Defence Digital Twin Implementation Road Map and Development Framework **Supporting Information**

Defence Digital Twin Implementation Road Map and Development Framework Background Papers

Introduction

Team Defence Information (TDI) looks to create value for Defence by bringing together MOD, Industry and Academic subject matter experts for short sprints. The latest Digital Twin team's aim was to improve our collective understanding of the Defence Digital Twin development framework, likely road map and hence Defence's ability to adopt these new technologies, support new ways of working and realise the benefits of Digital Twins.

TDI is in the process of setting up a Community of Practice to work on key framework items that will enable the adoption of Digital Twins as normal business for the Defence support community.

Background

When developing the framework items and road map the following use cases were considered:

- Improving asset availability;
- Improving safety by maintaining the design intent;
- Reducing cost of ownership by reducing maintenance both planned and unplanned;
- Supporting life extension; and
- Providing and supporting virtual training.

Also, existing Digital Twin road maps and frameworks from of domains such as Centre for Digital Built Britain were considered. It was found that the scope of the defence framework would be too large for one team to consider in the desired timescales. It was agreed that the task would be split into different working groups, these being:

- Governance and Life Cycle;
- Data and Infrastructure;
- Sense and Decision Making;
- Enablers; and
- Change.

The set of background papers provided in this document supported the development of the short Defence Digital Twin Implementation Road Map and Development Framework white paper released earlier this year. The working streams identified elements that could be either adopted or modified from existing industry good practice and those items that Defence need to create themselves.

The workstreams considered the total framework and road map to ensure it was consistent, logical and supportive

Workstream Long Papers

The following workstream papers provide a summary of the work and discussions from working groups noting that time did not allow for a complete assessment of all framework. Those identified as a priority were considered by the working group in more detail. The following workstream papers provide the outcome on the discussions held and the recommendations made with respect to the framework items. The workstreams also ordered the framework items and identified their relationships.

The workstream papers are a less formal set of documents that support the formal paper released in Q1 2021. The intention is to formalise this content, through learning, application and usage of the principles recommended in the Implementation Roadmaps. Building learning and experience, gathered through implementation, into these future documents is a deliberate mechanism to increase value and relevance through time. This future content will be released through 2021-2022.

The Community of Practice is focused on accelerating progress in realising the Defence Digital Enterprise; by bring coordination of effort in overcoming shared challenges and also the sharing of experience in implementation projects across the product lifecycle and the twin hierarchy.

The scope of the working group is primarily Defence support (aftermarket) but a full lifecycle consideration is paramount to ensure digital artefacts (models, system models and simulations) are used to enable value creation later in the lifecycle via digital twinning. The creation of robust data supply chains through the engineering and operations/production phases is paramount in releasing this value potential.

The Community of practice will also look to maintain relationships and seek out industry best practice identified during the collation of the Implementation Road Map. International collaboration and knowledge sharing will also be built into the working group, as will Government links via UKRI (EPSRC and Made Smarter), and the Centre for Digital Built Britain (CDBB) working across our national infrastructure.

1. Governance and Life Cycle

Digital Twin Roadmap - Section 1: Governance and Life Cycle

Strategy

Digital twinning is an opportunity derived from the inexorable digitisation of the ‘physical world’. As described in the Digital Twin white paper, the value created from the flow of data backwards and forward ‘from the digital to the physical, and back’ creates new value opportunities across the lifecycle. Maturing digital capabilities across traditional Engineering, Operations/Manufacturing and Services/Aftermarket sectors presents the opportunity to build a true lifecycle continuum, the digital thread. We are at the beginning of new products being conceived digitally (with a full model based enterprise) and are hence at the beginning of understand the true potential of digital twinning across an entire lifecycle. However, early product development has changed the paradigm in terms of defence acquisition, as has been well documented in the Dr. Roper papers. A similar paradigm shift is emerging in advantages observed in the most advanced ‘smart factories’ and within twinned logistics operations. Finally the retrospective application of aftermarket digital twinning, to existing programmes, is leading to optimisation and predictive maintenance regimes that are also liberating significant value. It is anticipated that the network effect of these early breakthroughs will increase value generation.

As traditional organisational data silos are broken down, analogue processes are systematically replaced, and data supply chains increase in quality and tempo the resulting flow of data will drive a corresponding creation of new value. This opportunity will also accelerate as new business models emerge and digital twins mature and are commercialised to greater affect.

Building on the definitions and examples described in the ‘Digital Twin’ white paper (Sept 19) and ‘Information Architecture’ white paper; this Digital Twin Roadmap paper looks to describe the building blocks for creation and maintenance of digital twins, at scale, as well as application and mechanisms of value creation.

The ability to create complex models and simulations plays a significant part in extracting value from digital twins as ‘real time’ connectivity between the digital ‘assets’ and mirrored physical assets enables modern data science to be applied. Machine Learning (ML) and Artificial Intelligence (AI) techniques enable complex systems to ‘learn’ and increase accuracy of prediction and optimisation allowing improved decision making across an enterprise. These opportunities present significant cost and decision speed advantage.

This report will look to highlight the correlation of these opportunities with the maturity of digital transformation across the Defence enterprise. Data supply chains, data quality and data standards will be focused on as key concerns in efficiently leveraging the opportunity of Digital Twinning.

This report recognises the complexity of creating a Digital Twin roadmap, it has been described as 'at least a three dimensional issue'. In looking to identify and simplify the key elements, two maps have been created;

1. Identifies the core component elements needed to create and maintain Digital Twins
2. Identifies the 'Twin Hierarchy' and technology themes that describe the Digital Enterprise.

The report also looks to recommend steps to take (and avoid) to take forward a 'considered path' to scalable value creation via Digital Twinning.

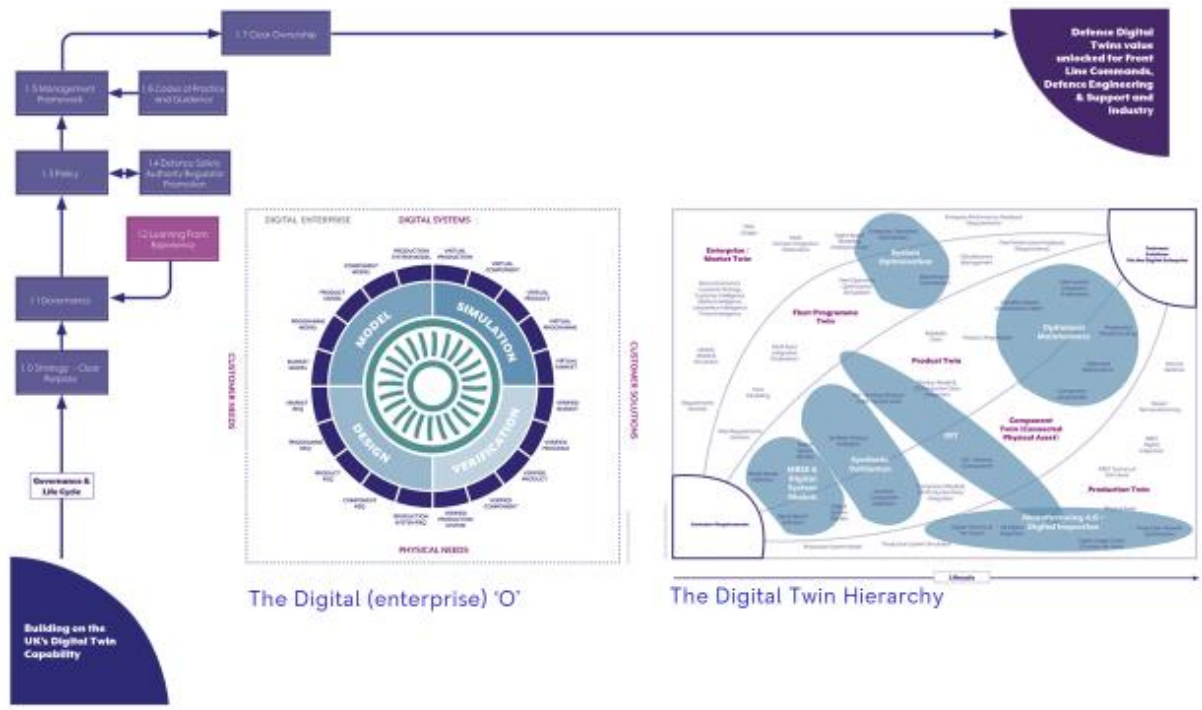

Figure 1 – The Lifecycle component of the Digital Twin Road map was described via two models, the Digital (Enterprise) 'O' and the Digital Twin Hierarchy.

An Enterprise Digital Transformation

The transitions from Systems Engineering (SE) to Model Based Systems Engineering (MBSE) has been well documented, with the Boeing 'Black Diamond' referenced in the Digital Twinning paper, outlining the SE 'V' of Design and Verification and the mirrored digital capability of Modelling and Simulation. These four quadrants are widely adopted across aerospace and collectively describe the Digital Enterprise. Maturing, integrating and securing data flows across these quadrants is fundamental to enterprise digital transformation and underpins digital twinning capability.

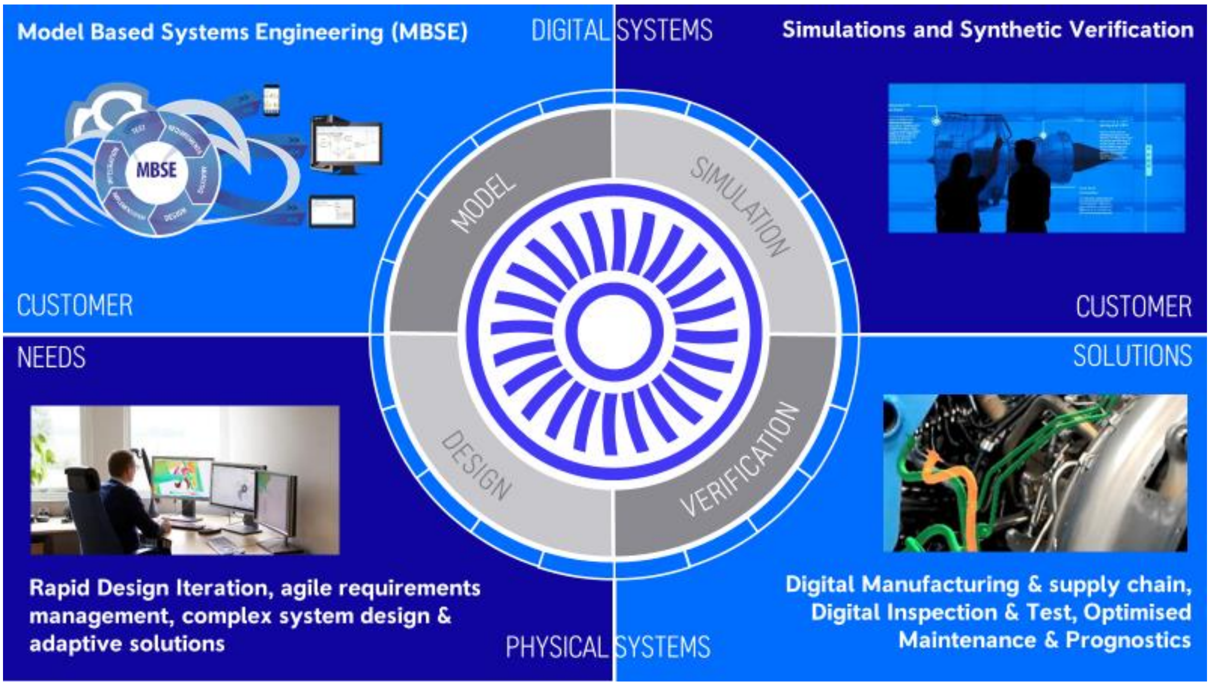

Figure 2 – The simplified Digital Enterprise Framework - Digital 'O'

The digital enterprise framework, a simplified view of the Digital "O", describes the transition from classical Systems Engineering, which was heavily anchored in physical systems (e.g., paper prints and physical testing) to the integration of Digital Systems (e.g., digital models and simulation). The four quadrants – Design, Model, Simulate, and Verify – are very important in describing the transition to future ways of working that enable the realisation of value. The integration of physical and digital systems, as well as fusion of data and analytics across these four quadrants, is having a transformative effect in the pace, productivity, and cost of product development and sustainment across the Aerospace & Defence industry landscape. As new requirements are defined through time the model also supports rapid upgrade cycles and ensures long-life, high value, assets remain competitive. This common framework is required to ensure integration across the lifecycle and compatibility within the larger Defence Digital Enterprise & Ecosystem.

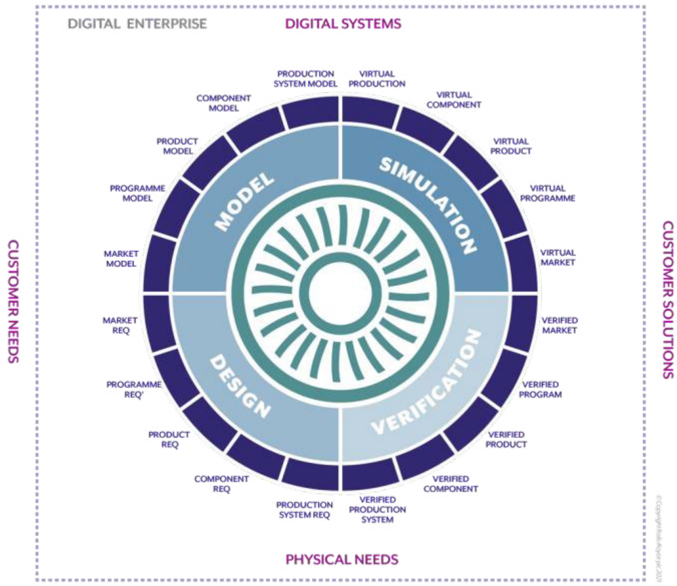

Figure 3 – The Digital Enterprise 'O'

To understand the relevant components of the Digital Enterprise, Figure 3 shows the full "O" diagram which connects the four quadrants by a series of "Twins". To make this 'leap' and identify the five twin levels, first consider the construction of a new manufacturing facility as an example of the Production Twin. New customer requirements cascade in the Design quadrant from product requirements, to component and production system requirement for the building of a new manufacturing facility for a new program. Based on the virtual factory requirements, production system models (in the Model quadrant of the "O") are built to assess facility size, internal infrastructure, manpower, energy requirements etc. That model is then brought to life in the Simulation quadrant of the "O" via a virtual production simulation to look at load capacity balance, throughput, ergonomics, power usage and more, virtually verifying every element possible through simulation. We then drop back down into the lower 'physical' world (from the digital Model and Simulation quadrants) the facility is built (ideally 'right first time') to verify the production system solution in the Verification quadrant of the "O". Finally, the data is then linked from the physical plant to the digital models and simulations to bring the twin to life, through time. By pulling the four quadrants together, the resulting facility is cheaper to build, more resilient, has a lower through life cost and carbon footprint and will continue to be optimized and efficiently upgraded through the lifecycle of the plant. By continually flowing data from digital to physical and back, the Production Twin is realised. Today, modern Defence companies are leveraging virtual factory modelling and Production Twins to design internal physical infrastructure, optimize process flows and ergonomics of production facilities to drive towards 'right first time'/zero waste production lines. This same framework and context can be exercised to build up Digital Twins across multiple levels of the system as illustrated in Figure 4.

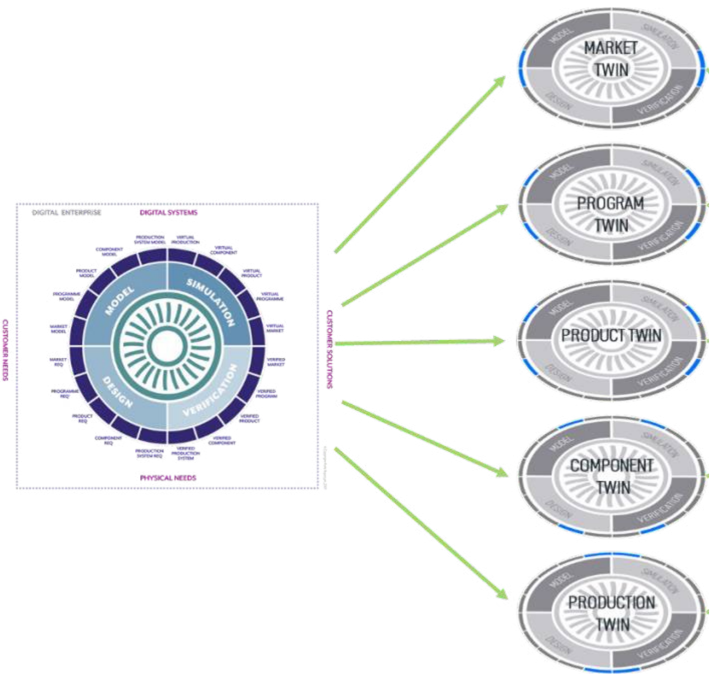

Figure 4 – The Digital Enterprise ‘O’ dis-integrates into the five Digital Twins (Production/Component/Product/Program and Market/Enterprise)

Further to describing the **Production Twin**, the “O” framework can be applied to a **Component Twin** where connecting the four quadrants with digital inspection solutions allows insights to more quantitatively assess and in some cases extend service life and repair limits, enabling Condition Based Maintenance Plus (CBM+) and Predictive Prognostic Maintenance to inform predictive degradation models of engine components to improve fleet readiness levels.

Similarly, the **Product Twin** is characterized by ‘self-aware’ systems, Optimised Maintenance and smart work scopes where product-specific asset information (models & data) enables automation of forecasting maintenance and ordering of spares. The **Program Twin** provides authoritative data and models that enable management of an entire fleet of assets and uses analytics to maximize availability, optimize life cycle costs, and minimize customer disruption. Finally, the Customer Enterprise, or **Market/Enterprise Twin**, enables the management of multiple fleets of differing capability optimized to deliver maximum effect while managing risk to readiness.

Extensive work was carried out, as part of this collective white paper effort, to describe the value of the Digital Enterprise ‘O’ an additional component of the model was added to ‘ground’ the model in the high value asset lifecycle. This additional vector was created as a horizontal axis to the five digital twin models vertical axis, and is described in Figure 5.

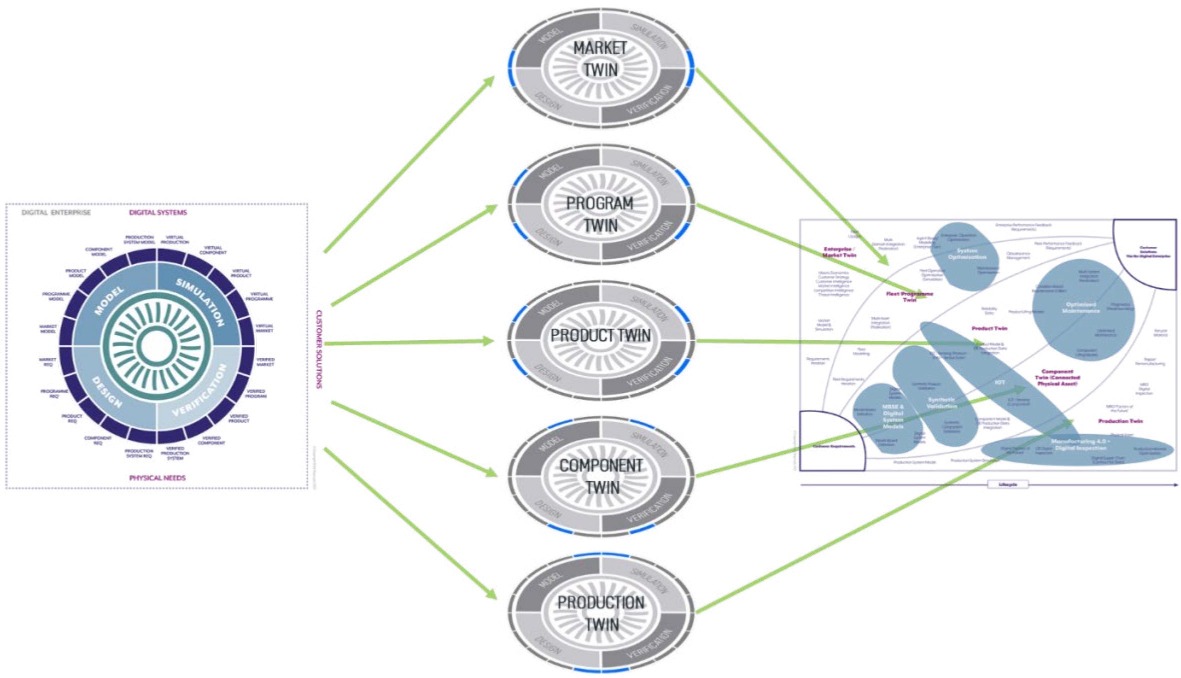

Figure 5 – The Digital Enterprise 'O' Expansion into 5 Digital Twin models, with the addition of the 'lifecycle axis' to create The Digital Twin Hierarchy

The five defined twins described in Figure 5 (Production, Component, Product, Programme and Market/Enterprise) are redescribed as the 'Digital Twin Hierarchy', this model spans the boundaries of the Digital Enterprise from the depths of the supply chain to the heights of the (multi-domain integrated) Customer enterprise. This is important as it gives us the road map to realising the true value of digital integration within the Defence Enterprise. The incremental benefits as described, realise a 'network effect' when data is integrated vertically through the enterprise and horizontally through the lifecycle**. We are able to achieve a new paradigm of value through this effect as incremental gains network to deliver exponential value.**

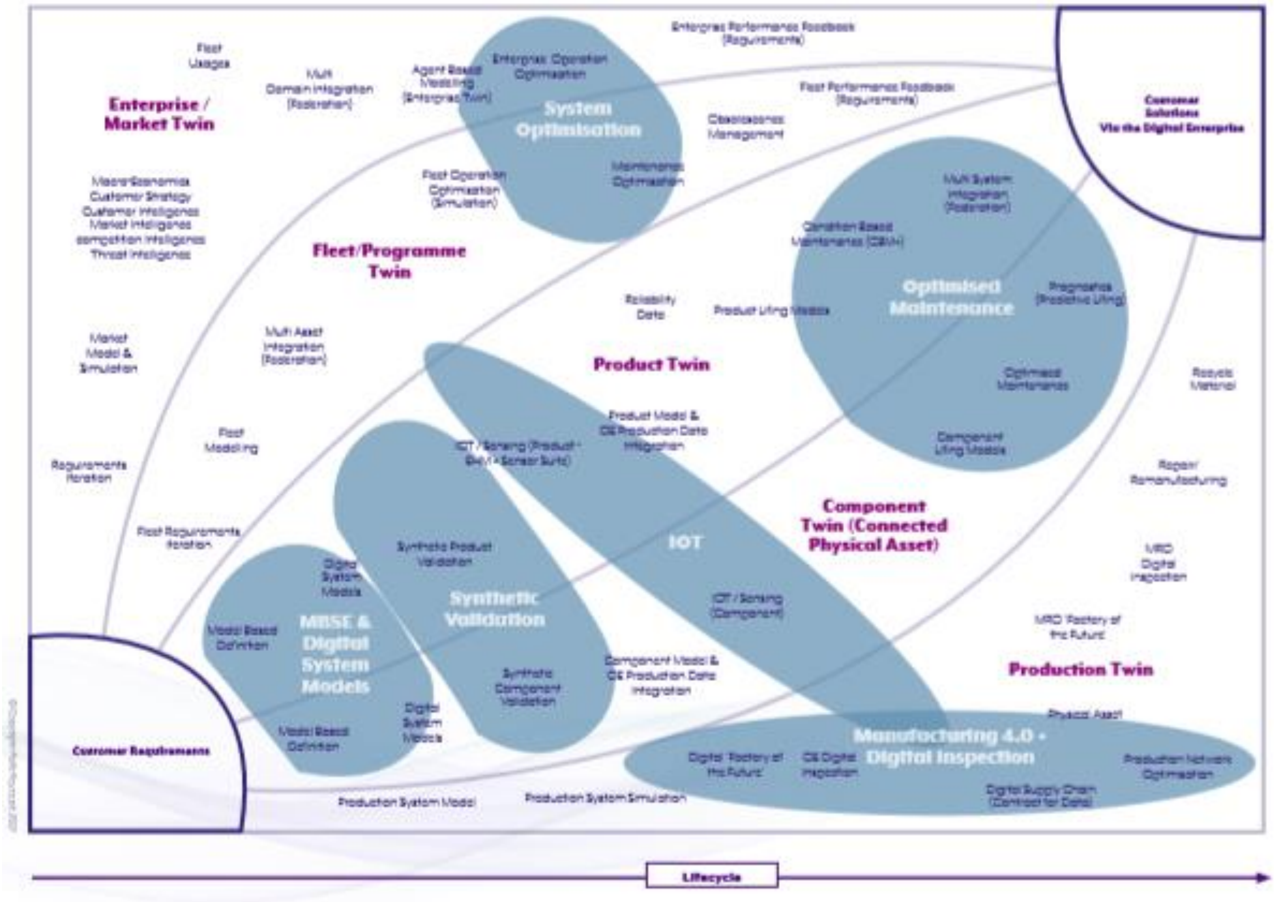

Figure 6 – The Digital Twin Hierarchy

The Twin Hierarchy also identifies technology themes through the lifecycle. This paper seeks to facilitate the navigation of complementary (and foundational) technology developments that support Digital Twinning capability. For example, identifying a development route that covers digital system models and model-based engineering, Manufacturing 4.0 and contracting for data through supply chains, remote sensing and Internet Of Things (IOT), synthetic validation, condition-based maintenance and enterprise modelling. The Twin Hierarchy plots a pathway for the creation of value through the application of the robust and sustainable twins that are created by following the Digital Twin Roadmap. The two models are intended for use in parallel.

The Twin Hierarchy addresses the Digital Twin uses through their lifecycle and across the digital enterprise. The clusters of capability highlighted in the model are 'figurative' in terms of highlighting the areas of key potential (i.e not exclusively bound by the regions identified).

The Digital Twin Hierarchy has proven significant value in identifying the foundational technologies that are required to underpin advances in enterprise wide digital twinning. It is also useful for highlighting specific technologies that exist within the blue capability clusters i.e the importance of digital inspection technology in creating data rich supply chains from production and overhaul operations. It also identifies the differing forms of technology within a capability area i.e the IOT applied to optimising logistics operations within the Production Twin is very different to the IOT technology applied within the Product Twin to deliver asset health monitoring. It has also been proposed that the model could be used for maturity assessments within an enterprise. This has not been developed, to date. Many maturity models exist to assess industrial maturity of digital twinning, it is believed that these must mature and no model has yet been identified as an industry standard.

The Digital Twin Hierarchy also supports recommendations pertinent to Governance. Value creation opportunities exist in isolation, within each horizontal twin layer, however greater potential is realised when vertical integration is also achieved. Governance and sponsorship of the Digital Twinning transformation must therefore reside throughout the Defence digital enterprise (as also must accountability for data ownership). (An observation has been made regarding the degree to which value can be extracted from the system, as being proportional to the degree to which the enterprise is operating 'digitally' and networked together, this has not been formally substantiated, but is a significant hypothesis of the working groups continued activity)

The final finding by this workstream relates to change management, adoption and particularly KPIs of value realisation. Digital Twinning is an opportunity available across
a digital enterprise. Many pilot studies have suffered from the failure to recognise the requirement for a minimum level of 'digital maturity' (established data supply chains) in their pilot study environment. The twin value proposition/KPIs become heavily eroded as lengthy and retrospective efforts are required to digitise currently analogue process flows. Digital twinning is an opportunity to create increasing value from digital transformation and an increasingly digital enterprise, digital twinning will not provide a 'silver bullet' solution to analogue organisations. Care must be taken to ensure the value proposition of digital twins is separated from the foundational costs of digital transformation.

The authors recommend the pathways within the Digital Twin Roadmap are followed, in conjunction with the Twin Hierarchy, to accelerate progress and assure the generation of value in realising a cost competitive Defence digital enterprise.

Policy and Standards

Fundamentally there is a need to create a 'data continuum' across the Defence enterprise. Interoperability (technology agnostic data connectivity) will be an important factor in efficiently and quickly realising the required enterprise connectivity (from multiple tiers of supply chain, though products, fleets and into the multi domain enterprise top level).

Interoperability is derived through commonality and this in turn relies on policy and standards. A 'proportionate' approach to this challenge is recommended, where common standards are taken forward and the 'burden' of excessive policy and standards is balanced with the opportunity of data standardisation.

The philosophy of open data is also an important concept to consider. Frictionless data and data visibility will stimulate commercial opportunity and innovation (macro and micro service opportunities). Transition from 'constrained environments' to micro-service architectures will again require a clear understanding of this opportunity and a progressive approach to balancing risk and opportunity.

Work stream 2 will address policy and standards in greater detail.

The authors also acknowledge an observed increase in pace of progress in areas of the US Defence enterprise as policies are enacted in a more 'directive' approach. 'Recommended' policies, for instance UK 'Cyber Essentials' across the UK supply chain, has delivered less progress in similar timescales.

The 'retrospective' aspect of digital twinning;

The defence domain is characterised by long lifecycle, high value assets. This presents a challenge in progressing digital twin maturity as products with decades of useful life have often not been conceived in the 'digital era'.

This introduces a complex 'cost/benefit' aspect to the defence digital enterprise in deciding how far to 'retrospectively apply' digital twinning. As well as high value assets, this applies to analogue and manual processes work flows that operate in the Defence Enterprise.

The twin hierarchy model does not answer all aspects related to the retrospective application of digital twins, this is an ongoing consideration, and the subject of future work. The model does highlight opportunities to create value relative to a programmes lifecycle maturity i.e. if a product was not conceived 'digitally' in design, value can still be derived by developing fleet optimisation and optimised maintenance capabilities. The assessment of any business case relative to investment in retrospectively 'digitising' and creating digital twins will be specific to that product, programme or process.

2. Data and Infrastructure

Data and Infrastructure

2.0 Definition of a Digital Twin

The term "Digital Twin" is one that can have many different definitions across industries; it is a term that is frequently used a buzzword to spark interest, but what actually is it? And what are the components of a Digital Twin? For this TDI paper we have defined a Digital Twin for the defence domain as the following:

Digital Twin: A virtual representation of physical assets, processes / people / places / systems / device that when fed or provided with real-world data enables effective decision making to optimise the performance and utility of the system of interest.

This highlights that "true" Digital Twins have closed loop connection, between a real-world item that provides data to a digital simulation/analysis platform which in turn provides predictions and decision support. Without this closed decision support loop, it is not a full Digital Twin as shown in the example in Figure 1.

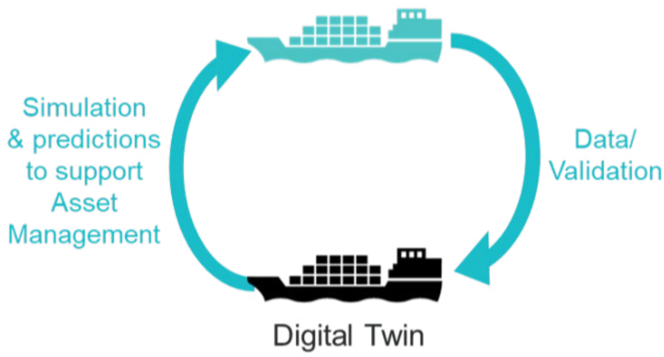

Figure 1- Closed Loop Digital Twin Model with Asset Example

In order to understand the data and infrastructure requirements of a Digital Twin we also need to understand what a Digital Twin is made of, and what components are required to create one. Using the example of an asset Digital Twin Figure 2 outlines the primary components.

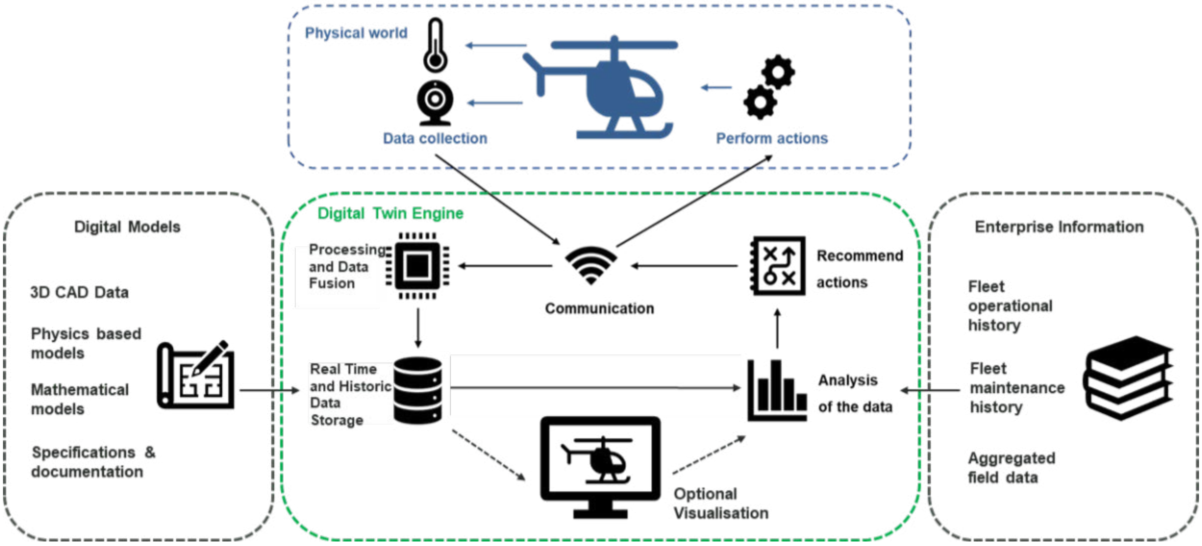

Figure 2 - Example Components of an Naval Based Asset Based Digital Twin

For simplification at this stage we can show the overall system to be made of these four primary building blocks:

1. Data collection from the physical asset

The Digital Twin collects information from the physical world asset. This information is essential for the Digital Twin given that it is used to mimic the behaviour of the physical asset in the most accurate way. The information comes mainly from sensors integrated in the physical asset, but it can also come from other sources, such as historical records, user interaction.

2. Communication between the physical asset and the Digital Twin database

The physical asset and Digital Twin are configured with a real-time (or near real-time), bidirectional and secured connection. The information that is collected from the physical asset is sent to be processed and stored in the Digital Twin database. This communication method is also used to feedback analysis and information from the Digital Twin engine to perform actions on the physical world asset.

3. Digital Twin Engine - Process and Analysis of the information

The main component of the system we have called the “Digital Twin engine”; it is this part that utilises the various data inputs providing data processing and fusion to support analysis and intelligent decision support. The data stream collected in real time needs to be processed and transformed in order to reduce the storage size, keeping only the key information. All the key information is stored in a database for future use (virtual representation and analysis). This database could be a single unit or a collection of multiple databases connected by “middleware” layer that brings multiple sources together.

4. Supporting Information and Digital Models

Wider information and models are also collected and input into the Digital Twin engine. Digital Models and documentation from the design and maintenance process are fed into the twin to ensure a single point of truth database is maintained. Additional enterprise information and wider information sources such as weather forecasts can also be fed into the analysis to improve the decision support process. With these multiple data streams it is best to think of the twin as a number of twins - or threads - a tapestry.

The Digital Twin is a complex system of systems, working together to provide insight and intelligent decision support. Many of these components exist on their own today, but it is by connecting them into an associated architecture that the Digital Twin is created.

2.1 Digital Twin Reference Architecture

Digital Twins have broad application across defence and the way that they are created is important to ensure coherence, commonality and interoperability as part of the digital eco-system to ensure they can be:

- Simultaneously used by multiple parties
- Scalable to provide a true representation of the physical counterpart, its characteristics and behaviours
- Adaptable through-life, along with the physical counterpart

The process of digital twinning involves a complex integration of different types of technical and context data (structured and unstructured), incorporates technologies and techniques such as Artificial Intelligence (AI) and Machine Learning (ML), data analytics and multi-physical simulations to model and predict the physical entity's behaviour.

The goal is to establish a common blueprint for Digital Twins and an environment by which digital twins can be created and utilised securely and effectively across defence. To achieve this requires:

- A consistent definition for digital twin types
- That all data and types required by the individual digital twins can be integrated into the model; combining both current and historic data, performance and behaviour characteristics, environmental and attributes related to the legal and regulatory contexts within which the assets operate.
- Data is consistently structured and machine-interpretable so it can integrated as part of the digital model
- The integrated data set can be analysed and modelled, using advanced analytics technologies, to truly represent different aspects of the physical counterpart
- The models and output can viewed an interacted with in a consistent fashion.
- There is confidence in data provenance and therefore risk appropriate interpretation of outputs
- Models can integrated to create composite[1] models and can be federated for use across the enterprise and across organisational boundaries.

A reference architecture in the field of software architecture or enterprise architecture provides a template solution for an architecture for a particular domain. It also provides a common vocabulary with which to discuss implementations, often with the aim to stress commonality.

Standardised reference architectures are emerging for digital twins at a National Level, through the Centre for Digital Built Britain National Digital Twin Programme[2] and at an international level though adoption of recognised ISO standards.

[1] A composite digital twin is a combination of discrete digital twins that represent an entity comprising multiple individual components or parts.

[2] https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme

The core of the Digital Twin reference architecture comprises:

> Foundation Data Model: A consistent, clear ontology for the digital twin ecosystem: The framework and principles for sharing, validating and integrating different types of data.
>
> Reference Data Libraries: The standardised models for creating different types of twins e.g. Asset, process, person. The definition of the data standards and protocols to be used for twin creation.
>
> Twin Integration Architecture: Defines the standards and Application Programming Interfaces that allow twins to be integrated to form composite twins and the ecosystem of digital twins to be created and connected in the right way.
>
> Twin Federation Architecture: Defines the protocols to enables sharing of digital twins models and interoperability of different types of digital twins as part of the digital twin ecosystem.

These elements are aligned to an underpinning Information Architecture Framework and infrastructure, or digital backbone, to support secure and resilient sharing of data across the ecosystem. This includes frameworks for device connectivity to physical assets as part of a Defence Internet of Things (IoT) and the communications infrastructure to securely manage IoT data and interfaces to core systems and applications required to support Digital Twins.

Implementation of Digital Twins requires integration of different technologies; open architecture principles should be utilised to reduce proprietary constraints and allow flexibility where software modules can be added, updated and changed within the basic framework provided by the architecture. Data should be exchanged through standardised approaches services and exchanges and Open APIs (Application Programming Interfaces) developed for major software elements to allow integration with digital twins and functionality to be enabled.

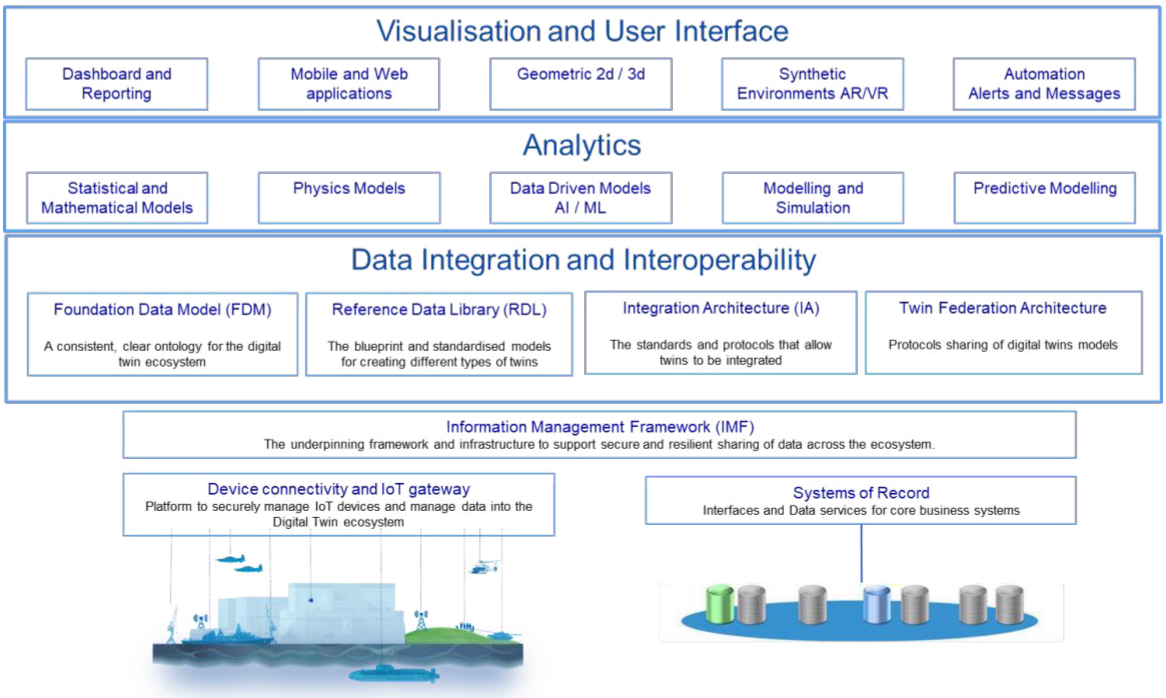

Figure 3: Example Digital Twin Reference Architecture

It is recommended that UK MoD adopt and develop a reference architecture for digital twins to provide the required guidance and a framework for best practice development of digital twins across the defence landscape in a coherent and repeatable way.

2.2 Secure Defence Technology Enablers (Digital Backbone)

Enablement of Digital Twins requires an infrastructure that facilitates easy flow and appropriate access of data, with storage capacity to manage the integrated data models and an environment to host and integrate the tools and technologies required to provide digital twin functionality in a federated way for all stakeholders and parties.

Realisation of digital twins require a modular technical architectural approach with strong information governance and user management. Modern architectural design paradigms for frictionless data[3] and use of micro-services are quickly becoming considered best practice and would provide a means of achieving the future Engineering Support vision for Digital Twins within the complex Defence landscape. These approaches are based upon the following broad design principles:

- **Focused, simplistic and lightweight**: A sharp focus on one part of the data chain, one specific feature and a few specific types of data
- **Extensible and Re-usable**: Design for extensibility and customization, reuse and build on existing standards and formats wherever possible
- **Decentralised and Distributed:** Design for a distributed ecosystem with no centralized, single point of failure or dependence. Data created and stored once, used many times
- **Open with Cross-technology support:** Provide Interoperability with support for a broad range of languages, technologies and infrastructures -- avoid being tied to any one specific system. Integrate to existing software
- **Continuous Development through a DevOps Culture:** a set of practices that automates the processes between software development and IT teams, in order that they can build, test, and release software faster and more reliably.

This type of approach is synonymous with Cloud platforms and architectures. Development of the MoD Cloud Infrastructure should provide the core capability to host Digital Twin technology enablers and services, this needs to be coupled with IoT capability development to provide the communications infrastructure and security framework for device enablement to allow connectivity of digital twins to the physical entities they represent (e.g. asset sensor devices) and extend to allow deployment of digital twin functionality to edge enabled "smart" devices.

Advanced Data analytics, including Machine Learn and Artificial Intelligence capabilities are key components of the digital twin infrastructure to allow large complex data structures to be analysed and sophisticated models to be applied to drive insight and value from the integrated digital twin data sets.

[3] Frictionless Data is about removing the friction in working with data through the creation of tools, standards, and best practices for publishing data using the Data Package standard, a containerization format for any kind of data. (Source: Open Knowledge Foundation)

Software development capabilities with standardised libraries are required to allow the development of digital twin applications (e.g. web or mobile applications) and integration of outputs to 3rd party software such as synthetic environments (AR/VR), reporting, business Intelligence systems and 3rd party systems.

Automation and service orchestration allows these technologies and capabilities to be integrated and data to be interoperable with monitoring of the infrastructure and automated alerts.`

All of these capabilities need to be considered within broader defence landscape architecture and infrastructure enablers to inform the development of common policies, and approaches that can incorporate digital twins, including:

Security: Information Technology (IT) / Operating Technology (OT), Data security and privacy, Network, Identity and Access Management. Encryption / Decryption, Device Management.

Governance: Master Data Management, Meta Data Management, Data Lifecycle Management, API management, model governance, release and version management, standards and protocols, policy enforcement, regulatory, commercial and legal.

Assurance: Data Quality and provenance, model explainability, verification and validation, software testing and assurance, transparency and ethics.

MoD Cloud and standardised technologies should be adopted for the development of digital twins, policies and roadmaps will need to be reviewed and modified as appropriate to incorporate new and additional requirements to enable a consistent and coherent approach and use of digital twins against a common referenced architecture. Where Digital Twins are created with industry, these will need to comply with MoD policy and security accreditation requirements.

2.3 Open Architecture and Standards

An open architectural approach that aims to produce systems that are inherently interoperable and connectable are key to digital twin creation, enablement and management; providing the flexibility required to augment and adapt digital twins through-life, ensuring that:

- Digital twins are discoverable, can be queried to determine their capabilities and composed to provide industrial solutions
- Digital Twin information models are well defined and can be interpreted, data can be surfaced, discovered and ingested from underlying data sources and integrated into the models in a synchronised and managed fashion
- Digital Twin transactions and output can be automated and monitored
- Digital twin models, content and data are securely managed end to end between connected tiers
- Users are authenticated with authorisations to use, update, develop and digital twin managed against information assurance policies and data security requirements

The use of standards play an important role in providing the structure and coherence within the digital twin eco-system both at the macro level to provide commonality and adoption of best practice approaches; within the UK Defence Domain to ensure compliance to policy, technical and security requirements; and at the data level for specific data exchange and information models for a given context.

At a high-level generic Industry 4.0[4] standards can be adopted to enable interoperability, automation and data exchange for manufacturing technologies, including cyber-physical systems, the Internet of Thing (IoT), cloud and cognitive computing; for example:

- Network and system security (IEC 6244),
- Information security and management system (ISO/IEC 27000),
- W3C Semantic Web Stack standards (Schema, Web rule and query languages)
- Enterprise control system integration (IEC62264)
- Classification and product description (ISO 13584/IEC 61360)
- Reference models (Digital Factory, Field Device tools etc..)
- MarkUp languages (Automation - IEC 62714…)
- Industrial automation systems and integration (IEC 61360 / ISO 13584)
- Industrial Process measurement and control (IEC 61987)
- Energy efficiency (ISO/IEC 20140)

These standards help define the basic technical infrastructure and interoperability framework required to support sharing of data and digital twins.

Data and digital twin models needs to be trusted, easily interpreted, contextually relevant and in a form that is usable with new and evolving technologies and concepts for digital twins.

The foundation for this is an Information Architecture that defines the principles, policies and guidelines for the creation, management, sharing and integration of data and models in an agile and flexible way. The Information Architecture should also address not only the means by which data and digital twin models are created, transformed and shared but how this can be formalised as part of commercial arrangements (i.e. contracting for data / digital twin models) with considerations for IP management and protection and any special requirements such as export control.

The ISO19650 standard for Building Information Management (BIM) is increasingly being recognised as an appropriate standard and blueprint to define an Information Architecture for Digital Twins. This standard has been adopted and used as part of the national Centre for Digital Built Britain (CDBB) National Digital Twin programme. This sets out the concepts and principles for specifying the information management process for asset/facility operation and maintenance, these concepts can be applied to complex assets and include the building of information requirements, data exchanges and models as part of an information architecture that can support digital twin implementation. It is recommended that a similar approach is considered within Defence.

From a data perspective there are a number of existing information and data exchange standards within the scope of Asset management, Product Life Cycle Support and Technical Documentation. Part of the development of an information architecture should consider the suitability of such standards to meet the future engineering support vision, their maturity, gaps, areas of conflict or overlap and practicality for Digital Twins.

The main internationally recognised standards associated with Product Life Cycle Support for Aerospace and Defence are:

[4] Industry 4.0 refers to the transformation of industry through the intelligent networking of machines and processes with the help of information and communication technology (ICT).

* ISO 10303 - an ISO standard for the computer-interpretable representation and exchange of product manufacturing information. Informally known as "STEP", which stands for "Standard for the Exchange of Product model data". ISO 10303 has a series of Application Protocols (AP) that can represent 3D objects in Computer-Aided Design (CAD) and related information for product life-cycle support

* The ASD S-Series of Integrated Logistics Support (ILS) specifications - A set of specifications associated to different integrated logistics support aspects, including:

    - Reliability engineering, maintainability engineering and maintenance planning
    - Supply (spare part) support - Packaging, handling, storage and transportation (PHS&T)
    - Support and test equipment/equipment support
    - Manpower and personnel
    - Training and training support
    - Technical data/publications

Any review of specific data exchange standards should consider maturity, future direction and alignment to modern service based technology architecture principles with their use considered alongside Industry 4.0 standards and ISO 19650.

It is recommended that existing standards be utilised where possible and incorporated into Joint Service Publications such as JSP604 (Defence Networks Governance), JSP440 (Defence Manuals of Security) and JSP935 (Software Acquisition Management for Defence) where applicable.

2.4 Twin creation and through-life management

This part describes the framework, which answers the questions 'What does a digital twin look like? How does it work?' and 'How to build a digital twin?'. It is composed of two main parts:

* Architecture: it gives an overview of what the digital twin looks like and how a digital twin works. It describes the components required to build a digital twin, and how they interact together to make the digital twin work.

* Building a digital twin: it is the main part of this chapter. It describes the steps that need to be followed in order to build a digital twin.

How to build a digital twin?

The actions that need to be undertaken in order to build a digital twin can vary in many ways, depending on the characteristics of the physical entity and the purpose of the digital twin. Although, there are a set of common steps that need to be followed in order to successfully build a digital twin. Figure 2 shows an overview of the process to develop digital twins.

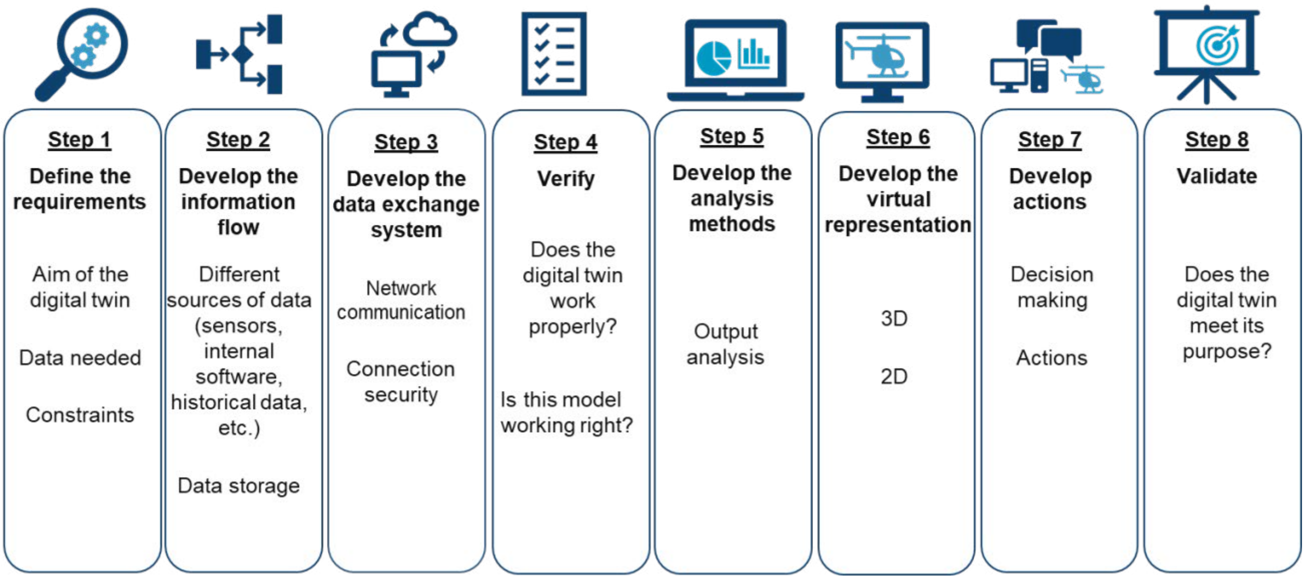

Figure 2. Process to build a digital twin

Each of the steps covered in Figure 2 have an emphasis in terms of data, models, or visualisation, which are highlighted in more detail across the following sub-sections.

2.5 Data collection and management

Step 1. Define the requirements

The first step of the building process is to define the requirements of the digital twin to be built properly. This also focuses on understanding what type of value does the digital twin aim to deliver. The main aspects of this step are:

1. *Aim of the digital twin:* A digital twin can have several purposes. To define the aim of the digital twin, the user needs to answer these two questions:

    - What are the outcomes / values and improvements that the user expects from the digital twin?
    - What kind of analysis does the user expect to carry out with the digital twin?

2. *Data to be measured:* Based on the digital twin purpose, the type of data that needs to be collected has to be defined. It is essential to define what data needs to be measured.

3. Constraints: In most cases, there are constraints that have to be taken into consideration for the development of the digital twin.

Step 2. Develop the information flow

One of the main functions of the digital twin is to collect real-time data that is going to be used later for analysis. Then, this data is stored in a database.
The data can come from different sources:

- *Physical sensors:* sensors are set up on the physical asset in order to collect data from the physical asset itself and its surroundings. Sensors mainly collect two types of data:
    - operational measurements (characteristics of the physical asset; such as position, displacement and torque)
    - environmental or external data (e.g. elements that influence the physical asset; such as barometric pressure, ambient temperature, moisture level).

- *Internal software:* a computer program can be installed on the physical asset in order to collect internal data from the system. These programs can be generic or developed specially for the digital twin, depending on its requirements (such as security, safety, integration, element to be measured, etc.).

- *Historical data:* historical data that has been recorded in the past and stored can be integrated to the digital model and used for further analysis.

- *Data entered manually by the user:* one source of data could be user input. For instance, the bill of materials of a new product, subjective data, visual inspection, etc.

Regarding data storage, and considering the requirements of the digital twin, such as accessibility, size, security, etc.; there are two main ways to store data:

- Local storage: data is stored on a local server.

- Cloud storage: data is stored on an online server. The data can be easily accessed by all the users from anywhere with an Internet access.

2.6 Model sustainment

Step 3. Develop the data exchange system

At this stage, the communication between the physical asset and the digital twin database needs to be established. This must be a real-time, bidirectional interaction/connection. Many different technologies can be used depending on the characteristics of the physical asset and where the digital twin database is stored. Some examples of these technologies are Bluetooth, Wi-Fi, 3G/4G, ethernet, optical fibre, etc.

Network security needs to be considered at this point. The data exchanged between the twins through network technologies can be sensitive. Therefore, the network communication needs to be secured. For example, data can be encrypted when using Wi-Fi or 3G/4G connection.

This is where there is a need to build a link between the data and model of model architecture. The link needs to allow a wide variety of data and models to interlink in an effective way. This is important as it is the basis for the digital twin to be sustaining an accurate representation of the physical asset and processes.

Step 4. Verify

The digital twin needs to be verified in order to ensure that it accurately mimics the physical asset's behaviour in the most accurate way. The verification consists of checking if the digital twin works properly and if both assets exchange data. For example, checking that the digital twin is updated after the physical asset performs some actions.

Step 5. Develop the analysis methods

Once the digital twin is verified, the data collected needs to be analysed. This step is crucial to ensure that the purpose of the digital twin is achieved. There are different ways to carry out analysis. Some examples are:

- Compare data taken at different times
- Check if some criteria are met
- Do statistical calculations
- Identify patterns
- Physics based models
- Rule-based reasoning
- Logical inferences
- Deductive and predictive models

Finally, based on this analysis, the digital twin can recommend the physical asset to perform some actions.

2.7 Output and visualisation

Step 6. Develop the virtual representation

This step involves building the virtual representation of the physical asset. This analysis can be displayed in tables, pie charts or graphs and many other visual methods. The virtual representation can be done in different ways, depending on the following possible analysis of a digital twin:

- Geometrical / Geospatial analysis: A 3D representation of the physical asset is created using a CAD software.

- Mathematical / Physical analysis: The physical asset is displayed as a 3D representation using a CAE software in order to carry out the simulation (for example, a FEM analysis).

- Business intelligence analysis: A can panel/dashboard is developed in order to display the main information. Even if it is not essential for this purpose, a 3D or 2D representation can be realised to have a better representation of the physical asset.

The focus here is on how do I want to communicate the outcomes from the digital to the decision maker?

  - Paper based
  - Desktop based
  - Virtual reality
  - Augmented reality
  - Mixed reality

Step 7. Develop actions

Once the data is analysed and visualised, the user has to implement condition-action rules to be automatically perform over the physical asset depending on the analysis obtained from data, and thus fixing errors over the physical asset.

Step 8. Validate

The validation is the final step. Considering the purpose, the user must define a suitable process to carry out the validation. The point of this validation is ensuring that the digital twin achieves the objectives defined by the user at the beginning of the creation.

Summary

To summarise the digital twin development process there is a need to apply a systematic process by addressing the following questions:

- What is the value creation opportunity?
  - Availability
  - Cost
  - Agility
  - Maintainability
  - Reliability
  - Efficiency
  - Net zero

- What is my role and what decision am I trying to make?
  - Strategic: e.g. what is the optimum profitability/ affordability?
  - Operational: e.g. what is an effective maintenance plan?
  - Tactical: e.g. how do I maintain a kit efficiently?

- How do I want to communicate the outcomes from the digital to the decision maker?
  - Paper based
  - Desktop based
  - Virtual reality
  - Augmented reality
  - Mixed reality

- What models will I need to develop to assist the decision making?
  - Physics based
  - Cost based
  - Performance based
  - etc

- Will there be any added value from interlinking different models?
  - Yes: e.g. cost and physics models
  - No

- What data will I need to feed the models? And how?
  - Degradation: e.g. sensors and visual inspection
  - Cost: e.g. incurred costs from suppliers
  - Maintenance outcomes: e.g. technicians filling paper/digital forms
  - etc

2.8 – Test and Assurance

The implementation of a Digital Twin will mark the introduction of a completely new methodology and will require new test and assurance processes to support this. This new methodology will be under significant public scrutiny, so it is important to plan for a rigorous testing programme to ensure a smooth transition period showing a positive impact of the technology.

As described in section 2.0 the Digital Twin is system of systems and will need to be tested and assured in such a way. Each individual component will need to be tested both in isolation and as part of the wider connected system. For this reason the standard V-Model for software development may also need to be re-configured to enable a more iterative process as elements are added and connected to the wider Digital Twin . We also need to consider the wider testing methodologies, for a complex system testing multiple connections with black box testing will not be sufficient to enable the effective identification of errors but white box testing could drive up testing time and costs. Instead a hybrid grey box testing approach could be used. This hybrid grey box technique will enable the transactions to be explainable and traceable, a key part of enabling trust in system design.

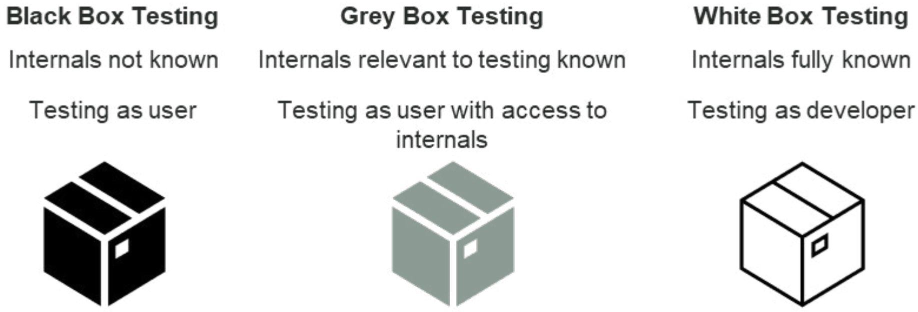

Figure 4 - Black, Grey and White Box Testing

Testing complex systems is nothing new, but the key additional part here is the data and the validation of the data as well as its transmission. It would not make sense to be doing full regression testing every time the system is changed or new components are added; instead there needs to be something in the system of systems federated approach to enable this or lay out the rules of engagement.

As with all computing applications the quality and governance of the data will be essential to extracting reliable actionable insights. Data Governance is the formal execution and enforcement of authority over the management of data and data-related assets; it ensures that the values of that data are identified and exploited to the fullest extent. Data Management on the other hand is the execution of managing data to achieve goals, i.e. it ensures that an organisation gets value out of its data. Assurance of effective data governance and management will ensure the strong foundation for sustainable and reliable Digital Twins.

Another important assurance consideration to make is the need for Information Security and Cyber Security. Digital Twins will need to adopt secure by design approach to enable effective progressive assurance throughout development, followed with comprehensive cyber testing.

A key question to ask is, “who in the MoD will have overall responsibility for regulating and assuring the Digital Twin?” There is potential for this role to be shared amongst the existing regulating bodies including the MAA in aviation, DMR and NAG in Maritime and DLSR in the Land domain. However, it is critical that the system is considered as whole, thinking towards the future and the possibility of joint force Digital Twins one body may need to regulate and assure the whole system. To enable this effective cross domain assurance there could be a range of overarching guidelines or standards to assure against. Further work is required to engage with stakeholders to understand requirements for a Digital Twin defence standard or guideline document.

Further Work
In order to progress this element of the roadmap further work is required to:

- Understand and test how an iterative V model could be developed for Digital Twins;
- Determine who the regulatory body for a defence Digital Twin will be; and
- Understand requirements for a defence standard or guideline document.

2.9 – Resilience and Adaptability

Resilience
Military platforms, especially in the maritime domain, are often designed to last 50+ years, the Digital Twin will also need to last just as long if not longer, covering the lifecycle of the asset from concept to disposal. The rate of change of the underlying technology for these platforms and their systems is much faster, for example looking back over just the last 10 years there have been three different windows operating systems in place all with different software and infrastructure requirements. If a Digital Twin is to last 50+ years then it will need to be resilient and adaptive to evolve with the changing technology landscape as time goes on. Going back to the previous sections of this report we will need to take a through life management approach to ensure the long term resilience of the twin. To remove this possibility of obsolescence the data has to be the lowest common denominator so that anything can read it and interact with it, and systems and databases can be upgraded around it.

As well as longevity the Digital Twin will need to be reliable. The system will need to be available, assessable, up to date and robust so that it can become a trusted part of the decision making process. To support this vision and enable accountability the twin will also need to implement version control, allowing a traceable record of changes in time. If any components fail or the system was to go down then the information will need to be secured. Component parts could utilise their own built in test or self-health monitoring to ensure data validity. This could form part of any data management and governance requirement ensuring

Adaptability
The Digital Twin will also need to be able to adapt, to ensure its continued applicability. The twin will need to be able add new systems and account for through life upgrades to the physical items adapting and changing in an analogous manner to the real item. In order for the item to stay up to date the system could deploy a data centric model instead of a document centric view, providing a central point of truth. This would enable guidance documents, training courses and maintenance guides to all change with a click of a button preventing hours of re-work. The benefits of such a system would be large but the challenges required to change both culturally and commercially are equally great. If you would like to know more about these commercial constraints please see section 4 of this paper.

The connections and communication networks are also likely to adapt as time goes on. As new items are added in real life and as contracts change new manufacturers and support teams can be added. The Digital Twin will need to be just as much as an evolving item as the physical item; this may require a dedicated support team to update and maintain the twin, ensuring an uninterrupted delivery of service.

Further Work
In order to progress this element of the roadmap further work is required to:

- Understand the through life support aspects of a Digital Twin

2.10 – Scalability and Interoperability

The question of scalability and interoperability in Digital Twin design shows an understanding that complex fleet wide systems cannot be created overnight but instead will need to be built up from multiple building blocks.

Scalability

When creating a digital twin for a large warship, it is probably unfeasible to assume that one can create a singular coherent twin system overnight, especially considering the large number of different original equipment manufacturers and potential information owners; instead it could be much simpler to start at a system level and scale up. Some systems like the prime movers may already have their own Twin systems allowing manufacturers to monitor performance with information going straight to their servers. Some smaller systems could be connected via the Integrated Platform Management System with information collected directly by the operator. Instead of forcing a rigid singular structure there is a need for a federated model that can scale to fit and allow MoD and industry twins to be combined for full platform/fleet level insight; in other words a Federated Enterprise Vision for Digital Twins.
Another scenario to consider which would support the call for this federated system, is the understanding of how parts and system can be interchanged between platforms. For example in the land domain it is common for faulty systems such as gearboxes to be switched out entirely to minimise workshop downtime and maximise platform availability. The faulty system can then be repaired in due course and used on other platforms in the future. Under the proposed federated model, the system level twin will remain intact but switch seamlessly between platforms when it is attached.

Interoperability

In order to extract the full benefits of a Digital Twin there is a strong need for interoperability been domains and allied forces. For example when operating a carrier strike group with combined selection of maritime, air, amphibious and land units, the ultimate goal would be to bring all these twins together to answer the key operational questions. In order to answer the question of “can this carrier strike group support another 2 weeks on station” we need this combined Digital Twin with a top level coherent view of all the assets current states and their predicted future states. This interoperability raises a wide range of challenges and need for consistency; this can be achieved either through standardisation or the implementation of middleware, great deal of the interoperability can be solved at the data level so it is not necessarily a technology issue.

One example of where this problem is already being tackled is by standardisation in the past is the NATO Modelling and Simulation Group (NMSG), who have produced STANAG 4603 for interoperability; whereby Participating nations agree that procurement and new development of simulation systems are compliant with the latest version of IEEE 1516 (HLA) and utilize the HLA Compliance Certification Process established by the NMSG. A similar approach and standard could be created and adopted for Digital Twins to ensure the wider interoperability not just between domains but for pan-national NATO Digital Twin interoperability.

As previously discussed under “2.8 Test and Assurance” the question of interoperability also raises the question of who can regulate and assure a pan domain / pan nation system. Individual systems can be individually controlled but some approval will be required for the overarching system and a suitable regulatory framework put into place.

In summary, when considering the constraints and application areas of Digital Twins to the UK Defence sector due to commercial and technical barriers a “federated enterprise vision” would allow a smooth scalable and interoperable model for digital twin creation.

Further Work

In order to progress this element of the roadmap further work is required to:

- Investigate requirements for an interoperability standard.

3. Decision Making Tools

Digital Twin Roadmap - Section 3: Sense and Decision-Making Tools

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3.1 Digital Twin Types

Digital Twins are made up of two main components: the Digital Twin Model and the Data Stream from the physical "Thing" it is representing. Without the data from real-life, any digital representation isn't really a Digital Twin, it's just a digital model.

There are many different models used in MOD and its supply chain to predict the outcome of some physical influence or process. It is in the feed of real operational data into these models that make them become digital twins.

Digital Twin Principal: A digital twin connects data from the real world to a digital model.

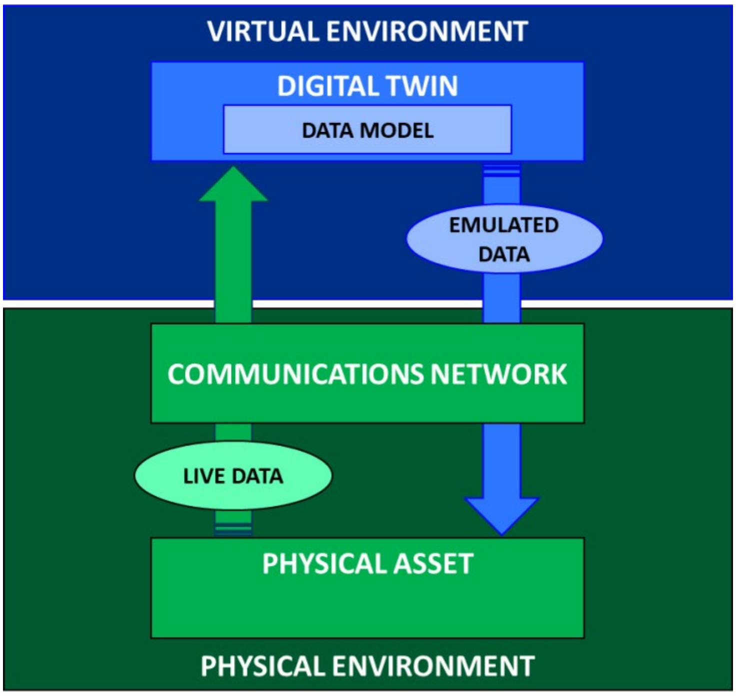


Figure 1 - Overview of Digital Twin

There are basically two methods to deliver digital twin:

- Forward facing. The model uses previously known rules to predict the outcome of an event. Data from real-life validates and improves the model.
- Rear facing. Rules and existing knowledge do not exist to predict outcomes, or the variables are too numerous to enable accurate and fast calculations. So large amounts of data of physical conditions and operational outcomes are streamed from real-life into a digital model and algorithms are used to analyse the data. Patterns are searched for to help predict future outcomes by matching previous conditions and previous outcomes.

The basic two types of deliverables of Digital Twins are:

- Digital Twins of People and Process; predictive models based on actions, decisions and likely outcomes.
- Digital Twins of Physical Objects; models based on physics-based rules, fed by real world environment variables.

Most Digital Twins will be a composite of a variety of types and as a result will require tooling to enable composition and orchestration in use. This especially true in a Defence Environment, where operational capability is delivered through a mix of equipment, facilities, people and process.

3.2 Digital Twin Modelling Types

There are hundreds of ways of digitally modelling something. From simple data lists, flowcharts, diagrams, rich pictures, 3D CAD, 5D BIM, VR walkthroughs, Physical prototypes and more. The closer to reality the model is in look and feel, the easier it is for people to understand, but the harder it is to create, so a balance must be made between effort and value.

As previously mentioned, the difference between a plain digital model and a digital twin is that real-life data must be connected to the digital model. This does not have to be a live stream, it might be incremental readings, or even manually entered. But if a digital model cannot take in data from the real world it doesn't become a digital twin.

In most cases the data will want to be automatically imported/ exported. Therefore, the digital twin model, and the data stream from the real world, must be aware of what the data is and where it maps to. This needs to be done in a robust fashion so that if there are changes to the type of data that it is flagged and checked as still accurate.

Digital Twin Principal: A digital model must be able to import and export data for it to be used in a digital twin.

An important aspect of enabling export and import is ensuring that information exchange is coherent and adequately described/captured to support the necessary analysis and decision support. Within the Defence environment, we will need to understand the importance of latency and delay in the information exchanges. For example, it may be that in exploitation of the digital twin to make purely supportability decisions may be acceptable with information exchange delays of days, however, the same digital twin information set may be exploited for an operational decision and require a latency in minutes. It is unlikely, that any information exchange will require real-time or near real-time data exchanges.

3.3 Digital Twin Tool Types and Examples

Noting the complexity of Digital Twin types and models an important aspect of exploiting Digital Twins and enabling informed decisions will be the governance, adaption/translation and on-going management (i.e. tooling to maintain adapter libraries, enable integration, and exploitation)

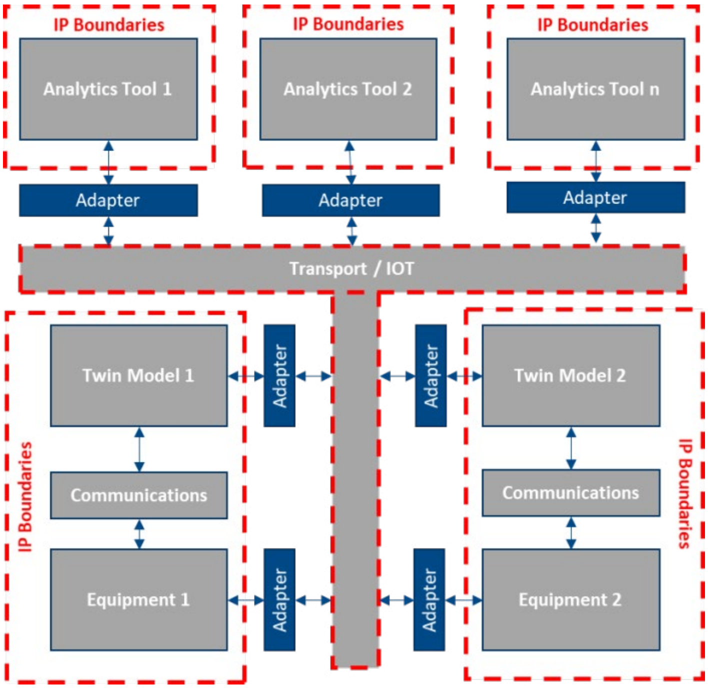


Figure 2 - Adaption of Information for Exploitation

3.3.1 People Digital Twin Tools

People like to think they have independent thought, but numerous statistical and analytic models can quite accurately predict people's behaviour. There are many very good tools to model how humans are likely to react in certain situations. These models can be driven by analysis of previous behaviours or by applying known rules. The rules can be based on process rules, physical constraints and ergonomics.

An example of a People Digital Twin Model could be a Process Simulation of a maintenance operation. 3D avatars can work on 3D CAD models to dis-assemble and re-assemble some machinery. The CAD model may contain the sequence for the operation and the avatar will perform the task. Using empirical knowledge about typical wrist strength will predict whether screws can be removed with hand tools or power tools. Multiply this by the number of screws will give fatigue predictions and can even model the reduction in quality and speed with the increase in fatigue. This model will be able to easily add up the time of each operation to give an overall process time, and quality estimate. These models become digital twins when data is fed back into them from the real operation. Modern process modelling tools usually have an added benefit that the predictive model can easily be re-purposed as an electronic work instruction and hence can automatically capture completed steps and time information.

A much simpler example of a People digital twin model might be a spreadsheet of temperatures and humidity's where people of different nationalities are comfortable to work. Connecting this spreadsheet to a thermostat and humidity sensor creates a simple digital twin.

In a defence environment, the exploitation of biometric sensors on individuals in the operational environment being compared with a generic model of a combatant to understand their supportability requirements, or operational suitability.

3.3.2 Process Digital Twin Tools

Process digital twin models are used to predict any discrete process, usually to optimise things like time to complete, quality and cost. Time and Motion Studies were and early form and combined visual and mathematical models into modern computer-based Process Modelling tools.

An example of a Process Digital Twin may be a factory floor. 2D drawings/ BIM models will show the layout of the factory. This might be coupled with an Excel spreadsheet of estimated time to process material through each stage in the factory. This may even be linked to the company Enterprise Resource Planning (ERP) tool, giving a target output of production and prediction of order fulfilment.

These digital twin models may be combined and can then be modelled into an animated predictive model showing material flow through the factory and the appropriate estimated processing time at each station. What-if analyses can be completed to see if adding more machinery or personnel to certain stations increases overall output. It is also possible to step this up to full 3D interactive models, which with VR environments can be used to train personnel and test the model.

To enable the digital twin by connecting real-life data in this case it’s quite easy; machine tool completion time and counts can stream live from each cell. Inspection reports and order completion notes can come in from each point in the manufacturing process. Then the model becomes a Digital Twin, and analysis can happen on the discrepancies between predicted values and actual values and corrective action can be made.

Within the Defence environment, it is likely that the process model will be key to managing and continually optimising the support chain in response to changes in the operational environment, such as location, environment, usage.

3.3.3 Physical Object Digital Twin Tools

Physical object digital twin models usually combine geometry and physical or mathematical rules to give confidence the object will perform as required in the expected physical conditions. The infamous Engineering Formulas Handbook by Gieck has been used by engineers to apply these rules since the 70’s. Fortunately engineers have worked with software developers and there’s now a piece of software that will be able to apply nearly every rule and condition you can think of making calculations quicker and more accurate.

An example of a Physical Object Digital Twin could be a Gas Turbine. 3D CAD models combine with Simulation software packages to apply the rules of physics and predict items like: Stress, Temperature, Erosion, Fatigue, Combustion, Electromagnetic emissions, Vibration and Noise. These all help to optimise the design for weight, cost, durability and performance, before even any component has ever been made.

This raises a further issue for Digital Twins: nesting models together and maintaining the appropriate configurations and versions so that they all update together. We'll deal with that more in section 3.4.

When the turbine has been commissioned and is operating, data can be measured like temperature, pressure, rotational speed and vibration. This can be fed back into the digital twin models to re-run the simulations and get up-to-date predictions for life, efficiency and performance. This creates a digital twin of the turbine.

For simpler objects, the design checks may be made by standard engineering calculations stored in a spreadsheet. These can similarly be linked to the real-world data to update the outputs and confirm the operational parameters.

3.3.4 IoT and Data Connection to Physical World

As discussed, real-life data is key to digital twins. There are three main areas these are broken into:

1. Manual Analogue Transfer: Reading the appropriate data from real-life and then manually entering it into the digital twin model. This has high risk of data errors, is high manual effort and hence tends to happen at low frequency.
2. Manual Digital Transfer: A data set is manually extracted from real-life, usually into a spreadsheet or csv file, and then manually imported into the digital twin model. This has a low risk of data error, but high risk of incorrect mapping of the exported data points to the imported drivers of the digital twin model. It's a medium effort process, so tends to happen at a medium frequency.
3. Automatic Digital Transfer: Data is automatically exported from real-life and sent to the digital twin model. This method is very easy and accurate but requires more up-front development and validation to ensure the right quality.

It is clear that most users of digital twin will want to get to position #3 as quickly as possible, which brings more considerations of how to achieve it robustly.

Methods of collecting data are nearly as numerous as the data types themselves, but all usually are made up of a chain of:

- Sensor
- Collector
- Transmitter [maybe expand here about transport layer/ network etc.]
- Receiver

The sensors stream data to the collector, this stores data and prepares it for transmission. Sometimes the collector can also perform some first-pass analysis, filtering out unwanted data or recording only trending data. At the required intervals (or live) data is transmitted over the inter/ intranet to the receiver. The receiver host computer is then where the digital twin model runs with the inputted real-life data. User-monitors can then be informed of the new updated model results and apply any corrective action.

Two key enabling technologies in this chain are:

- Edge Computing, small computers with limited tasks, enabling running digital twin models, or collecting and analysing data, at the real-life asset location.
- IoT Operating Systems provide a location to transfer and source data and run digital twin models. Use of IoT OS simplifies deployment of digital twins.

A real-world example is a Wind Farm that has a "Model Predictive Control" (MPC). Wind speed is measured across the wind farm with LIDAR, sensors on the turbine measure rotational speed and vibration. The wind states and turbine condition are fed in to the MPC digital twin and algorithms predict the control variables that need to be fed back to the blade controls. All this is done with edge computing at the wind turbine. Further sensor data measures power output, and this together with the trending data from the MPC is sent via the internet to an IoT OS for trend analysis and operational reporting. This data is then fed to a further digital twin modelling predictive maintenance requirements.

Demands on communications capacity are high in the Defence environment. This means that the capacity management and prioritisation of specific information exchanges is and will continue to be important as demand and supply of communications capacity continue to rise at different rates. It should be noted that the demands of security and cost of investments tend to result in information exchange capacity lagging the commercial sector.

3.3.5 Data Science and AI

Data Science is a very broad topic, but generally is the art of combining traditional statistical analysis with computer science techniques to create repeatable, testable models on scales that would be otherwise impossible. The reasoning behind this function definition rather than classical statistics is the scale and volume of data involved; the advent of increased computer processing power has meant that statistical models can be built using black-box techniques (machine learning/AI). Machine Learning gets its name from the concept the model parameters are not explicitly set, but instead 'learned' by the model (commonly through gradient descent) by feeding it vast quantities of example data. With traditional computer science these models would need to be hard coded, and with traditional statistics these models would be too simple. The output of these machine learning models is sometimes called AI and have permeated our everyday life (online recommenders [Amazon, YouTube], automatic pricing [Zoopla, WeBuyAnyCar], image recognition [locating faces in photos]).

Much like the advent of machine learning producing accurate predictive models, new techniques around neural networks (or Deep Learning) are showing remarkable accuracy with broad ranges of applications. Whilst neural networks are not a new concept, they have traditionally taken too long to train to be useful; moving the computation from CPU to GPU has made this leap possible.

The common pipeline for data science runs like the following:

- Data ingestion
- Data cleaning
- Model Selection
- Model Training
- Model Testing
- Validation
- Deployment/Visualisation (depending on use case)

The tools and methods for data science are varied. They tend to sit in either Python or R, but the differences are mostly user preference – the concepts are broadly the same. Machine learning libraries are too numerous to list, as they each have their own speciality, but a few Deep Learning libraries have set themselves out as the popular choices (TensorFlow, Keras, and PyTorch).

3.3.6 Composition and Orchestration

A very simple model may take only a single data point, or stream of single readings, from real-life to create a digital twin of that point. Taking a federated approach and nesting the models together and bringing in multiple data streams will make a more comprehensive digital twin that will result in higher level insights such as, “Will I survive this manoeuvre” or “When should the next maintenance activity take place under these operating conditions”.

As has been discussed above a “Digital Twin” may be made up of many different digital twin models, each one calculating, simulating and analysing a different effect or phenomena. The tools simply do not exist yet to incorporate all these multi-aspect parameters, to the level of detail that each require, into a single model. So, a multiple model approach must be used and there are several considerations around the composition and orchestration. Those considerations are largely around the trade-off’s between robustness and flexibility, and between accuracy and speed (of supplying the answer).

Digital Twin Principal: A simple digital twin must be able to be nested into a complex digital twin to enable higher level insight.

Robustness is the considerations of sensitive the digital twin models are to change. Change is inevitable, but how hard is it to incorporate change into the model, how easily does the change flow through the federated and connected models. **Flexibility** is the ability for changes to be made at any point in the chain, and not break the links, so different insight can be gained.

Accuracy is the confidence level that the digital twin model will match reality. **Speed** is the calculation time to reach the required level of accuracy, on the compute resource that is available to calculate it.

Here are some of the considerations you will need for robust federated Digital Twins:

a) **Units**. It is critical to ensure matched units, if one model is exporting mass in kilograms, you need to be sure that the next model isn’t expecting it to be imported in grams or pounds.
b) **Tolerance.** Each model needs to be considered at a similar level of detail so that the overall accuracy can be considered correctly. Much like tolerance stack-up on an engineering drawing, it’s no good machining 10 parts at +/- 0.1mm, and then one part at +/- 10mm and expecting the overall assembly to be accurate to +/- 0.1mm.
c) **Federation Structure.** Do you need to connect models together from different disciplines to form multi-physics twins of components and sub-assemblies? Or do you need to connect models together from the same disciplines to form functional digital twins at the top level?
d) **File Location and Access.** Where are the files of each digital twin model stored, and who has access to change them? Do the tools used to create them allow the separation of permissions to change the file as opposed to just running the model? And critically, who has permissions to <u>move</u> the files, and how do links to related models get updated if they are moved?
e) **Change Management.** How do you track the changes made to the models, and ensure they are still in line with the physical objects they are supposed to be twinning?
f) **Configuration Management.** How do you track variations in the digital twin models between similar configurations? For example, differences in components on the physical objects of the same items in a class?

Digital Twin Principal: Complex federated digital twin models need to be carefully managed.

Two common solutions to the issues listed above are: Model-Based Systems Engineering (MBSE) and Product Lifecycle Management (PLM)

MBSE loosely deals with issues a) to c) above. MBSE isn't a "tool" it's a methodology to connect things together in an auditable chain and deal with some of the interface issues listed. The method and tools used to implement successful MBSE depends on your models and processes, but frequently link Requirements management tools, Systems Simulation tools (also known as 1D simulation), and Data management (frequently PLM).

PLM will manage the issues d) to f) (and more). The underlying deliverable of PLM is a combined environment for managing process and file management. If PLM is not available, it is possible to use separate process management and file management tools as long as the data links are robust between them to deliver a strong digital thread. Typical parts of this chain may include Engineering Lifecycle Management, Content Management, and Knowledge Management tools. Separate tools also exist for Change Management and Content Management that either integrate or run parallel to the previously mentioned tools.

A final consideration will be **Integration** between the various tools and environments. Most software applications will have some form of IO that enables data import and export routines, and most IT departments will have some skills writing bespoke scripts to link systems or extract data. But there are also many COTS software applications that deliver a standardised platform for integration between multiple tools. The advantage of the platform approach to integrations is that each tool integration is written in the same way, and therefore is easier to manage when applications are changed or updated to new versions. These applications are usually branded in **Manipulation and Integration (MI)** for integrating software applications at a platform level, or **Business Intelligence (BI)** for interrogating multiple software applications to extract key pieces of information.

3.4 Tools Adoption Roadmap

The good thing about the current analysis is that nearly every part of the defence supply chain is already on the digital twin journey. There is a plethora of digital twin models in existence and in extensive usage. Some of those have already been connected to real-life data to create functioning digital twins. As has been previously discussed, some of these models and tools are better suited to the connected digital twin and federated modelling techniques due to their open architectures. If a model has no standard way of getting data in and out automatically, it drastically limits its usefulness in digital twins. It is true that nearly every digital tool can be reverse engineered to enable a bespoke script or custom modification to enable IO. But any bespoke scripting is both slow and hard to maintain, when versions are updated, or models change the scripts will need re-writing.

Digital Twin Principal: Models should use standardised methods of IO and have configuration not customisation at heart.

To continue getting better and extracting more value from digital twins the following steps must be taken on the tools.

1. Audit your models:

a. Can they be un-picked and understood by future generations, so people know what it's actually doing?
b. Does it have an easy IO method, like an open API, or standard IO with ASCII, CSV etc?
c. Does it offer real value?
d. Does it have proven accuracy?

2. Audit information and data ownership:
    a. Join consortia, organisation and standards bodies that are defining approaches and standards associated with Digital Twins;
    b. Ensure all equipment, modelling, data extraction, transport and analytical tools provide digital data in a known format;
    c. Gain data access and exploitation rights for existing equipment, modelling, data extraction, transport and analytical tools;
    d. Ensure acquire data access and exploitation rights for future equipment, modelling, data extraction, transport and analytical tools from point of purchase;
    e. Build information and data adapters to allow data to be exploited;
    f. Maintain a library of information and data adapters for exploitation through life and across Defence.
3. Decide where to improve:
    a. Re-model where needed, adding value as a must if doing so
    b. Standardise on methods and tools as much as possible, focussing on openness and interoperability
    c. Identify nested and connected requirements and start creating complex models
4. Start to connect to real-life:
    a. Use a robust standard method as much as possible. Don't re-invent the wheel each time with bespoke solutions.
    b. Extract value, store data for future analysis.
5. Implement a Digital Twin Management System:
    a. Decide how to manage change, configuration, validation
    b. Create or use an Enterprise Architecture that delivers now, and in the future
6. Create Complex Digital Twins:
    a. Connect digital twin models together in a robust way
    b. Increase the accuracy and performance of individual models
    c. Optimise system model performance by running high-resource models at the right time
7. Iterate #2 to #5 until you reach the required Platform level vision.

4. Enablers

4.00 Use Cases and Demonstrations

Relationship other elements:

1.0, 5.0, 5.1

Description

This would be a description of the uses cases and demonstrations, against each, that would describe the scenarios in which a DT approach is expected to add value for stakeholders across the Defence Support Ecosystem.

It should be based on a strategic plan linked to drivers e.g. JF 2025, Defence Support Strategy 2025/30.

Its purpose is to provide a pragmatic and realistic “glide path” to demonstrate a maturing approach over time that can be followed using agile development techniques. Intention is to avoid too much time developing an end state before practical evidence is created

The use cases can provide evidence to wider business case(s) and support the development of the concept of operations for managing the use of DT.

Use cases should be sought from across the Support Network and Supply chain.

Current State of the Art

The initial white paper has some indicators as to the likely source of use cases and describes some of the enablers that use cases would need to resolve.

Current good practice can be found in the application of the following techniques:

- Strategic Road Mapping
- Ecosystem Mapping
- DevSecOps
- Persona Analysis
- Design Thinking
- Portfolio Analysis
- AIOps

As already recognised the Centre for Digital Built Britain has much valuable content that can be transferred directly of with tailoring to the defence environment.

Suggested Investment activities

A Strategic road mapping exercise to capture key drivers across defence support.

Early investment in co-development of demonstrations.

Key MOD Stakeholders

Defence Support, DE&S, FLC’s.

Supporting Evidence Links

https://www.cdbb.cam.ac.uk/

4.0 Data Access Rights

Description

Data access in the context of Digital Twins is a critical component of the enabling digital infrastructure and has a number of dimension:

- Ownership & commercial relationships and Intellectual Property (IP)
- Export control
- Security requirements
- Technical solutions & standards

Digital Twins may enable access control over specific data. A complex system which has multiple suppliers accessing it, will require different access rights for each, as owners of the information. Access management provides a common framework for systems, services and applications to conform with for coherence for the entity and for the business.

Access rights is a fundamental capability to ensure security through the different security levels within the context of the Defence Industry. It is also an enabler to ensure efficient and relevant access to user needs depending on their role within an organisation.

Data access rights will need to take into consideration:

- Data systems architecture
- Data standards and management principles
- Data governance structures
- Metadata generation and management
- Assurance and quality

As data is created, stored, and utilised, the digital twin environment will need to be aware of the implications of Intellectual Property (IP) ownership, management and security. Working in aligned collaborative environments will elevate the requirements for systems to classify data efficiently and effectively, and provide assurance that with a multi-layered security data system these standards are maintained. There is therefore a clear link into element 4.1 of the Digital Twin roadmap.

Current State of the Art

Current industry access management standards:

Auth 2.0 is the industry-standard protocol for authorization. OAuth 2.0 focuses on client developer simplicity while providing specific authorization flows for web applications, desktop applications, mobile phones, and living room devices. This specification and its extensions are being developed within the IETF OAuth Working Group.

The OpenAPI Specification (OAS) defines a standard, language-agnostic interface to RESTful APIs which allows both humans and computers to discover and understand the capabilities of the service without access to source code, documentation, or through network traffic inspection. When properly defined, a consumer can understand and interact with the remote service with a minimal amount of implementation logic

Alignment with BIM: BS EN ISO 19650-5 Security minded approach to Information Management - This document is intended for use by any organisation involved in the use of information management and technologies in the creation, design, construction, manufacture, operation, management, modification, improvement, demolition and/or recycling of assets or products, as well as the provision of services, within the built environment. It will also be of interest and relevance to those organisations wishing to protect their commercial information, personal information and intellectual property.

The referenced TD.info work with MOD on federated identity has focused so far on federated authentication but further work with the MOD project team is expected to commence in 2021.

TD.info has also done some work under the Export Controls / Waterguard project on the consistent marking of digital items with metadata covering national security and commercial sensitivity as well as export control, see the Metadata Standard for Team Defence.

The combination of these two activities provide much of the foundation for the federated authentication capability which will be required to support many digital twin scenarios.

The emergence of zero trust approaches, architectures and technologies.

Suggested Investment activities:

Further investment into how technologies and methodologies such as NLP and distributed ledgers could enhance the IDAM (ID Access Management) capability landscape should be considered. Together with this additional consideration into the overlap or hybrid relationships between biometric security technologies and how they can play a role within distributed networks.

Look at how Digital Twins operate in a zero trust environment.

Key MOD Stakeholders:

Unaware of any Stakeholders at this stage.

Supporting Evidence Links:

https://secure.teamdefence.info/community.php?sid=e6fe14894e0686562a65117705f0b744&community=1000098

https://swagger.io/specification/

https://oauth.net/2/

4.1 Intellectual Property

Relationship other elements

Interlinks strongly with data access rights (4.0), data / cyber security (4.5), contracting models (4.4) and business cases (4.2).

Description

In general terms, according to the World Intellectual Property Organization, Intellectual Property (IP) refers to 'creations of the mind—inventions, literary and artistic works, and symbols, names, and images used in commerce'. IP is protected through various IP rights which are enshrined in national law and which seek to prevent the unfair exploitation by others of IP in which the creating organisations have invested.

Whilst the development and use of digital twins falls within this general definition of IP, the concept and use of digital twins is seen by many to introduce considerations which are not necessarily well catered for by existing legal IP frameworks, rights and laws.

Features of the development and use of digital twin models which may challenge existing approaches include:

- Digital twins which extend in scope and complexity beyond the confines of IP owned by a single organisation, including the use of inter-connected networks
- Digital twins which capture explicitly the know-how inherent in developing the real-world artefact they model
- Changes in underlying business and trading models
- The reliance in digital twins on less tangible entities such as configurations of virtual systems or interconnected processing algorithms and data, where existing rights such as copyright and database rights may not be adequate.
- The mirroring by the digital models of real world artefacts – to what extent do IP rights read across?
- The need to cater for varying levels of data completeness, robustness, timeliness, accuracy and reliability.

Organisations need to consider what can and cannot be utilised and shared within the digital twin context without risk of adverse effects on business outcomes.

Providing a Digital Twin for use by a third party, as an object or a service whilst protecting the IP within it.

Current State of the Art

The current 'state of the art' is reflected in existing Intellectual Property law, which is broadly similar in most leading industrial nations. There appears to be general recognition in the context of digital twins and, more generally, in relation to the fourth industrial revolution (albeit that this is not unambiguously defined), that the existing frameworks of legal rights and protections may need to be refined. Some have suggested that this is a 'digital disruption' akin to those caused by the move towards digital music distribution, or the ability to copy designs through 3-D printing.

Existing legal IP frameworks are typically not designed specifically to cater for what should or should not be done in the context of digital twinning. Issues such as warranties for performance, liabilities associated with misuse, how compliance can be monitored and what constitutes a trade secret may need new approaches in this context. However, there will still be a need for organisations to capture and secure rights in order to make the case for investment. Existing law and processes around data protection and cyber security may also be challenged by aspects of the digital twin approach. Data ownership, data governance and access control are all important features affecting IP in this area.

There are few established standards for digital twins, but there are efforts in this direction through an Object Management Group (OMG) consortium – see www.digitaltwinconsortium.org. Adaptations of laws and practices may well need to fit with the outcomes of this.

Alignment with BIM: An 'Information Protocol' was developed by the UK BIM Framework in support of BS EN ISO 19650-2. It provides the standards for managing information for the whole life of assets of the built environment, and the potential to anticipate the requirement for integration across portfolios.

Suggested Investment activities

Support standardisation efforts and efforts to refine legal frameworks for Digital Twins.

Support efforts to develop mechanisms to allow data and digital models to flow freely and securely through wider digital twin enterprise whilst protecting originators' IP.

Key MOD Stakeholders

Key stakeholders are MoD Legal and Commercial teams, whose current IP guidance is summarised in MoD Commercial Toolkit: IP Policy and Principles

Other UK government stakeholders include the UK Intellectual Property Office.

4.2 Digital Twin Business Case

Relationship other elements

1.0, 2.0, 4.00, 5.0

Description

There exists the opportunity to develop a compelling case for the implementation of Digital Twins across Defence, with increased activity around POCs within UK Defence, directly demonstrating value today. Emerging POCs and uses cases provide the fundamental direction of travel and vitally continue to define the emerging vision for Digital Twins in Defence.

Defence priorities[1] focussing on integrating information and physical activity across all domains and Simulating future battlespace complexity demonstrate a clear demand signal for the capability delivered through a broad range of Digital Twins.

This roadmap has identified a number of areas which could be targeted for POC development, however Defence will need to ensure effective expenditure, through confidence in benefits estimation and alternative implementation strategies that may exist as Digital Twin concepts begin to mature in Defence.

There exists the opportunity to accelerate development and adoption across Defence, through development of an overarching Strategic Outline Case, to enable a coherent Defence wide approach. The case should also look to define Defences preferred way forward and whether a more federated vs centralised approach is favoured.

Digital Twins will have an Enterprise wide impact, this systemic and disruptive impact will likely result in significant opportunities to reconfigure Defences overall Transformation portfolio, a Business case for Digital Twins should look to capture opportunities for efficiency across the portfolio, including avoiding expenditure on potentially redundant systems, superseded by Digital Twins.

Given the scale of transformation Digital twins could bring across Defence activities, a standardised and agreed Defence wide benefits framework would provide a significant cohering factor. Additionally as commercial offerings from suppliers mature, the business case should look to understand cost implication from various approaches, to ensure value for money.

Ultimately accelerated development and adoption can be achieved through a creating a shared vision, and development supported through a clear Defence wide programme, which looks to understand cost and benefit implications of Digital Twins.

Current State of the Art

Individual organisations are addressing model development e.g. Rolls Royce have a business case on DT, BAE Systems looking at Model Based Systems Engineering (Air and Maritime), and outside Defence mature programmes at Network rail. Industry partners should be leveraged to support Defence's understanding of the cost implications, and projected benefits.

Little evidence of a defence wide end state for Digital Twin exploitation that is bought into collectively. (End Application, Ownership, business model, value proposition. c/f Digital Built Britain.)

Indications are that business cases are made around specific applications of DT that are tightly bounded to use cases and expected benefits.

Defence lacks many of the enabling aspects that are likely needed to enable a DT application to realise its potential e.g, Information architecture not conducive to making data available, proprietary standards and IP restrictions. Commercial considerations.

The end state is not well enough articulated to build a case – effort in the short term may be better focussed on a strategic route map that has consensus across defence support.

It's not clear presently if the case and associated investment for these underpinning enablers is endorsed across defence.

Built environment being addressed through CDBB has strong end state and value propositions. Not clear if there is a "business case" behind the DBB strategy.

Defence may need to decide what the case is for – digital twin per se or for the **integration** of digital twins along the line of the "National Digital Twin" concept in CDBB.

The ability to use operational data to optimise an enterprise has been proven through the TyTan contract.

Suggested Investment activities

Development of a clear vision for Digital Twins in Defence and articulation of an end state.

Development of a Strategic Outline Business case – to accelerate Defence maturity and understanding of the Digital Twin concepts and identify pan defence appetite for a transformational shift to Digital Twins.

Key MOD Stakeholders

Business case development guidance

Supporting Evidence Links

1. Defence Innovation Priorities
2. ISO 23247 - Automation systems and integration — Digital Twin framework for manufacturing
3. https://www.manufacturingmanagement.co.uk/news/rolls-royce-invests-in-digital-twin-technology

4. https://www.baesystems.com/en/product/eurofighter-typhoon-support

4.3 Digital Twins Policy (1.2) & guidance for scrutineers

Description

Policy will be essential to ensure that the value of Digital Twins can be realised for the defence customer and across industry, enabling provision of services and handling of digital artefacts in a way that is scalable and repeatable.

Policy will be delivered by a range of elements including standards, regulations, and guidelines; and will require engagement across customer and industrial teams, professional institutions and associations, academia, toolsets vendors, and more.

Successful policy will require be championship from positions of authority, including contract offices and regulators, with compliance linked to financial incentives.

Despite the potential for complexity, it is critical that policy remains clear, well communicated, and has the support across the range of stakeholders.

It must be recognised that policy is never "done", and will mature with time, continuously evolving in response to technological, economic, environmental and other stimuli, and also as a result of experience.

State of the Art

Examples of successful policy can be seen in the automotive industry, where a combination of regulation (carbon emission targets) and standards (AUTOSAR) have enabled a highly model-centric supply chain, and supported a shift in market trends towards Electric Vehicles, and ADAS.

There are similar examples in the construction industry, where Building Information Modelling (BIM) has matured through successive policy increments, to the release of ISO 19650 in 2019. The UK Government has enabled this through a number of activities, including the *BIM Task Group*, and the *Centre for Digital Built Britain*.

The UK MathWorks Aerospace & Defence Industry Working Group published guidelines for DO-178B compliance in modelling, supporting increased auto-code generation across aerospace. This is a great example of collaboration within industry.

In defence, the US DoD is leading by example on setting a clear vision for digital engineering, the methodology, strategy and transformation.

Defence should not reinvent policy from adjacent industry. Doing so is both wasteful, and would create barriers to non-defence technologies, tools and companies. For instance, many automotive practises can be applied to the design and operation of military platforms. BIM solves challenges around project planning and lifecycle costs.

Suggested Investment activities

Survey of best practice across other industries and use those as a basis for defence policy adding defence context and specificity

Engagement with the scrutineers to understand their position and come up with a joint positioning paper

Supporting Evidence Links

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi544P02tLtAhWIh1wKHcatClUQFjACegQIAhAC&url=https%3A%2F%2Fwww.arup.com%2F-%2Fmedia%2Farup%2Ffiles%2Fpublications%2Fd%2Fdigital-twin-report.pdf&usg=AOvVaw0HAi2cAji1FvA7ukYRMgnE

4.X Digital Content Maintenance

Description

Digital artefacts support key decisions throughout the lifecycle of systems. In a digitally enabled product lifecycle, it needs to be recognised that design models, test data, and similar artefacts, will need to be revisited, and must be considered as an "in-service" component of the Digital Twin. As-such, they must be maintained and kept operational just as a physical asset would be – "Digital Content Maintenance".

Models are generated to perform a design phase of a system, or tools are created to analyse test data from rigs. These artefacts are typically used for their purpose and then left to gather dust. Problems arise when these artefacts are required at a later date, and are dependent on obsolete software, outdated operating systems, or hardware that is no longer available.

A traditional approach to managing this risk has been to preserve models or IT systems in their current state. This is already costly, and will become increasingly unfeasible as systems become increasingly networked, cloud-based, and cybersecurity becomes a more critical factor.

Achieving this will require a number of activities:

- Adoption of open-standards to improve maintainability.
- Proactive obsolescence management of digital artefacts, software and infrastructure.
- Increased automation, and greater application of CI/CD, to reduce costs of regression testing and certification.
- Contracting and commercial models to incentivise Digital Maintenance.

Current state of the art

Evolutionary design approaches embedded within MBSE that would keep the model up-to-date. Similarly operational IoT gathered data can be used to continually improve machine AI and ML based algorithms.

Aurora Labs' Self-Healing Software enables car manufacturers to proactively respond to future vehicle software architectures, processes and services. They're making connected cars more predictable for the maintenance through the detection of potential software issues, fix, update and validation.

Suggested Investment activities

Develop framework technologies and standards and commercial agreements to ensure the digital twin content is configuration managed and distributed to all the relevant instances of the digital twin, so all users benefit from the improvements.

Supporting Evidence Links

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi2zbWO2dLtAhUIWsAKHXOrD-sQFjABegQIAhAC&url=https%3A%2F%2Fwww.auroralabs.com%2Fwp-content%2Fuploads%2F2019%2F04%2FAuroraLabs_CorpBro_Apr-19_Web.pdf&usg=AOvVaw1w4BBJhf3_SnMBRMvt017p

4.4 Contracting and Specifying Digital Twins

Description

Adoption of Digital Twin technology poses a significant change in operating practices for all organisations, in the Defence context with classification of Data and National Security impacts, commercial arrangements require significant robustness in order to provide all parties with confidence of the existence of necessary protections, safeguards and clarity on requirements.

Service Models for Digital Twins (e.g. SAAS vs supplied software) are maturing, a variety of such models will require a comprehensive and diverse range of commercial mechanisms. Where Digital twins are offered with support contracts consideration will need to be given to managing supplier power and clear guidance on the complete Digital Twin lifecycle including arrangements when 'decommissioning.' Commercial arrangements will need to incentivise delivery of output and clearly define risk and who owns it.

The breadth of potential digital twin 'types', and use cases provides a broad landscape , interoperability between twins creates additional requirements. As Digital Twins use cases emerge across defence, the identification and definition of these potential archetypes, complete with defined 'base' standards may support development of commercial arrangements.

Data will be at the heart of a Digital Twin Ecosystem, - given the high dependency and rapid transfer rate, poor data is likely to have exponentially greater negative impact than currently understood with existing tools and techniques. Risks to direct decision making and implications for interdependent models will require a set of commercial arrangements that appropriately incentivise all parties to deliver to the necessary standards. Commercial arrangements will need to encourage suppliers to understand the impacts of substandard delivery on a broader ecosystem.

Given Defences supplier base and the systemic potential for Digital Twins, an end state is likely to achieve an ecosystem of models with significant interoperability between digital twins from various organisations. Commercial arrangements will need ensure such interoperability. Suppliers are likely to attempt to enforce restrictions and stipulations to protect perceived IP, it is vital that Defence adopts a set of principles, agreed with industry, which ensures it can achieve the interoperability it is likely to require. Inability or exceptions may result in siloed models, with Defence unable to exploit their full capability.

Commercial arrangements will need to balance ease of contracting with ensuring equitable outcomes, whilst reducing the overall contract management burden across all parties.

Current State of the Art

Digital Twins within Defence are emerging as a priority, however programmes within the UK (e.g. Network Rail) and specific industries (e.g. Manufacturing), have a mature understanding and significant experience

Digital Twin initiatives:

- Centre for Digital Built Britain

Mature Digital Twin programmes:

- Network Rail – ORBIS programme

Suggested Investment activities

Initiation of a working group comprising Defence and Industry Partners to mature commercial considerations and aim to develop shared frameworks and standards to support contracting

Key MOD Stakeholders

Defence Digital

- MoD Commercial

Supporting Evidence Links

- https://www.cdbb.cam.ac.uk/system/files/documents/TheGeminiPrinciples.pdf

4.5 Cyber Security Case (2.1)

Description

Digital Twins can help monitor the operational effectiveness of cyber security arrangements across both industry and the military.

Taking a view of cyber security operations the digital twin could cover the following processes and associated information sets:

- Intelligence cycle
- Asset identification process (incl. data/information)
- Risk cycle
- Incident processes (major & minor)

The intent would be to create a twin of the operation and based on established rules, create process automation and analytics and insights as input parameters change over time. As historic data is captured this could also be fed back into the twin to identify and act on suggested improvements.

For example, input parameters (to the twin) that could be analysed & used to optimise (further codification needed):

- Threat intelligence (volume & severity)

- Risk responses (actions taken linked to threats)
- Incident levels (volume & severity)
- Asset changes/updates
- Process measures (timeliness/throughput)

Additionally the digital twin's need to operate in a cyber-secure resilient manner.

Current State of the Art

Existing infrastructure, automation, security applications and analytics could leverage operational data sets, subject to information sensitivities and other constraints.

One approach may be to start off with a Minimum Viable Product to determine early learning and what other adjustments may be possible.

Cloud/cloud-like services that could inform or be adapted to support DTs (data storage solutions will need to be backed up with High Power Computing – HPC for data analytics

- Amazon Relational Database Service (Amazon RDS) – one databased (single source of truth) maintained across entire enterprise
- Amazon Virtual Private Cloud (Amazon VPC)
- Microsoft Azure
- US DoD Joint Enterprise Defence Infrastructure (JEDI) (Dev Sec Ops Policy)
- Cloud (based on Microsoft Azure)
- UK government IT infrastructure
- Cloud/Cluster/Grid computing

- Zero Trust Architectures
- Sidecar security

Suggested Investment activities

Developing a cyber security use case

Looking at how to make digital twins and particularly digital twins' as a service and cyber resilient

Key MOD Stakeholders

DIAS – setting the rules, what they're going to credit

Supporting Evidence Links

https://www.researchgate.net/publication/342276415_Integrating_Digital_Twin_Security_Simulations_in_the_Security_Operations_Center

https://www.cloud.mil/JEDI-Cloud/

https://www.iotsecurityfoundation.org/best-practice-guidelines/

4.6 Digital Twin Programme risk management

Description

Defences vision for Digital Twins is still emerging, however it's clear Digital Twins could provide a significant enabler, discrete Projects would likely be cohered by an overall programme. This programme would likely provide the central support in development of Business cases and the unblocking of fundamental enablers to Digital Twin adoption.

Digital Twin's will reduce uncertainty, enhance decision making capability and ultimately inform better risk management. Therefore, it is vital within a Digital Twin programme to ensure Digital Twins have a level of resilience, ensuring the system is robust, and that a potential overarching programme provides direction, guidance and support.

Discrete Digital Twins Project delivery should leverage standard good practice informed by broader industry principles with a focus on agile delivery and Government Digital Service direction. As a broader Digital Twins Programme however, emerging risks around interoperability, integration and dependencies on Defence Systems will require significant attention to ensure effective delivery.

In their first iteration Digital Twins across defence are likely to be Greenfield deployments, superseding less integrated potentially non-digitally driven approaches to solving current problems. Although this doesn't reduce overall programme risk, it provides an opportunity to de-risk through delivering effective and resilient solutions before organisational dependences grows. Digital Twins are a significant technology trend, however at a programme level, clarity should be provided on projected capability, to reduce overreliance on the Digital Twin 'silver bullet'

Given the evolving nature of Digital Twins in Defence, understanding of cost is immature, however it's likely given the significant development activity necessary, an ecosystem of Digital Twins will require significant investment, including to support emerging infrastructure that is still being identified and developed. Management of cost at a programme level will be vital to ensure value for money, however given the emerging nature of DT, this is likely to require significant scrutiny.

Additional considerations:

- Management of user adoption and organisational change necessary for success should be consider

Suggested Investment activities

Initiation of a working group, to support overall development of strategic vision, including input on programme risk.

Key MOD Stakeholders

GDS

Supporting Evidence Links

Government Digital Service – Service Toolkit

Government Digital Service – Technology Code of Practice

4.7 Digital Twin Value and Performance Demonstration (KPIs – 1.7)

Description

The digital twin of performance comprises the performances of both production and product. It is constantly fed with data from the product and the production facilities, which leads to new insights. Thanks to the connection with integrated automation components, the shop floor provides all relevant data which is then being analysed in the cloud to enable continuous optimizations along the entire value chain with the help of the Digital Enterprise portfolio.

Information from an organization's digital twin can be made available to its ecosystem of partners, enabling them to innovate and improve the design and performance of their products or services. This creates secondary and tertiary systems of data around which companies can base decisions.

Operations teams use the data to optimize performance, service and maintenance over the lifetime of a product, enabling organizations to avoid costly downtime, repairs, replacements and future performance issues.

The overarching result of data twins is that organizations can create customer value and satisfaction throughout the entire lifecycle of its products and services.

Current State of the Art

Siemens existing industry tools:

- SIMATIC IT Preactor – family of production planning and scheduling software products
- SIMATIC R&D Suite – helps optimising the development of innovative, high-quality products
- Quality Management System – IBS QMS Automotive is a system for integrated quality assurance in automobile construction
- MindSphere – the cloud-based, open IoT operating system that connects products, plants, systems and machines
- SIMATIC RTLS - navigates material flows, control mobile robots, monitor component use and fully document the final product assembly

GE Digital:

Predix Asset Performance – suite of software and services designed to help optimise equipment reliability and O&M efficiency across the plant and entire fleet. The Predix Platform is available both as a cloud-based service as well as on-premises software.

TyTan fleet optimisation and planning – providing ground crew, maintenance, fleet planning and training support to enable availability to RSAF.

Factory Environmental Monitoring System – BAE Systems in conjunction with AMRC North West - use of environmental monitors and micro services architecture to collate and display environmental conditions in the facility.

Suggested Investment activities

Look to leverage existing Platform data acquisition capabilities and adapt them to support Digital Twin capabilities. For example Typhoon LTE, Maritime SIE.

Optimising the customers' operational performance in support, missions and operations.

Key MOD Stakeholders

Defence Digital, RAF IX, NavyX, Government Digital Service standards (GDS). Industry open architecture standards.

Align with Digital Built Britain?

Supporting Evidence Links

https://new.siemens.com/global/en/markets/automotive-manufacturing/digital-twin-performance.html

https://www.ge.com/digital/applications/asset-performance-management-power-generation

https://www.comparethecloud.net/articles/exploring-the-business-value-of-digital-twins/

https://www.baesystems.com/en-uk/product/available-and-reliable-weapons-system

5. People and Change

People and Change – 'Long White Paper'

Darin Tudor, Defence Innovation Cluster and Tia Tang KPMG

Overview

The people and change element cover the critical topic of stakeholder engagement and good practice for change management for implementation of Digital Twins.

We aim to show here the lead up to the journey so far, its senior stakeholder interest to date and the simple but fundamental steps to achieve the vital people change element of the Digital Twin journey.

Fundamental Digital Twin planning, adoption, implementation and harnessing enduring benefit is not just about utilising technology, and it cannot happen without senior people 'believing in and selling it' and operational teams 'buying into and getting it'.

Digital Twins just do not happen naturally they require executive decisions to enact and facilitators to create, manage and bring all their many benefits to life.

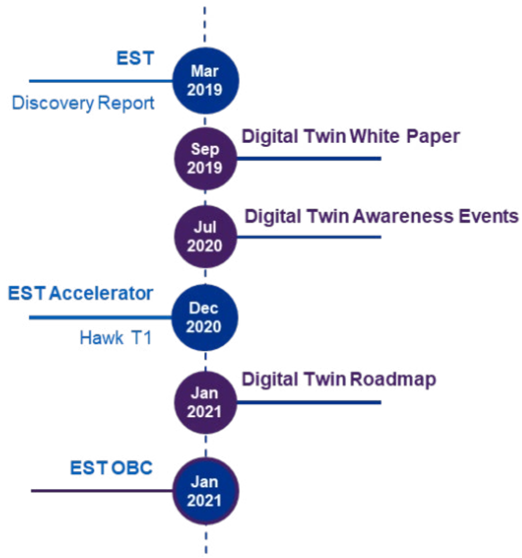
When the impact of Digital Twins is realised with their game changing positive results on operations the reward to risk and effort (pain to gain) ratio to implementation is considerable.

Other markets such as Oil and Gas, Renewable Energy, Construction, Automotive and Rail, via its people, have already taken this decision to 'change'. Typically, they take incremental and staged steps at first to ensure the process is tailored for their environment and confidence to scale is built on evidence.

When adoption does commence all have drastically accelerated its wider implementation, but none have discontinued it which illustrates its power for unquestionable benefit.

Background

As part of the Engineering Support Transformation (EST) Discovery phase in 2019, Digital Twins was identified as a theme. Digital Twins were then selected by the Engineering Support Transformation User Forum (E-STUF) as a key focus area, then a Team of 20 (mix of Industry, Academia, MOD and Commands) worked collaboratively considering 5 different industries as exemplar examples who collectively published the joint 'Digital Twins White Paper' in September 2019.



The 'Digital Twins White Paper' was promoted within wider defence (MOD and Industry) to stakeholders and influencers who could potential benefit from this whole concept, an appetite to know more ensued and as a result a series of four on-line awareness seminars took place in July 2020 in order to explain, explore and debate this topic, 285 interested parties signed up initially and in fact a combined total of 630 attended these events which illustrated the applicability and interest for the subject.

Stakeholder Engagement to-date

The topic of Digital Twins has gathered considerable interested from senior stakeholders within Defence who are seeking wider collaboration on how Digital Twins can be applied to their area and the benefits realised.

It was agreed at the end of these awareness seminars the 'what' had now been established the next logical step was to explore the 'how' via a Digital Twin Roadmap for support. The Digital Twin Roadmap activity was initiated in August 2020 by Gary Cox (MOD) and Alisdair Wood (Leonardo) as Co-Chairs of ESTUF with management support from 2* Defence Authority for Technical and Quality Assurance (Stephen Wilcock).

Defence Support D Jt Sp 2* (Major General Simon Hutchings) supporting DT paper from Def Sp CIO/CTO perspective to cohere the support data to ensure common design architecture standards are employed (brought before the DSDA) to allow freedom and agility to develop a solution that is fit for purpose. Gen Hutchings identified Lt Col Richard Craig as his representative into the task team to help steer direction in support of 2* intent.

Defence Support D SpTx 2* (AVM Richard Hill) Sponsor for SpTx and EST including current accelerators and future EST pilots.

DE&S D Spt 2* (Steve Glass) and team will be engaged as coordinating gateway for DE&S where future initiatives could result in delivery teams assisting with future pilots and accelerator to prove concept.

MOD Testing and Evaluation have also recognised the significance impact Digital Twins can bring to their operations in the future.

The Digital Twin Ecosystem

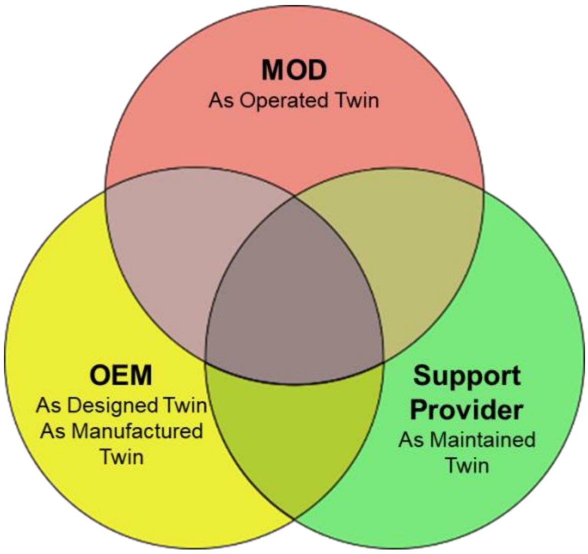
Digital twins are reliant on data and information inputs from multiple stakeholder groups crossing the boundary between Defence and Industry.

An understanding of the stakeholder ecosystem and how MOD (1), OEM/Prime (2) and Support Provider (3) interface and collaborate with each other is vital such that all parties gain value from the Digital Twin and its significance to fit within the simulated environment.

(1) MOD - Digital Twins can be applied to an enterprise, infrastructure, supply chains or equipment. The end user or customer should articulate the objective the digital twin will support and the desired level of integration (for example whether one Digital Twin will interface with another or if it exists as a standalone Digital Twin). The Defence ~~as~~ owner generates operational data but are reliant on OEMs to provide 'as designed' data and 'as maintained 'data where support activities are provided by a third party. In Defence, independent of acquisition and support arrangements, a Digital Twin will be reliant on operational data. Information inputs and value of operational data should be addressed as part of specification, commercial and security arrangements.

(2) OEM/Prime – OEM'S or Primes are generally ~~as~~ owners of 'as designed' and 'as manufactured' data, this data is usually safeguarded as IP. Design/manufacture data is required as part of support activities such as major repairs, modifications, upgrades or if there's deviation from expected performance. Defence and OEM/Primes can put in place commercial arrangements where Defence has access to outputs required for decision making with industry whilst retaining IP ownership. Alternatively, a Digital Twin could be commissioned and owned by Defence with appropriate contractual provision. New insights provided by Digital Twins is what informs decision making, therefore OEM/Primes can use utilise this insight to provide evidence and product support to their customers.

3/ Support Provider – Support organisations rely on information from both MOD and OEM. As maintained data is useful to both Defence as owner operator and OEMs as it provides condition data which informs anticipated performance for a period. Ingestion of as operated and as designed data enable support providers to better forecast potential support required. Digital Twins independently provide visibility, demonstrate, and prove/predict vital facts such as achieving operational outcomes, reliability, effectiveness, and cost of ownership.



Importance of Change Management

Driving sustainable change in large and complex organisations is difficult. Ambitious strategic change in organisations can fail to deliver benefits if they do not proactively and tactically address the people and organisational challenges associated with transitioning to a new way of working. Proactively attending to people and organisational concerns is key in managing risks associated with transformational activities.

In adopting Digital Twins, people in Defence will need to transition being able to specify their needs from a Digital Twin then, use and exploit the outputs. The pan Defence guide to change management provides a framework which aligns the change lifecycle to the programme lifecycle to so that Defence can adopt the right culture, behaviours and mindsets needed for transformations to realise their benefits.

The MOD Change management methodology describes 4 phases.

Applying this framework to adoption of Digital Twins, some illustrative steps are provided below.

1.Make the Case.

Evidence of opportunity, benefits, and savings: Document case for change, this should provide a common narrative for leaders to get buy in from their teams. Articulate the benefits both financial (investment, savings) and non-financial (effectiveness, behaviours).

Stakeholder Engagement & Communication Planning: Identify stakeholder groups and individuals who will be impacted by introduction of Digital Twin. Change interventions and engagement should be tailored to each group.

2.Make it Ready.

Define new ways of working, process changes, system changes: During this phase, a change impact assessment is conducted to understand impact on process, systems, safety, environmental and other factors identified to be relevant.

3.Make the Change.

Stakeholder Support - Change to GEAR and KiD: Make required changes to artefacts and tools/systems which are used.

Competency and Skills Definitions and Development: Develop Defence Digital Twin specialist training benchmarking best practice. Identify new skillsets required to use and maintain Digital Twin.

Defence Digital Twin Training: Deliver training using current and relevant projects and tools to help embed leadership behaviour and approaches. Consider what continued training requirements will be to remain up to date with latest industry, technology, and Digital Twin specialisation trends.

Cultural change for implementation e.g., digital mindset: New ways of working and behaviours which provide cultural shift to a digital mindset. Cultural change will be evident over a longer term. Adoption of new ways of working should be monitored.

4.Sustain the Change.

Collaboration and clear roles in digital ecosystem: On going collaborative relationship in Digital Twin ecosystem to achieve mutual benefits and identify new incentivisation models for data collaboration and sharing.

Defence Library of Defence Digital Twin: Continue to build library of use cases for Digital Twins. Resources which can be referred to and leveraged by future parties interested in implementing Digital Twins.

Defence Digital Twin Community of Practice: Leverage existing and establish new specialist forums where required. Communities to help capture experience and develop or amend policy, guidance, training materials and creation of business cases.

The Process of Successful Change - Checklist

1. ***Set the stage*** *– Create a sense of urgency, help others see the need for change and the importance of acting immediately.*
2. ***Pull together the guiding team*** *– Ensure there is a powerful group guiding the change, needs a mix of skills and disciplines in leadership, communications, authority, analytical, credibility, urgency.*
3. ***Decide what needs to be done*** *– Change and Vision strategy development; how the future will differ from the past and how it will be made a reality.*
4. ***Make it happen*** *- Communicate to ensure understanding and buy in.*
5. ***Empower others to act*** *– Remove as many barriers as possible so that those who want to make the vision a reality can do so.*
6. ***Produce short-term wins*** *– Create some visible, unambiguous successes as soon as is possible as evidence it is working.*
7. ***Communication, communication -*** *Remember that communication is essential and a two-way street. Make sure to communicate with staff promptly and before change happens.*
8. ***Do not stop –*** *Press harder and faster after the first successes. Be relentless with initiating change until the vision is achieved.*
9. ***Make it stick*** *– Create a new culture, hold on to the ways of behaving, and make sure they succeed, until they become ingrained and strong enough to replace old tradition.*
10. ***Data fuels success.*** *Make sure you have proper data on whatever you are focused to change, gain relevant information, analyse it, and use it. Data is the new fuel.*

The Role of Thinking and Feeling in Change - Checklist

1. ***Thinking –*** *Doing this differently can help change behaviour and lead to better results.*
2. ***Collect data*** *– When done analyse it!*
3. ***Present it*** *– To change people's thinking.*
4. ***Changed thinking****- Can change behaviour.*
5. ***Feeling differently*** *– Can change behaviour MORE and lead to even better results.*
6. ***Create*** *– Surprising, compelling and if possible visual experiences.*
7. ***These experiences –*** *Change how people feel about a situation.*
8. ***A change in feeling*** *– Can lead to a significant change in behaviour.*

Summary

'Purpose of the 'Digital Twin Roadmap': This document is the result of 70 people from MOD, Industry, and Commands closely collaborating over a 3-month period to produce a detailed RoadMap to illustrate 'how' Digital Twins can be applied into and therefore benefit UK Defence with all their powerful and game changing management capabilities.

Objectives and Goals: As has already been proven in practice with the creation, communication and promotion and the Team Defence/MOD/Industry White Paper on 'Digital Twins' published in September 2019 there has been significant interest and resulting engagement in this subject, hence this led to the creation of the 'Digital Twin – Roadmap'. This new document will only continue this requirement to satisfy this need for knowledge if it is actively and widely promoted by Defence within Defence.

Change management tools:

The MOD Transformation and Change community have developed the Change Management in Defence (CMiD) Methodology and toolkit can be accessed via MODNet. The toolkit provides templates users can access and use. The Transformation Change Community can be contacted at Transformation-ChangeCommunity@mod.gov.uk for more information.

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