UNIVERSITY OF LIVERPOOL

VEC VIRTUAL ENGINEERING CENTRE

Transforming digital twins into digital products that thrive in the real world.

Foreword

From their origins in the aerospace industry, digital twins have emerged as a lynchpin technology of the Fourth Industrial Revolution within industries as diverse as automotive, construction and utilities. By creating digital representations of real world assets, engineers are transforming how complex systems, infrastructure and products are designed and maintained.

The potential benefits are vast.

By assimilating real time data from a physical asset into a digital twin, engineers can accelerate R&D by, for example, accurately modelling the impact of efficiency projects or managing risk through predictive maintenance. The ability to make interventions in accurate, simulated digital environments also holds major upsides for industries where security and safety are paramount, such as nuclear power.

Considering these possibilities, it's unsurprising that adoption is on the rise.

Research from Gartner, published in 2019, found that 13% of organisations implementing Internet of Things (IoT) projects were already using digital twins, and 62% were either in the process of establishing them or planning to do so.

While this proliferation of digital twin technology is tremendously exciting, it also raises important questions about interoperability.

As their use grows, one asset's digital twin is likely to need to be connected to that of another, for their full benefits to be realised.

To take the automotive industry as an example, a manufacturer with a digital twin of a vehicle's braking system may wish to integrate it to the digital twin of the vehicle's engine for a particular project. That may be relatively straight forward within one organisation where there is a common digital framework. But if these twins need to be integrated with a wider connected system involving multiple suppliers or stakeholders – such as a smart traffic network – this interoperability will become more of a challenge.

The need, therefore, is to agree a common definition and design framework for digital twins now, while the technology is still developing. Failure to do so will create significant challenges as digital twins reach high levels of maturity – particularly given that digital twins are likely to play an important role in meeting the smart infrastructure ambitions of local and national governments in the UK and beyond.

This paper covers the factors influencing the development of digital twins and the need to consider and plan for the integrated digital environments that they will operate within in the future.

It seeks to spur new thinking around a transformative technology which will impact a wide variety of industries; and one which, properly harnessed, can support the UK's scientists, engineers and the wider public for decades to come.

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Dean of the School of Engineering
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Summary

The world is becoming ever more complex, and products are increasingly becoming connected systems. Currently, digital twins are seen as a mirror of a real-world asset. However, these twins often require interfaces with other physical assets, virtual systems and organisational interfaces to be effective. They will often have separate business models, operational set-ups and requirements to their real-world equivalent. Therefore, it is now time to recognise that digital twins are becoming digital products in their own right.

When the live feedback loop that provides the continual update is broken, the virtual representation ceases to be a digital twin. Instead it reverts to a digital representation of the physical asset at the point of the break and can form the basis of a virtual prototype.

However, current research is primarily on the technology development of digital twins, rather than the broader environment the product will operate within, namely the digital context.

This paper will clarify the concept of digital twins and current developments. It will then explore the importance of moving towards a design paradigm focussed on creating a digital product. The digital context will be explored, and a new model proposed to design and develop these digital twins in an efficient, standardised and scalable way. This new model will seek to better encapsulate the complex environments these technologies operate within and to capture that as a critical first step in any digital product design process.

The adoption of a standardised approach would allow opportunities for the exploitation of synergies between products, applications and sectors and accelerate the rate of maturity of these digital technologies.

1. Defining digital twins

Recent literature surveys have shown inconsistences in the definition of digital twins.[1,2]

Many reported developments are not digital twins. Rather, they fall into two categories:

- **Digital shadows** – a digital representation of a physical object with a one-way flow of information from the asset to the simulation
- **Digital models** – a digitised replica of a physical entity with no automatic data exchange between the two[1]

For this article, a digital twin is defined as the functional digital representation of a real-world entity.

Functional means the digital twin only contains sufficient information relating to and linked with its physical counterpart to allow analysis and to support decision making for a specific purpose.

A digital twin requires:

i. A specified purpose or scenario that it is used to replicate

ii. Validation versus its real-world equivalent and a resultant accuracy found to be within limits required by the purpose defined in (i)

iii. Continual updating and optimisation based on the input of 'real-world' data from its physical counterpart, as required to deliver the purpose defined in (i)

When the live feedback loop that provides the continual update is broken, the virtual representation ceases to be a digital twin. Instead it reverts to a digital representation of the physical asset at the point of the break and can form the basis of a virtual prototype.

Although the concept of digital twins has existed since 2003[1], development was slow from then until 2011, partially as the foundational technologies required to realise them were insufficiently mature.[2] However, since the rapid growth of sensors, cloud computing, big data and the Internet of Things, there has been an increasing interest.[2] Digital twins are now considered a linchpin technology for the Fourth Industrial revolution.[3,4] In 2019, Gartner predicted that digital twins were now entering the mainstream.[4]

Research is already underway into the adoption of these technologies into aerospace, agriculture, renewables, energy generation, healthcare, smart cities, manufacturing and supply chain management.[1,5] Various industry leaders such as Siemens, Oracle, ANSYS, Dassault and Altair have already established the infrastructure for digital twins.[6] With results such as GE reporting savings of over $1.5 Bn from improved operational and maintenance efficiencies from their asset performance management application[7] the hype around these technologies is unsurprising.

Digital twins and cyber-physical systems can exist at any stage of the lifecycle or at any level of a product architecture. This can include: system conceptualisation; design; virtual prototyping and testing; smart manufacturing; in-service performance optimisation; condition-based maintenance; and fleet management. The only requirement is that they leverage aspects of both the virtual and physical environment to improve elements of the real-world entity over its lifecycle.[8]

Digital twins and their associated capabilities support three of the most powerful tools in the human knowledge toolkit: conceptualisation, comparison and collaboration.[9] Their benefits come from increased data transparency and analytics, that can then be used to improve the performance of the associated physical asset.[2] Realisation of their benefits requires widespread adoption and seamless integration with the people and organisations using them.

2. Digital twins are becoming digital products

Gartner's 2019 survey found that nearly a third of respondents who were developing digital twins required them to serve more than one partner.[4] These partners were both internal and external to their organisation.

For example, the users of a digital twin for an aircraft engine could include: the manufacturer; the operator; insurers; and maintenance providers. Each user would have different requirements of the tools. Digital twins will therefore require customisation to provide the specific answers required by different stakeholders.[10]

In addition to providing performance improvements to physical entities, digital twins will enable new solutions and services to be generated.[10] The simplest of these is that an existing twin could be sold on for adaption or repurposing to meet a separate application. Advances in big data mean that both the input data and resultant analytical data from these technologies will likely see an increase in their inherent value.

Organisations which are able to realise novel analytical, connectivity or software solutions and approaches that deliver improved performance or development times for physical products would likely seek to spin these out as broader service offerings.

As the previous section highlighted, the key trait that defines a digital twin is dynamic connectivity. However, this connectivity may be broken at many stages in the lifecycle. For example, the twin could be deliberately moved offline to allow innovation while protecting intellectual property (IP).

There will also be unique requirements for digital twins that are not applicable to the physical product. An obvious example of this is the data security and standards required to manage the data contained within it. There will also be separate recycling and disposal requirements for the physical and virtual entities. The end-of-life digital twin for one product may have value in influencing the maintenance and design decisions in another.[3]

The creation of these twins is complex and specialised, requiring advanced skills in data management, fusion and analysis. There are also separate skillsets required to determine the purpose, scope and business case of a digital product.

The successful integration of a digital twin requires advanced systems architecture knowledge. Many end users or operators of the physical system do not have the capabilities to be able to design, build and operate its virtual counterpart. Therefore, they subcontract or turn to digital twin providers. Online users are now able to buy, access and use the various elements needed to make a digital twin.[6]

The cost and complexity of such an undertaking has been likened to the next Manhattan Project. For example, developing such technology for the United States Department of Defence's Next Generation Air Dominance aircraft are estimated to cost $1-2 trillion and take up to 250 years to complete, even with a team a third the size of Microsoft.[11]

It is likely that these costs can be reduced by establishing a realistic purpose, an efficient design – reusing existing elements where possible – and an effective project team which includes spreading the development load across organisations. This would also increase the likelihood of a fit-for-purpose outcome.

For these reasons, it is now more appropriate to consider digital twins as **digital products** in their own right.

These digital products may have different scopes, purposes, use cases and economic models to their physical counterparts. The costs of developing these digital products mean the same level of rigour should be applied to their design as with their real world equivalents.

3. Integrating digital products with their environment

As mentioned in the earlier section, digital twins should reflect the real world. However, that world is becoming more complex. Products can rarely be isolated from their environments. For example, cars are moving towards being self-driving which rely on real-time interaction with traffic systems and other vehicles.

A 2019 Gartner survey reported that 61% of companies who had already implemented digital twins, had integrated them with at least one other digital twin.[4]

This is necessary as complex systems, such as powerplants, may have individual digital products for valves, pumps and generators. Increasingly, they may also have twins of their manufacturing processes, logistics and organisational functions. In this new paradigm, digital twins not only need to be connected to their physical counterparts, they also need to be integrated with other virtual assets.

One way of conceptualising these interfaces is that they are multi-dimensional, connecting lifecycle stages, process steps, disciplines, and the physical world.[3] Each of these interfaces is required to influence and share information with the other.

Therefore, it is no longer enough to develop digital technologies in isolation. These products operate within a **digital context** that defines requirements essential for the design phase. The result of combining a digital product with its digital context becomes an **integrated digital environment**, Figure 1.

Integrated Digital Environment

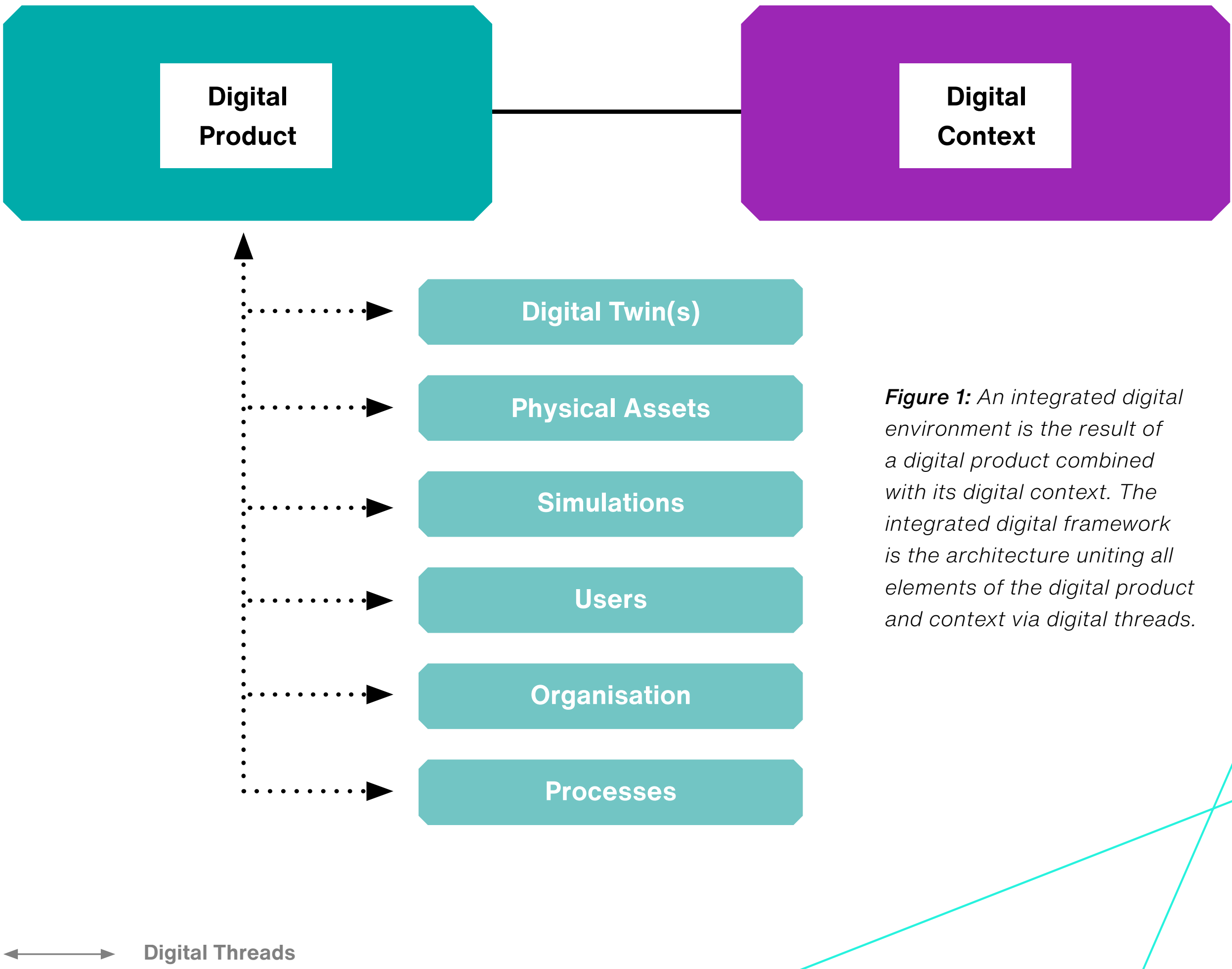


***Figure 1:** An integrated digital environment is the result of a digital product combined with its digital context. The integrated digital framework is the architecture uniting all elements of the digital product and context via digital threads.*

3. Integrating digital products with their environment

Systems architectures ensure the co-ordination and collaboration of complex physical products. In the same way, digital twins of physical products require a similar architecture. This is known as the **integrated digital framework**. This framework's purpose is to allow the integration of all hardware, software, user and organisational interfaces and seamless operability for an application. These frameworks must include the protocols and procedures needed to define this common way of working, in addition to hardware and software.

Digital threads connect software, processes, twins and systems within this architecture, to ensure that the *right people* have the *right information* at the *right time*. Digital threads can connect data through: the different layers of the system hierarchy; product lifecycles; the digital and real-world; or any combination of the above.

The architectures of the physical and virtual asset need not be the same, however. Adamenko *et al.* posited using a data-based framework.[12] As the name suggests, this structures the architecture around different functionalities or data properties rather than the physical systems.

Although the benefits of integrated digital frameworks are well established, there is a significant gap in understanding of the best approach for realising them. The majority of research in this area has explored the technologies and technical approaches to realise the digital twin or product.[e.g.13,14,15,16 & 17]

Similarly, while most papers acknowledge the importance of good design and architecture for digital twins, there is a lack of a unified approach or design paradigm for implementing them.[1,2]

4. Establishing the digital context

Each digital product is created for a specific application and a specific task. Therefore, a clear scope must be established for any new development. This scope will also define the digital context. This context is unique to the boundaries of operation and will encompass many factors such as the interfaces with the physical world, legal and regulatory requirements, economic and commercial considerations, the organisational and operational demands, and the user needs and expectations (Figure 2).

The physical world

For a piece of low-level equipment, the context can be the digital product immediately above it in the hierarchy. However, many digital products mirror complex engineered systems. For example within integrated transport, different digital products can and are being created for road infrastructure, traffic management systems, fleet management, individual vehicles and refuelling, recharging networks and smart cities.[1] These complex interactions with the physical world need to be mapped out and understood.

Legal and Regulatory Compliance

For many sectors (including automotive, aerospace, and retail), supply chains span many organisations and geographies. Each may bring with it differing legal and regulatory requirements. A recent literature survey into research on digital twins found that over 75% of relevant papers published between 2018 and September 2019 focussed on the manufacturing and service lifecycle stages.

The application and task of the digital product will significantly impact the legal and regulatory landscape. For example, in healthcare, separate digital twins of patients are being created to i) monitor, diagnose and predict the health of a patient or ii) present a prototype for autonomous surgeries. Separately, Hewlett- Packard has developed AI technologies that enable individuals to model the impact of their lifestyle choices on their digital twin.[1] In all cases, the digital product or twin seeks to replicate the same physical asset, an individual. Still, the requirements governing these three distinct tasks will vary widely. Decisions on where these patient twins are stored, who owns them and who can access them will significantly affect the rules governing their operation. These rules will, in turn, inform and dictate the detailed design of the digital product.

Some papers have recognised that further work is required on managing data privacy and security to meet specific legal requirements.[18,19] In the absence of universal approaches, the conditions and mitigations will need to be established on a case by case basis.

4. Establishing the digital context

Commercial considerations

Economic and commercial considerations are complex too. As previously mentioned, digital products may generate revenue streams independent from their physical counterparts. For example, their components parts can be upcycled or repurposed to create the next generation simulations. Digital products may be sold as a service or as independent commercial software. Building Infrastructure Management (BIM), one of the most mature integrated digital frameworks, used the latter approach.

The pricing model for digital products also requires consideration. The sale price of the resultant product will need to reflect high development costs. In BIM, the high initial software cost is cited as one of the critical obstacles to implementation.20

The success of a digital product, especially those encapsulating multiple partners, requires the provision of data. This data can be proprietary to the individual commercial entities along the lifecycle or value chain. Therefore, commercial contracts will be required to agree on the sharing of data and protection of both partners' and product IP. A digital framework can also provide an inherent level of IP protection, through the ability to shield sensitive information within black boxes and thus controlling what is accessible to users.

A reward mechanism may also be needed for those earlier in the supply chain who will provide input data but will not see efficiency gains from the final digital product.

If a virtual representation is used to inform the operation of a physical asset, then product warranties will be required. These warranties will likely increase exponentially with semi and fully-autonomous systems. Risk mitigations and protection strategies need to be identified and built into designs.

Operations

Organisational and operational demands can be significantly different to the physical asset. In the initial stages, there is a need to agree on standards to enable consistent connection and communication. Regular monitoring and stewardship will be required to ensure these protocols are applied. Any digital system will also need ongoing maintenance, such as updating operating systems or upgrading capabilities.

Governance

The very nature of the cyber-physical fusion means that both the cyber and physical spaces can create threats to digital products. These threats need to be carefully studied and protected against on an ongoing basis. Stewardship roles require a level of technical competence beyond most users.

Governance mechanisms are needed to make decisions on the direction of development. Governance will also be required on an ongoing basis to agree on future improvements, manage the commercial and operational demands, and to ensure compliance with regulatory and legal requirements. Digital products can sit above organisational and geographical environments. In some cases, these over-arching products will require an independent organisation to manage them.

Users

The users of any system must also be considered at the outset. Users could include the individuals providing data or accessing the outputs as well as the creators, maintainers or operators of the system. For digital products such as smart cities or transport, the general public's perception of the technology will determine their ultimate adoption.

Even within one strand of users, organisation, cultural and individual norms may require different tailoring and or presentation of the user interface.

It is not enough to simply consider the user needs. Integrated digital frameworks constitute a disruptive change to a way of working. Training and organisational commitment is required to support the technology. The implications of possible human resource reduction as a result of the improved efficiencies offered by these tools, must be understood and managed – as must the opportunity for their misuse.

4. Establishing the digital context

Not only will the digital context determine costs, but it may also determine the development approach and boundaries of the resultant digital product. Simple, stable real-world products may lend themselves to a closely coupled integration strategy for the digital framework. This approach saves time in the development but is much less flexible to subsequent changes compared to other approaches.21 Initial introductions of digital products to an organisation may require simpler interfaces in recognition of lower skill levels within the organisation.

Simplified twins may have to be designed for those unwilling to commit to high research costs before any benefit is proven or without access to high-performance computing.

The digital context can be a significant cost driver of any digital product development. Therefore, it is proposed that the digital context, and the constituent elements of it outlined in Figure 2, are scoped as part of the concept stages of any digital product development.

Integrated Digital Environment

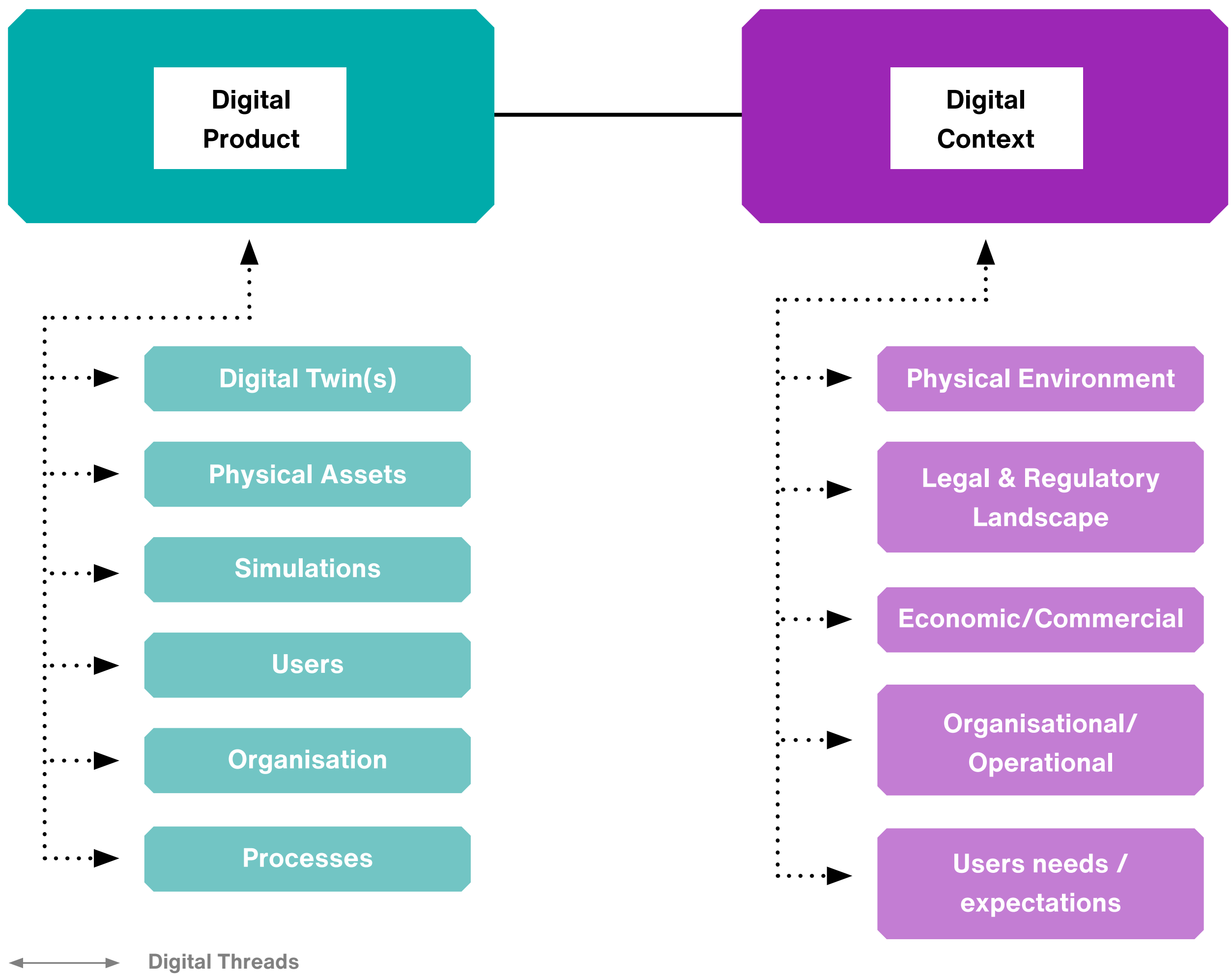


Figure 2: *Integrated digital environment is the result of a digital product combined with its digital context. The integrated digital framework is the architecture uniting all elements of the digital product and context via digital threads.*

5. The case for a standardised approach

As this paper has discussed, digital twins have evolved to the stage where the factors influencing their development are myriad and multiplying.

As separate enterprises and industries pursue their own digital twin strategies, there is a risk that the approaches they take will diverge to the point that they hinder or prevent future use cases which rely on data being exchanged between different twins.

If we assume that the natural evolution of digital twins – particularly those relating to public infrastructure, such as power or transport networks – will include a role in larger connected ecosystems (a smart city, for example) then it is challenge which must be addressed.

For example, if digital twins were to be used to model initiatives to tackle inner city pollution, it is conceivable that a wide range of different assets or artefacts would need to be considered – from transport networks, to built environment assets. Each of these artefacts will themselves be made up of a combination of different systems (in the case of transport networks this would include road, rail and potentially air traffic).

To take a holistic approach to tackling pollution, these twins could be used to model whether changes made in one system is beneficial across another – but only if the twins can interface readily with each other. For this to happen, common taxonomies, naming conventions and descriptions become important and therefore so does some sort of governance.

The solution is for a common framework or design standard to be developed which will guide the development of digital twins. This will need to be flexible enough so as not to encumber innovation within private enterprise or discrete sectors, but with enough commonality to ensure future compatibility.

The question of how this can be achieved requires more debate. Given that the public sector has a long-term stake in the successful interoperability of digital twins as an enabler of smart infrastructure, it has the impetus to play a role.

The progress made with rolling out BIM across the built environment sector, demonstrates there is a means and precedent for establishing a common purpose across the public and private sectors. And in initiatives such as the Centre for Digital Built Britain and the Nuclear Virtual Engineering Capability there are already examples of digital collaboration within sectors.

Establishing a coordinating body such as a *Digital Twin Infrastructure Advisory Board* could provide a cross sector vehicle to combine the expertise of regulators, government departments and industry to curate a common framework for the development of digital twins. This would ensure the opportunities of interoperability are not lost to time.

6. Discussion and conclusions

As digital twin technologies enter the mainstream, it is no longer enough to consider these as merely a digital representation of an active product. They are becoming digital products in their own right, with independent business models and requirements. The increasing interconnectivity of the world means that these products need to integrate with other virtual and physical assets, processes, organisations and industries. To avoid poor decision making and costly mistakes, the digital context must be considered from the concept stage.

There is a lack of consensus about how to design a digital product. Also, there is a recognised gap in the literature about the digital context and how to embed it within the design process. This article is intended to provoke discussion on this subject. However, it is not exhaustive and offers no answers on how best to unify approaches to encapsulate context and more importantly address the issues arising from it. Further work is urgently required to address these gaps.

Although addressing these gaps would require additional funding, the solutions would have broad applicability. Effective design for digital context would also likely improve interoperability, better identify synergies and reduce project risks.

Spending time establishing the digital context in the design stage may add time and money in the short-term. However, these will likely be more than offset in the medium to long term. Most importantly, any resultant digital products will be designed to operate and thrive in the real-world.

NVEC: Digital Reactor Design

The University of Liverpool's Virtual Engineering Centre (VEC) is a key delivery partner in the Nuclear Virtual Engineering Capability (NVEC) – a BEIS-funded programme to achieve a step change in the way that nuclear design, development and construction projects are delivered.

Led by Jacobs, the project aims to develop infrastructures and architectures to enable users across the nuclear life cycle to collaborate between sites, provide innovative solutions to manage 'big data' and to operate digital twins.

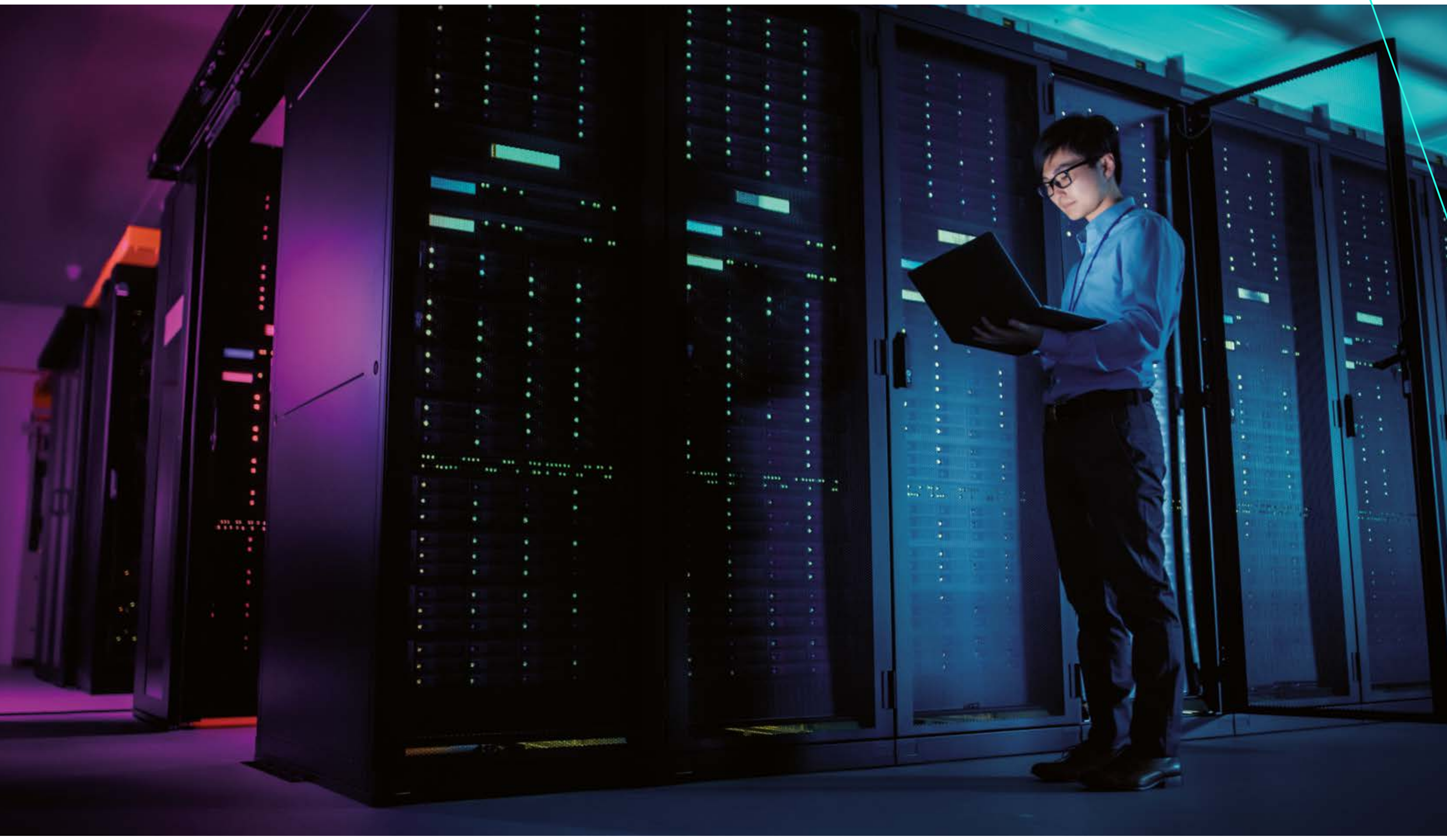
VEC's role is to develop a common digital framework to support future nuclear reactor build. Delivering systems integration is key. The framework VEC is creating will provide an opportunity for project partners to combine their capabilities, via an infrastructure between collaboration for organisations across the whole sector.

Phase 1 of the programme demonstrated an effective proof of concept by developing a computer-simulated design and management platform, positioning the UK as a world leader in this area.

The focus of Phase 2 was to implement new tools and disruptive technologies in a digital framework, utilising real-life case studies and applications to demonstrate improved efficiency, enable supply chain collaboration and ultimately deliver cost-savings and a cultural change across the industry.

The programme has used expertise and facilities of the VEC to improve the processes used to design and build new nuclear reactors, and to optimise their performance during their operating life.

The NVEC Digital Reactor Design core team, supported by partners and sub-contractors from industry, academia and science included; Wood, EDF Energy, Rolls-Royce, National Nuclear Laboratory, and the University of Liverpool's Virtual Engineering Centre (VEC).



About

The Virtual Engineering Centre (VEC) is the UK's original Digital Engineering Impact Centre.

The combination of the knowledge, experience, and world-class research we offer helps our clients explore the adoption of digital technologies to solve complex industry problems in a safe, neutral and friendly environment.

Established in 2010 by the University of Liverpool, supported by EU funding and in partnership with BAE Systems and the National Nuclear Laboratory. The Virtual Engineering Centre sits within the University's IDEAS (Institute of Digital Engineering and Autonomous Systems) and works to bridge the innovation gap between academic research and new product and process development.

We provide access to digital test-beds and the latest scientific infrastructure. Through our partnerships and networks, we inform future government policy in the area of applied digital technology to support future research for impact.

References

1. Fuller A, Fan Z, Day C, & Barlow C .2020. Digital twin: enabling technologies, challenges and open research. *IEEE Access* (doi: 10.1109/AACESS.2020.2998358).

2. Tao F, Zhang H, Liu A & Nee AYC. 2019. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Industr. Inform.*, **15-4**, 2405-2415, (doi: 10.1109/TII.2018.2873186).

3. Harik R, Romero D, Wuest T, & Thoben KD .2020. Towards a Cyber-Physical PLM environment: the role of digital product models, intelligent products, digital twins, product avatars and digital shadows. *21st IFAC World Congress July 2020*. (Available at: https://www.researchgate.net/publication/340952548_Towards_a_Cyber-Physical_PLM_Environment_The_Role_of_Digital_Product_Models_Intelligent_Products_Digital_Twins_Product_Avatars_and_Digital_Shadows).

4. Gartner .2019. Gartner Survey Reveals Digital Twins Are Entering Mainstream Use. Available at: https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital-twins-are-entering-mai#:~:text=Gartner%20defines%20a%20digital%20twin,business%20operations%20and%20adding%20value.&text=%E2%80%9CWe%20see%20digital%20twin%20adoption%20in%20all%20kinds%20of%20organizations. (Accessed: 20 Oct 2020).

5. Calatayud A, Mangan J & Christopher M. 2019. *The self-thinking supply chain*. 2019: Emerald Publishing Ltd. (doi: 10.1108/SCM-03-2018-0136).

6. Qi Q, Tao F, Zhau D & Zuo Y. 2018. Digital Twin Service towards Smart Manufacturing. *Procedia CIRP*. **72**, 237-242. (doi: 10.1016/j.procir.2018.03.103).

7. General Electric. No Date. Digital Twin. Available at: https://www.ge.com/digital/applications/digital-twin?utm_source=Google&utm_medium=Paid%20Search&utm_campaign=2020-08-GLOB-DG-HORZ-MULT-Google_SEM_Dig_Twin-Parent_PDSRCH&gclid=CjwKCAjwlID8BRAFEiwAnUoK1TN26i9HcjsValSrm1bU-pFLHs41QWt2gsyu8bNeF9g6LmlxQlqPlhoCylQQAvD_BwE (Accessed: 20 Oct 2020).

8. Hicks B. 2019. Industry 4.0 and Digital Twins: Key lessons from NASA. The Future Factory. Available at: https://www.thefuturefactory.com/blog/24. (Accessed: 18 Nov 2019).

9. Grieves M. 2013. Digital twin: Manufacturing excellence through virtual factory replication, Whitepaper.

10. Rosen R, Fisher, J, & Boschert S. 2019. Next Generation Digital Twin: an Ecosystem for Mechatronic Systems? *IFAC papers online* 52-15, 265-270. (doi: 10.1016/j.ifacol.2019.11.685).

11. West T D & Blackburn M. 2017. Is digital thread/digital twin affordable? A systemic assessment of the cost of DoD's latest Manhattan Project. *Procedia Comput*. Sci. 114: 47-56. (doi: 10.1016/j.procs.2017.09.003).

12. Adamenko D, Kunnen, S, Pluhnau R, Loibl A and Nagarajah A. 2020. Review and comparison of methods for designing the Digital Twin. *Procedia CIRP*. 91, 27-32. (doi:10.1016/jprocir.2020.02.146).

13. Zheng Y, Yang S & Cheng H. 2019. An application framework of digital twin and its case study. *J. Amb. Intel. Hum. Comp.* **10**, 1141-1153. (doi: 10.1007/s12652-018-0911-3).

14. Lu Y, Liu C, Wang K I, Huang H & Xu X. 2019. Digital twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robot CIM-INT Manuf*, 61, 101837 (doi: 10.1016/j.rcim.2019.101837).

15. Calatayud A, Mangan J & Christopher M. 2019. *The self-thinking supply chain*. 2019: Emerald Publishing Ltd. (doi: 10.1108/SCM-03-2018-0136).

16. Vrabič R, Erkoyuncu JA, Butala P & Rajkumar R. 2018. Digital Twins: Understanding the added value of integrated models for through-life engineering services. *Procedia Manuf.* **16**, 139-146. (doi: 10.1016/j.promfg.2018.10.167).

17. Tao F, Cheng J, Qi Q, Zheng M, Zhang M & Sui F. 2018. Digital twin-driven product design, manufacture and service with big data. Int. *J. Adv. Manuf. Technol.* **94**, 3563-3576 (doi: 10.1080/00207543.2018.1443229).

18. Bruynseels K et al. 2018. Digital twins in health care: ethical implications of an emerging engineeering paradigm. *Front. Genet.* **9**, Article 31. (doi: 10.3389/fgene.2018.00031).

19. Jones D, Snider C, Nassehi A, Yon J, & Hicks B. 2020. Characterising the digital twin. *CIRP-JMST.* **29**, 36-52 (doi: 10.1016/j.cirpi.2020.02.002).

20. Liu S, Xie B, Tivendale L, & Liu C. 2015. Critical Barriers to BIM Implementation in the AEC Industry. *Int. J. Mark. Stud.* **7**, 162. (doi:10.5539/ijms.v7n6p162).

21. Bowman D, Dwyer L, Levers A, Litskevich D, Merk B, Patterson EA, Purdie S & Vikhorev K. 2020. On the benefits of bringing integrated digital frameworks to life – a UK nuclear case study. Manuscript submitted for publication. Virtual Engineering Centre, University of Liverpool, Liverpool. United Kingdom.

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