

Due to their complexity and human-centric nature, smart cities are some of the clearest examples of principle-driven systems that involve digital twins. The Nordic MyData Model, for example, is based on three core principles: "human centric control and privacy; usable data; open business environment", [16] each of which has a parallel in the Gemini Principles. This model has been used in the development of a city operating system platform, including digital twins, for the city of Helsinki, where an emphasis on co-design, energy efficiency and better decisions are explicit and core motivations. While not provided in a framework format, this appears to be a pioneering example of the type of digital twin envisioned in *The Gemini Principles*. City Digital Twins (CDT) that give decision-makers a consistent and transparent evidence base for planning decisions are proposed elsewhere in the literature [17].

7 While *The Gemini Principles* draws an implicit distinction between outcomes and principles, a clear delineation between the two is not provided.

Digital twin frameworks

A subset of the literature presents frameworks for how digital twins might integrate with business or manufacturing processes, software and data storage configurations or other existing frameworks such as production value chains, model-based systems engineering (MBSE), or the circular economy. For example, with the motivation of sustainability, [18] provides a framework for integrating digital twins into the sustainability assessments of value chains.

One methodological framework for smart cities uses pre-existing models such as Bhutan's *Gross National Happiness* and the *Happy Cities Hexagon* (Fig. 8) as a basis for exploring how digital twins can help decision makers meet these benchmarks. [19] While these are principles underpinning a smart city rather than a digital twin, they may help unpack the "public good" facet of the Gemini Principles into a potential set of outcomes and metrics.

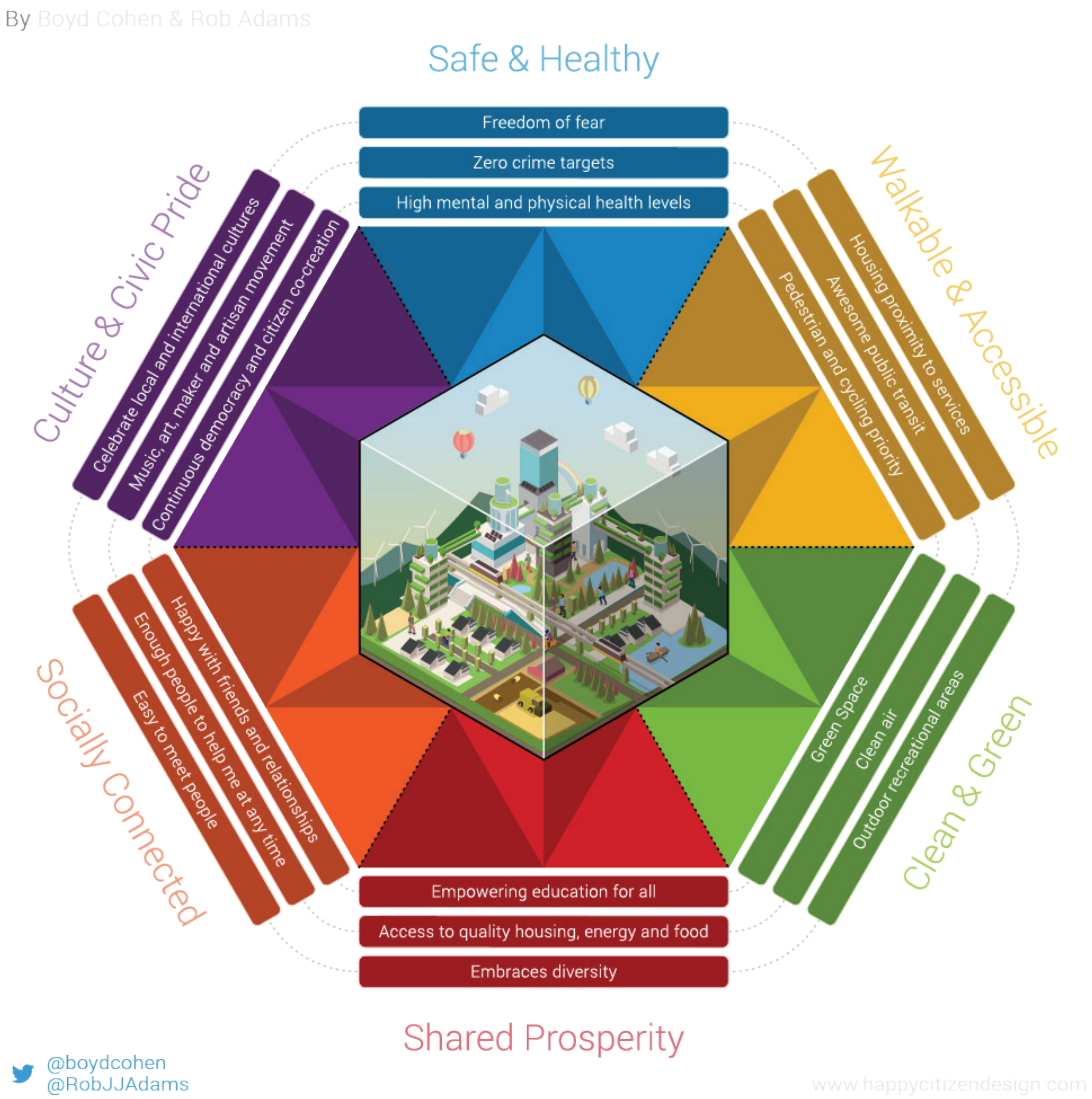


Fig. 8: The Happy Cities Hexagon by Rob Adams and Boyd Cohen.[8]

8 http://www.happycitizendesign.com/

Meanwhile, [20] features an 8-dimensional framework for digital twins, including a maturity spectrum along each of the following dimensions:

3. **Integration breadth:** how widely integrated the digital twin is with other systems, from individual assets to global interoperability.
4. **Connectivity modes:** how the data transfer takes place, from uni-directional and manual to the potential for automatic connectivity between models and assets as appropriate.
5. **Update frequency:** how often the model is updated, from weekly to real-time or event-driven.
6. **CPS intelligence:** how capable the cyber-physical system is of automating decisions and interventions from human-triggered to full-autonomy.
7. **Simulation capabilities:** how predictive it is of future states, from a static representation of the current state to the ability to look ahead and prescribe actions based on simulations.
8. **Digital model richness:** how varied and descriptive the data are, from descriptions of geometry, position and so forth to multivariate modelling of physical behaviour.
9. **Human interaction:** how users can interface with the model, from smart devices to intelligent multi-sense coupling (via augmented/virtual reality).
10. **Product life cycle:** how much of a product or asset's life cycle benefits from insights from a digital twin, from a focus on the beginning-of-life (design and build) to whole-life monitoring.

This framework provides some scaffolding for a principle-driven "living" digital twin by considering whole systems and lifecycles into which digital twins integrate, though it leaves out crucial aspects of the Gemini Principles such as public good, insight, security and curation. [20]

Other frameworks outline how digital twins fit into individual aspects of the design, build, operate and maintenance lifecycle of assets. For example, [21] provides a digital twin-driven design framework and demonstrates how it can be applied through a case study. Similarly, [22] provides a framework for application of digital twins to industrial manufacturing processes, with parallels to the build phase of the asset lifecycle, [23] outlines a planning process for realising the benefits of digitalisation, and [24] introduces a framework for defining information quality for digital twins. These frameworks focus on the "what" and "how" of digital twins, when the underlying "why" is less frequently explored.[9]

Other frameworks address user needs and information requirements for digital twins. [3] provides a useful framework for considering the types of information that are required in a digital twin, underpinned by the concepts of effectiveness, efficiency, confidentiality and integrity. This paper traces these information needs through to the structure and management of a digital twin. Another paper provides a motivating framework for digital services, exploring how the customer experience interacts with the physical, digital and social realms. It considers how a better understanding of these interactions will help inform insights generated by an NDT [25]. Meanwhile, [26] provides a high-level look at reverse engineering digital model specifications from stakeholder needs and [27] provides a strategic roadmap to Industry 4.0, in which digital twins play a crucial role for simulation and decision-making. Each of these frameworks touches on ways in which principles might be applied in the context of existing or future information needs.

9 It should be noted that [23] assesses the literature differently, saying that the "why" of BIM and other digital technologies are well covered, and it is the question of "how" that has limited coverage. However, this may fit better under a discussion of remaining barriers. The literature often discusses common barriers that have yet to be solved, which could be classified as limited coverage of "how". Some of these barriers are highlighted in Section 3.

Comparative National Strategies

Given their scale and positioning, a useful parallel to the Gemini Principles may be in digital twins and other digitalisation projects that are aligned with a national strategy. There are several national industrial strategies focused on digitalisation, such as *Plattform Industrie* 4.0 (Germany), *Industria 4.0 National Plan* (Italy) and *Made in China 2025*. Like the smaller scale studies mentioned above, these strategies are primarily focused on industrial improvements, such as efficiency, optimisation and whole-life monitoring. However, they encompass a much larger scale in an attempt to organise otherwise disparate activities around common aims. "After analyzing those national strategies carefully, it is found that although the background is different, there exists one common goal, namely to realize the interconnection and interoperability between physical world and cyber space of manufacturing so as to achieve smart manufacturing." [28] This goal is most closely related to the "function" facet of the Gemini Principles.

Other national strategies outline a more comprehensive vision of digital transformation. Japan's *Society 5.0* strategy, for example, seeks to meet the challenges of an aging population and shrinking workforce by digitalising healthcare, automating various sectors including mobility services and leading on financial technologies. [29] The UK Industrial and Digital Strategies are similar efforts in this country [12] [13]. These strategies tend to be driven by broad principles rather than narrowly defined outcomes. As an exception to this, the *Scottish Digital Strategy* outlines a vision of how digitalisation could help the government serve its citizens in a variety of ways, including by stimulating innovation, delivering public services that meet user needs, sharing data, tackling the digital gender gap, and providing opportunities to everyone. [32] These outcomes provide greater elaboration on "public good", without being tied to specific metrics.

At the heart of these national strategies is an aim to better manage and use data and information in order to make better decisions at all scales. However, the principles they represent are implicit rather than explicit. The parallel to an NDT is clear, so these policies and their roll-out present useful learning opportunities throughout the development of principle-based digital twins in the UK.

Section 3

Barriers and challenges

Given the variety of contexts in which digital twins are deployed throughout the literature, the stated barriers may depend on the intended use. However, there are many common barriers and challenges remaining in order to implement digital twins at any scale. Many of these are shared with digital processes or technologies such as BIM [35], [36]. They can be loosely divided into technological and non-technological, but these categories can intersect in complex ways and both need to be addressed in conjunction with one another.

	Digital twins in logistics [37]	Digital twin in manufacturing [38]	Digital twin of a building [34]	Digital twins for sustainability [18]
Cost	✓	✓		
Interoperability / data integration	✓	✓	✓	✓
Cyber security	✓	✓		✓
Precision in the face of complexity / heterogeneity	✓	✓	✓	✓
Data quality	✓		✓	✓
Real-time synchronisation			✓	✓
Skills and education	✓	✓		
IP protection	✓			
Achieving business value		✓		
Change management		✓		

Table 1: Examples of common barriers and challenges to digital twins from a random sample of the literature.

For example, Intellectual Property (IP) management is frequently cited as a technical barrier but has social and organisational dimensions as well. The solutions to enable access to data while protecting ownership and rights, therefore, may need to be a mix. Of the sectors leading in digital twin development, aerospace and defense would seem to be the most likely to be leading on navigating data ownership and access issues since the organisations that operate aircraft are separate from the ones that design and build them. According to [39], data sharing is technologically possible for advanced aircraft like those used by the United States Air Force, but data sharing is not written into the contracts, meaning that operators do not have access to the digital twin data. Overcoming the data sharing barrier is a matter of finding the right organisational solutions. This situation is echoed throughout other sectors. According to a survey of smart city initiatives, IP was a very common barrier to implementation. "Collaboration agreements were found to be the most common way of formalising these arrangements between multiple partners. Projects unanimously reported that these agreements took considerably longer than expected to put in place, with legal negotiations typically lasting between six months and one year." [40] A key piece of good practice mentioned in [41] is for CIOs to have a strategy around identifying and protecting priority data, transparently reporting about data security and understanding and documenting the value of IP created by the organisation.

Data quality is one of the most universally cited barriers throughout digital transformation literature, and effective management of data quality would have a tremendous effect on the ability to scale up these technologies. While data description [3] and automated monitoring are essential components in ensuring data quality, this is another intersectional challenge. Individuals and organisations need to be invested in processes and practices that contribute to data quality, as well as investing in automated methods.

Security is also a key priority, since "[digital twins] are exposed to security threats from both cyber and physical spaces" [4]. Like data quality, cyber security will have technological solutions but also requires culture and processes that support it. It is likely that these will be developed at the national level, for example by the Centre for the Protection of National Infrastructure (CPNI)[10], supported by academic and industrial research.

Creating smooth data and information handover processes is a challenge for many sectors that are exploring digital twins face. For example, in the offshore sector, "Handover documentation has only been fully specified in contracts for project started within the last decade. Even so, a recent study found that only 32% of projects received the information they requested." [42] This is an issue of organisational processes as much as a technological issue. Other intersectional challenges mentioned in the literature include the need to scale them up, whether that is done in order to better understand the role of digital twins in untangling the complexity of systems of systems [43], or to scale up monitoring and data processing to larger buildings or campuses [44]. Scaling up digital twins requires advances in technology as well as engagement with a wider pool of stakeholders. Coordinated technical and social solutions to common barriers need to be developed in order to develop principle-based digital twins.

That being said, there are barriers with primarily technological solutions. For example, [45] point out that new software tools are needed to integrate digital twins into existing digital processes. The Cambridge-based digital twin case study concludes that much more work is needed on the software supporting the data/model integration layer, particularly on AI-supported data analysis and decision-making in order to make dynamic digital twins work [34], while [4] argues that "the fusion algorithms should be improved regarding robustness and applicability". Other papers conclude that current software is not ready for the complexity and volume of data needed to support digital twins [46], and that data processing power needs to be increased [4]. These technological barriers have received much attention in the academic literature, and they benefit from an active body of research.

However, human factors are equally important for developing digital twins. Stakeholders need to buy in to and understand the value of digital twins in order to invest in and plan for their use. A future research agenda emerging from the Cambridge study is to explore methods of "effective and efficient communication and interaction between people and DTs" [34], while [40] points out that better access to and engagement with digital twins is needed to overcome many of the social and cultural barriers, such as fear of surveillance, lack of trust and the usual change management issues that come along with digitalisation. The same paper also argues that the evaluative frameworks for large projects like smart cities need to be improved, as the existing frameworks used on major infrastructure projects, "are not deemed fit for purpose to assess impact and success for innovative demonstrators". Assessing the impact of digital twins and related technologies on organisations and societies requires new tools and ways of measuring that goes beyond physical performance. The way we present, communicate and evaluate digital twin projects will go a long way to facilitating their development.

Finally, [38] proposes a broad set of research questions to address the barriers and gaps, and there are many other recommendations for future research throughout the literature, but as yet there

10 https://www.cpni.gov.uk/

is limited discussion in the literature of a unified research agenda for scaling up current digital twin technology to the scope and complexity of a National Digital Twin. The Digital Framework Task Group (DFTG) Roadmap addresses this need and lays out a plan for technological and organisational development toward their desired future state:

> *"Effective information management across the built environment, enabling better decisions, leading to financial savings, improved performance and service, and better outcomes for business and society per whole-life pound." [47]*

Conclusion

While a scoping review can give an indication of the academic landscape, it cannot provide definitive conclusions. That said, based on a sample of the extant literature, this review can conclude that the nearest equivalents to Gemini Principle-based digital twins exist in the built environment sector underlying smart city initiatives. National and organisational strategies may also underpin digital twins, but these are less frequently cited, though observing the impact of these strategies may hold lessons for the development of an NDT. All digital twins are motivated by outcomes, but whether those motivations are based in principles cannot be concluded in this review.

The Gemini Principles provide high-level guidelines for digital twins that will underpin an NDT that contributes to the performance of the nation's built environment and to public good. Existing digital twins are most often motivated by optimising or controlling specific processes, meaning that there is a gap in practice and assessment centred on the alignment of digital twins with principles. While some useful frameworks and examples are highlighted here, principle-based digital twins are underrepresented in the literature. Future literature studies could provide more granular detail, aligning sector competency to different technical and managerial aspects of digital twins, and more closely exploring the relationship of digital twins to outcomes and principles.

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Annex 1 - Methods

The literature search and scoping review underlying this paper took place over a short period of time, which prohibited an in-depth review the vast body of work. The methods are described here in order to demonstrate the basis of the claims made in the review. There is scope for much more in-depth literature reviews to explore this topic, including how the existing literature aligns with *The Gemini Principles* and an evaluation of past case studies involving digital twins.

Search strategy

The search strategy was based on the following research questions:

- Has anyone previously proposed a set of principles for digital twins like *The Gemini Principles*?
- Has anyone built a digital twin based on those principles?
- What types of motivations are used for creating digital twins?

The nature of the questions and the time allowed meant that a fairly broad but shallow search was needed, to get a sense of the breadth of the literature without delving into the depths of individual articles. This meant using the titles and abstracts as indicators, and then skimming the articles where these were inconclusive and electronic access was available. One caveat to this approach is that abstracts vary in their usefulness for understanding the full contents of an article and it is possible that relevant articles were missed. There was an attempt to further refine the results and target searches to find relevant material to answer the research questions, as shown in the next section.

Search history

Digital twin			
Date and database	**Search term**	**Number of results**	**Observations**
19/08/19 Construction Information Service	“digital twin”	4	All superficial mentions of the technology
27/08/19 Scopus	"digital twin"	822	Mostly manufacturing related, some offshore and aircraft manufacturing, a few medical, built asset and logistics.
03/09/19 Web of Science	"digital twin"	398	High relevance, large overlap with Scopus.[11]
23/10/19 OpenAIRE	“digital twin”	200	High relevance, some overlap with Scopus. Less metadata about affiliation, country, etc.
28/08/19 Scopus	"digital twin" AND "case study" OR demonstrator	76	High relevance
03/09/19 Scopus	"digital twin" AND operationali*	2	Low relevance
18/09/19 Scopus	"digital twin" AND framework	153	Low relevance. “Framework” is used in many different ways.
18/09/19 Scopus	“digital twin” AND objective	35	Low relevance. Tends to refer to quite specific objectives.
18/09/19 Scopus	“digital twin” AND “use case”	38	Low relevance. Used interchangeably with “case study”, not as a framework.
18/09/19 Scopus	"digital twin" AND "decision support" OR "decision*making"	19	Low relevance. Decision support as a motivation, not as a framework.
19/09/19 Scopus	"digital twin" AND "whole*life" AND framework	0	
30/09/19 Scopus	“digital twin” AND barriers	6	Low relevance
30/09/19 Scopus	“digital twin” AND literature W/3 review	12	Mixed relevance
03/09/19 OnePetro	“digital twin”	13	High relevance

11 The results break down as follows: Web of Science only = 88; Scopus only = 448; both = 312. This is why subsequent searches focused more on Scopus, but results from both databases were assessed.

Digital twin			
17/09/19 ProQuest	"digital twin"	52	Low relevance – all J.P. Morgan research reports with minimal coverage of digital twins
17/09/19 EMIS Reports	"digital twin"	88	Mixed relevance. Many pseudo advertisements and financial forecasts.
03/09/19 NASA technical reports	"digital twin"	44	4 relevant

Gemini Principles			
Database and date	**Search term**	**Number of results**	**Observations**
27/08/19 Scopus	"digital twin" AND principles	29	Mixed relevance
27/08/19 Scopus	"digital twin" AND "public good"	0	
27/08/19 Scopus	"digital twin" AND "value creation"	4	High relevance
27/08/19 Scopus	"digital twin" AND "insight"	34	Mixed relevance / mixed use of "insight"
27/08/19 Scopus	"digital twin" AND motivat*	11	Low relevance
27/08/19 Scopus	"digital twin" AND secur*	38	High relevance
27/08/19 Scopus	"digital twin" AND open	49	Mixed relevance / mixed use of "open"
27/08/19 Scopus	"digital twin" AND data W/5 quality	15	Mixed relevance / mixed use of "quality"
27/08/19 Scopus	"digital twin" AND trust	4	Mixed relevance
27/08/19 Scopus	"digital twin" AND federat*	23	Low relevance / more technical use of "federated" than in Gemini Principles
27/08/19 Scopus	"digital twin" AND curat*	2	Mixed relevance
27/08/19 Scopus	"digital twin" AND evolv* OR evolution	55	Low relevance / too broad a term
27/08/19 Scopus	"digital twin" AND function	47	Low relevance/ too broad a term

Synonyms for digital twin[12]			
Database and date	**Search term**	**Number of results**	**Observations**
28/08/19 Scopus	"asset administration shell"	23	10 also mention "digital twin" / mixed relevance
28/08/19 Scopus	"cohesive zone model*"	3,418	Not relevant
28/08/19 Scopus	"cyber*physical convergence"	2	Not relevant
28/08/19 Scopus	"cyber*physical system"	493	9 also mention "digital twin" / mixed relevance
28/08/19 Scopus	"digital counterpart"	361	11 also mention "digital twin" / mixed relevance. The results go further back in time and are much more up and down by year.
28/08/19 Scopus	"digital model"	8,949	48 also mention "digital twin". Low relevance, too many to be useful. Very wide spread of disciplines.
28/08/19 Scopus	"digital representation"	1,644	22 also mention "digital twin" / moderate difference. Upward trend of use. More use in non-technical disciplines, including built heritage.
28/08/19 Scopus	"digital shadow"	69	12 also mention "digital twin". Manufacturing and management focus, some on digital shadows of people. Slight upward trajectory of use.
28/08/19 Scopus	"embedded system"	84,535	170 also mention "digital twin" / low relevance. Too many to be useful, computer science is the most prevalent discipline.
28/08/19 Scopus	"product avatar"	12	2 also mention "digital twin".
28/08/19 Scopus	"virtual counterpart"	176	3 also mention "digital twin" / mixed relevance.
28/08/19 Scopus	"virtual factory"	431	9 also mention "digital twin" / mixed relevance
28/08/19 Scopus	"virtual twin"	63	18 also mention "digital twin" / high relevance. Results go back further than "digital twin", with a peak in 2018.

12 These synonyms were based on an initial search of "digital twin" on Scopus and Web of Science to identify keywords associated with those search results.

Patents landscape			
Database and date	**Search term**	**Number of results**	**Observations**
27/08/19 Lens	"digital twin"	638	Of which 9% are patents that have been granted. High relevance.
27/08/19 Espacenet	“digital twin”	103	High relevance
17/09/19 Patentscope	“digital twin”	116	High relevance

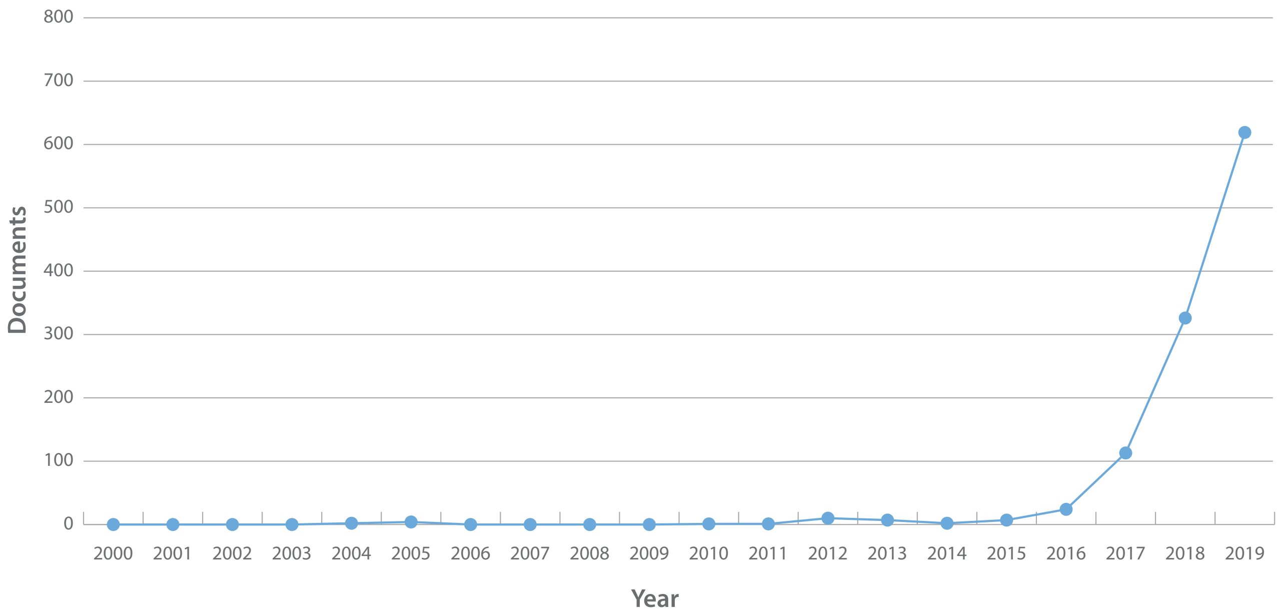
Bibliometrics

Scopus search on 16/12/19: TITLE-ABS-KEY "digital twin" = 1,162

The following are the results of searching Scopus for articles mentioning the phrase "digital twin" in the title, abstract or keywords. This is not a perfect way of retrieving articles that are about digital twins because they may merely be mentioned in the abstract as an example of IoT technology, for instance, while the article itself discusses a different topic. However, these results provide some interesting insights into how the academic landscape is developing with regards to digital twins. The analytics provided are built into Scopus, and no separate numerical analysis was conducted.

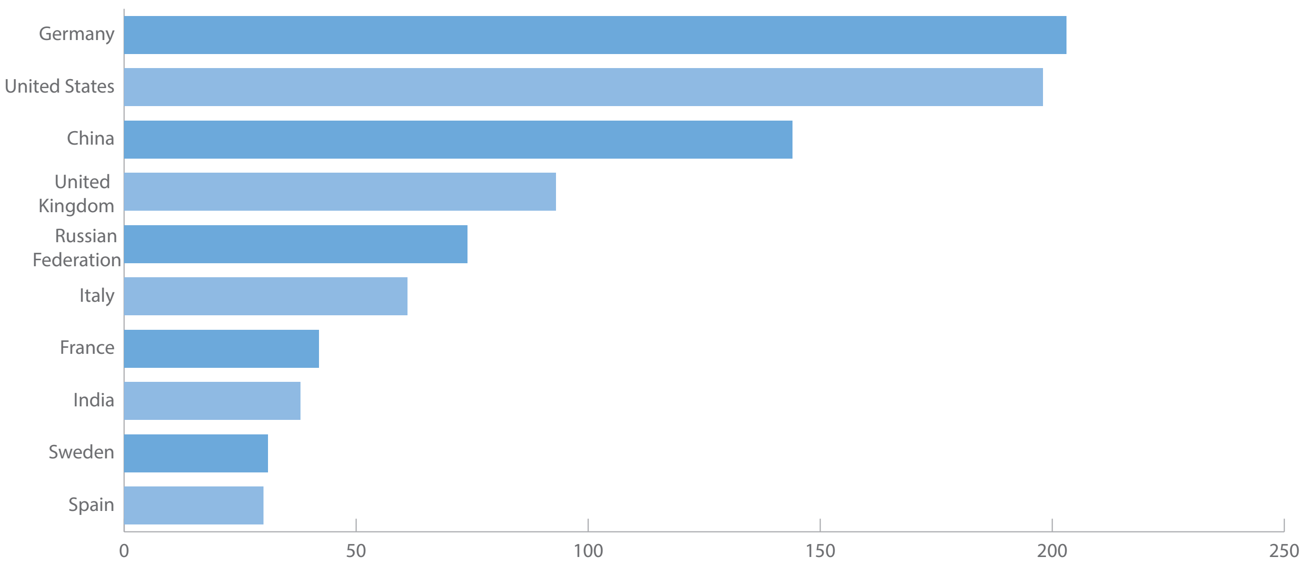
Documents by year

This graph shows the sudden increase in articles discussing or mentioning digital twins beginning in 2016. While not all of these articles are about digital twins, it shows that the term has captured attention in academic research and it is at least frequently leveraged in titles, abstracts or keywords.



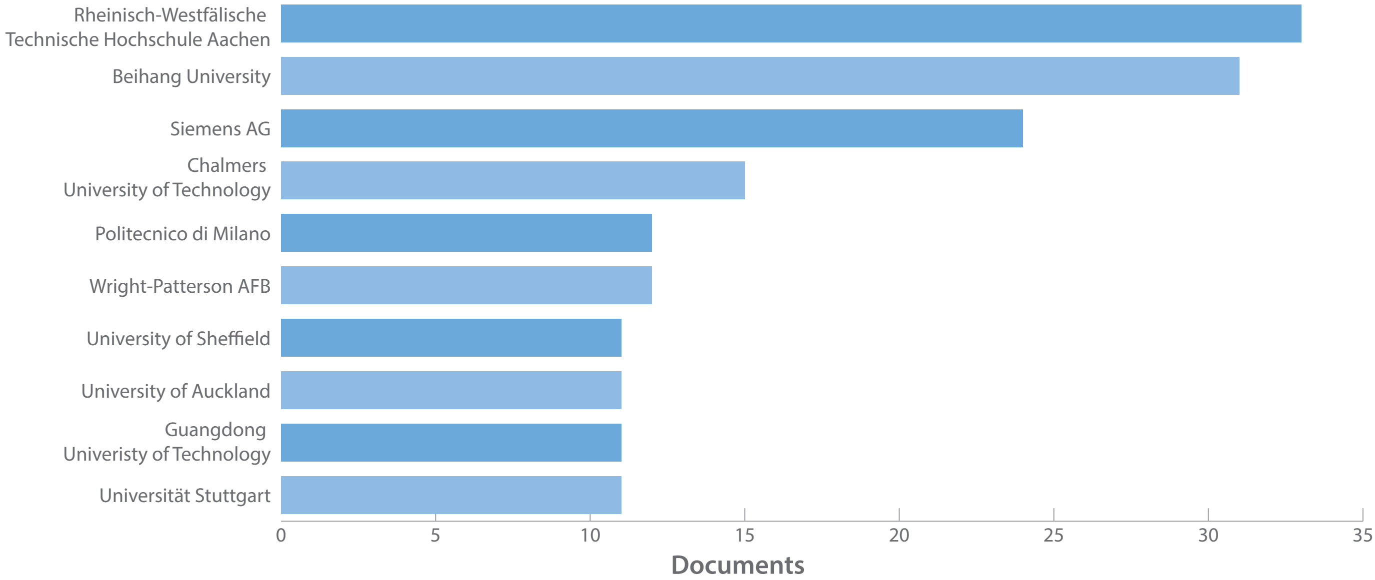
Documents by country

These results show the most prolific countries publishing on digital twins. On a previous search, the top two countries were reversed, showing that Germany and the United States have equally active research communities and both are global leaders. The graph shows only the top ten countries, while there is a long tail of countries with fewer articles mentioning digital twins.



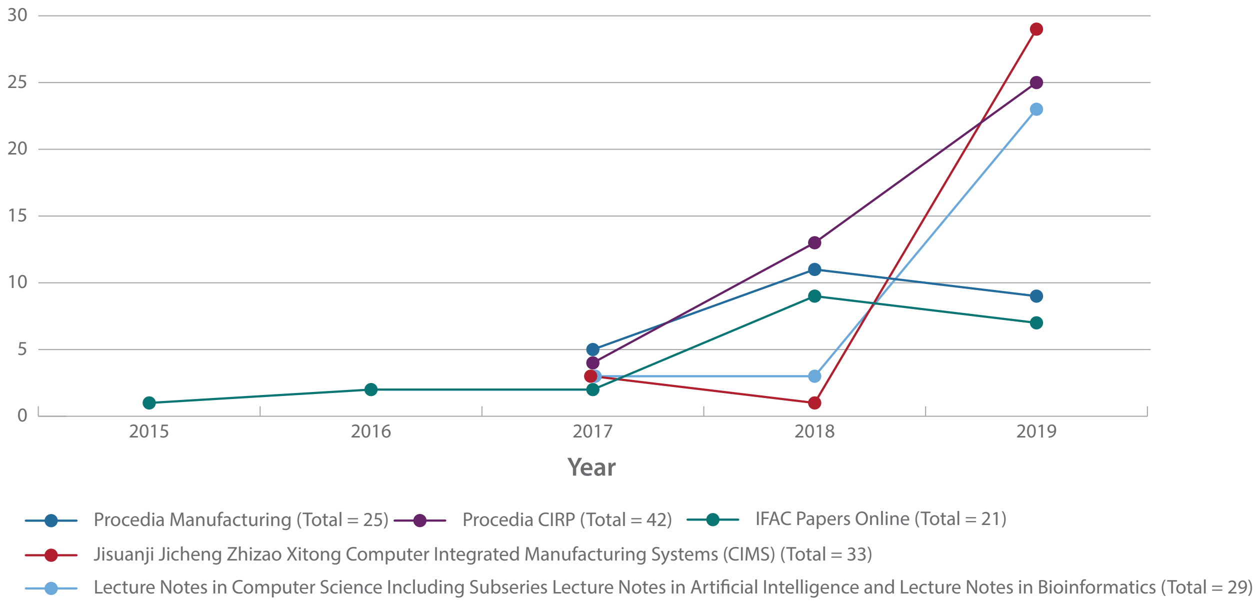
By affiliation

These results show the most prolific institutions publishing articles mentioning digital twins. Note that there are industry leaders as well as academic institutions in the top ten results, Siemens being one of the leading patent holders for digital twins.



By source

This shows which journals publish about digital twins most frequently. The literature is widely distributed, with 65 sources publishing more than one article mentioning digital twins. The vast majority of sources have only one article in 2019 mentioning digital twins (350 sources). This long tail of sources is unlikely to be worth tracking, and the top few sources shown below are more likely to have relevant and up to date articles about digital twins.



These results mirror other databases. They show how new the topic is and where the bulk of the relevant academic community is based. No one yet has done a detailed bibliometric review of this field to identify the leading research networks and the most influential authors and papers. That type of review has limited benefit for identifying gaps in the literature or most authoritative information as it is only as good as the data on which it is based, but can give more texture to the understanding of the academic landscape in a particular area. For example, an analysis identifying clusters of authors or papers about digital twins could identify where there are ideological silos that could be usefully bridged.

Digital twins and security by country

A further inquiry was made into regional differences between the UK and the rest of the world with regards to security. The following Scopus search was used:

Scopus 23/10/19: "digital twin" AND secur* = 44

Of these, only two have a listed affiliation with the United Kingdom (4.5%), and 42 are from other countries. The UK is tied for 6th by number of articles listing these search terms in their title, abstract or keywords. A follow-up search for "data" AND "security" showed a slightly higher representation from the UK, 5.8% of the total, and placing 4th behind the USA, China and India.

This method will not pick up published papers that mention security in the full text. To get a full picture of how security is discussed in the literature and where, a review of the full text of more of the literature would be needed, e.g. by using text mining techniques or a human reviewer with more time to read full articles. Another caveat with this approach is that the metrics for grey or non-academic literature require much more legwork to acquire and therefore it may be that the grey literature would paint a different picture, but this was not achievable in the timeframe.

Categorising the results

The articles retrieved by the Scopus and Web of Science searches listed in the search history were assessed for relevance to the research questions. Then they were categorised according to the motivations and purposes given for employing digital twins based on reading titles and abstracts, and skim reading articles to which access was available.

These results are based on around half of the results from Web of Science and Scopus due to time. For this exercise, 471 abstracts out of 882 were consulted, and full text skimmed where the abstracts were inconclusive, so these results should be taken as indicative rather than exhaustive.

Purpose

- Environmental: Sustainability; energy efficiency; material efficiency (6%, n=28)
- Human-centred: Employee and public safety; ergonomics; interface design; emergency response (8%, n=38)
- Value-centred: Decision support; analytics; insights; public good (16%, n=76)

Trust

- Collaborative: Openness; transparency; co-design (8%, n=37)
- Data-centred: Security; data quality; consistency; interoperability (10%, n=46)

Function

- Performance-centred: Efficiency; productivity; precision; cost-effectiveness; product quality (27%, n=128)
- Product-centred: Asset health monitoring; whole life performance; fault detection; minimising downtime (22%, n=103)
- Virtual: Rapid prototyping; virtual commissioning; control; remote working; flexibility (37%, n=174)

Inconclusive

- Not stated; no access; not relevant (18%, n=84)

In the short time frame of the review, these categories were not refined or tested. In retrospect, the "virtual" category would have been more useful if it had been split into a category for simulation, design and other fully virtual uses, and a separate category for control and flexibility relating to an existing physical twin. Future research could categorise the articles differently, spend more time with each article and align them more closely to the Gemini Principles.

Annex 2 - State of the Art

The state of the art of digital twins is well summarised by [4], which concludes that the most mature application is product health management. Indeed, construction lags behind many other sectors in its adoption of digital twins. Deloitte rank the sectors from highest to lowest digital maturity as follows:

11. Aerospace
12. Nuclear
13. Infrastructure
14. Oil and gas
15. Mining
16. Construction

They also note that all of these sectors lag behind IT, media and finance in the maturity of their digital processes [33], though this ranking does not refer to digital twins specifically.

There is some nuance to this, as each sector – and each organisation within that sector – uses digital technology to create value in different areas, with some specialising in data capture, some specialising in structural health monitoring and others specialising in simulation. These provide a range of examples of how digital twins can be implemented, integrated and governed.

However, in terms of technical capabilities, the expertise is more concentrated. The early adopters of digital twins have been able to leverage their expertise to provide software and platforms to a variety of sectors, whether they are the major technology firms or small start-ups. General Electric, for example, sells their Digital Twin Framework (GENIX), which then uses customer data to generate insights.[13] However, the uptake of bespoke or platform digital twins in industry is unclear as there is limited reporting on it in open access literature.

In the world of digital twins for the built environment, a Cambridge-based case study represents the state of the art.[14] The initial study is a digital twin of the Institute for Manufacturing (IfM) building, with plans to expand to the West Cambridge campus, and eventually the whole city. A summary of a recent write up and literature review [34], which focuses on data management in digital twins, is provided here.

13 https://www.ge.com/research/project/digital-twin-framework
14 There are other digital twins for built assets, but this study maps out the frontier, at least among academic-led projects.

The IfM case study takes a five-layer system approach to creating a digital twin of the building:

- Data acquisition layer
- Transmission layer
- Digital modelling and data complementary layer
- Data/model integration layer
- Application layer

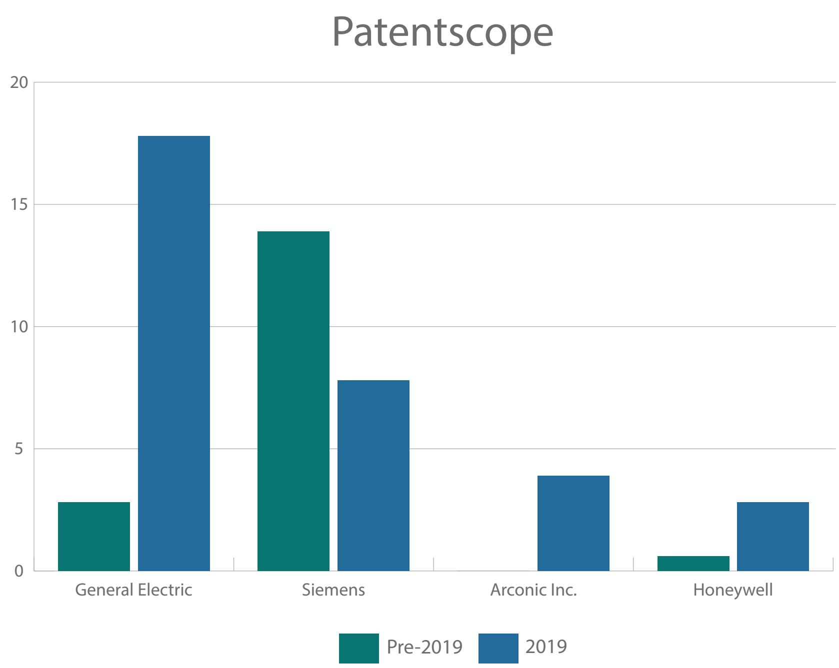
The innovations in this case were the selection of sensors for the data acquisition layer and new data processing techniques at the data/model integration layer. The sensor network was selected for its computational efficiency and its scalability, as the intention is for this digital twin to integrate with site- and city-wide digital twins in further iterations.

Otherwise, the review points to a mature body of existing technology at the early layers. Sensor technology, wireless networks and techniques for digital modelling are readily available, though they need to be improved, tested at larger scales and integrated into existing processes. There are also technical solutions for integrating heterogenous data from a variety of sources, though finding solutions for the challenges of deduplication, differentiation and standardisation are priorities[15]. The main novel applications for this case were for as-is asset management monitoring and future performance prediction, but each of these innovations needs to be tested at larger scales.

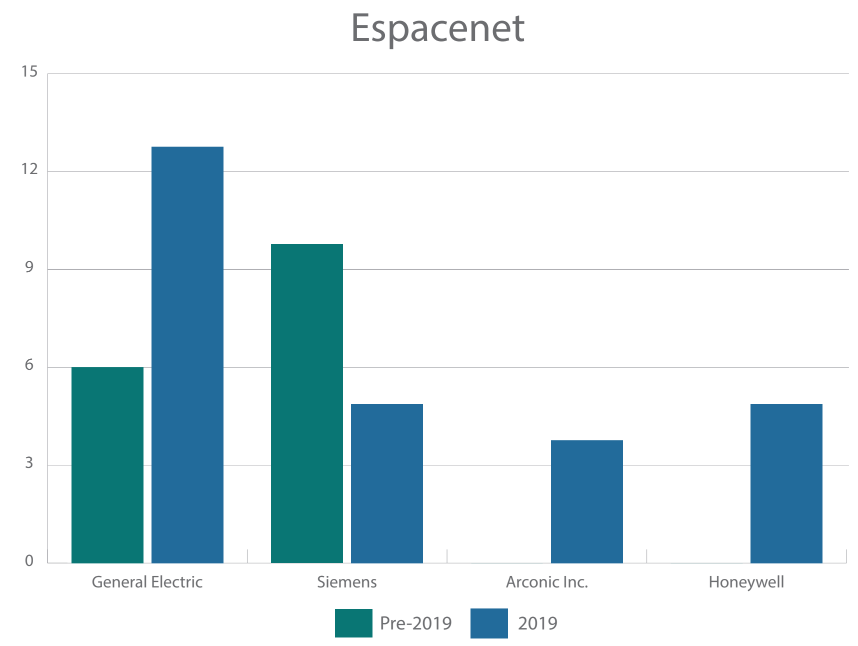
Patents and standards

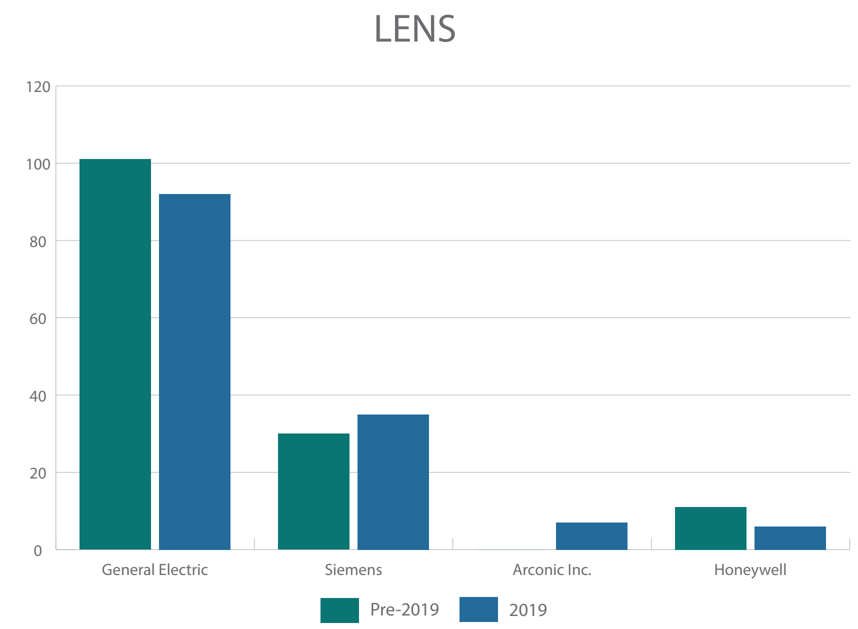
Patents provide some sense of who is leading the state of the art in technological innovations. However, this is not a perfect indicator, as patent publishing trends differ between organisations, with a bias toward larger organisations that can allocate staff time to the preparation of patents. General Electric and Siemens, for example, are two of the largest patent producers for digital twins (see below), both over time and for the current year. However, there is room for newcomers; Arconic Inc. has only had patents published in the last year – with a focus on digital models for additive manufacturing – and already they are one of the leading patent producers. This does not necessarily equate to leading the industry, but it does point to an intensive innovation focus among those organisations.

Top patent applicants:



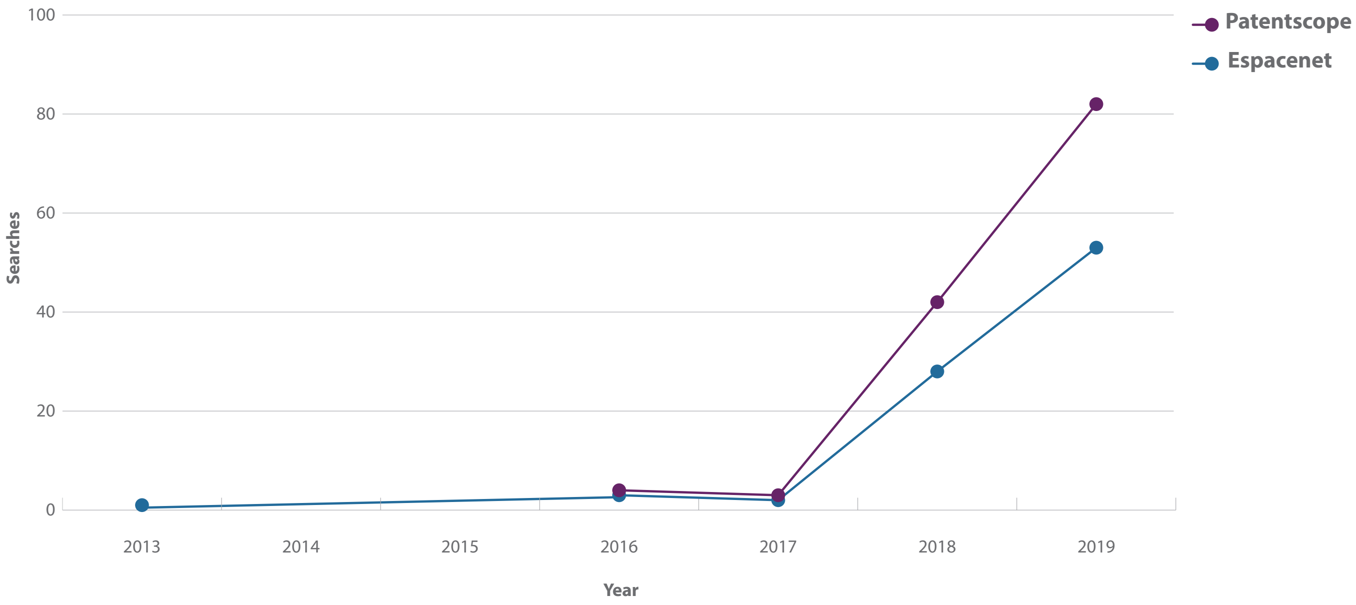
15 Master Data Management (MDM) is a key concept here, dealing with "how to reach a consensus on the definitions of data and manage its changes and evolution over time." [34]





The top 4 most prevalent patent holders across the three databases. Others, such as IBM and Bentley, were not consistently prevalent on all of them even if they ranked higher on an individual database. The discrepancies in numbers are due to the individual cataloguing practices and scope of the databases. Based on searches of Patentscope, Espacenet and LENS on 23/10/19.

Patent applications mentioning digital twins, like the academic literature, have skyrocketed since 2016 with very little activity prior to that (see below). This demonstrates that while the concept of digital twins has existed for longer, industry was not far in advance of academia in its research and development of digital twins.



Number of digital twin patents by publication date. Based on searches of Patentscope and Espacenet on 23/10/19.

The patents landscape does not give a sense of purpose or principles, focusing instead on technical innovations. Standards on the other hand, while often technical in focus, will sometimes outline the social or organisational structures into which technology fits. Searching British Standards Online does not yield any standards specifically about digital twins, but standards on smart cities provide a useful roadmap for principle-based digital twins.

For example, BS ISO/IEC 30182:2017 presents a framework for the types of insights that data, whether open or protected, should support within smart cities:

- **Operational:** "which examines characteristics of things such as buildings, communities and organizations, using data to evidence and improve their value for the city";
- **Critical:** "the real-time monitoring of incidents and current cases, involving all relevant organizations from across sectors, who work together to achieve the desired outcome or response";
- **Analytic:** "the exploration of the data ecosystem to determine patterns, correlations and predictions. This allows the development or innovation of systems or services, impact assessment of proposed changes to systems or services, or the evidencing of challenges and opportunities for the city";
- **Strategic:** "an overarching approach that examines outcomes related to strategic objectives, decisions and plans".

Like the Gemini Principles, this list of insights is outcome agnostic. Smart city frameworks, like an NDT, need to be applied in a range of contexts where objectives may differ, so an underlying set of principles for how data is used becomes essential for interoperable, secure and beneficial management of digital information at scale.

BS ISO 37122:2019 points to the following purposes that smart cities should serve:

- "Respond to challenges such as climate change, rapid population growth, and political and economic instability by fundamentally improving how they engage society;
- Apply collaborative leadership methods, work across disciplines and city systems;
- Use data and information and modern technologies to deliver better services and quality of life to those in the city (residents, business, visitors);
- Provide a better life environment where smart policies, practices and technology are put to the service of citizens;
- Achieve their sustainability and environmental goals in a more innovative way;
- Identify the need for and benefits of smart infrastructure;
- Facilitate innovation and growth;
- Build a dynamic and innovative economy ready for the challenges of tomorrow."

Other standards specify principles such as security-mindedness (PAS 185:2017) and interoperability (PAS 183:2017) for smart cities, as well as indicators of smartness (BS ISO/IEC 30146:2019).

The current state of the standards landscape reveals that, while digital twins do not yet have standards to support the technological developments that are visible in the patents landscape, there has been thought on and development of standards that outline principles for the smart built environment.

Lamb, K. (2019) Principle-based digital twins: a scoping review.
Centre for Digital Built Britain. DOI: 10.17863/CAM.47094

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