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Developing a Digital Twin and Digital Thread Framework for an 'Industry 4.0' Shipyard

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Abstract: This paper provides an overview of the current state-of-the-art digital twin and digital thread technology in industrial operations. Both are transformational technologies that have the advantage of improving the efficiency of current design and manufacturing. Digital twin is an important element of the Industry 4.0 digitalization process; however, the huge amount of data that are generated and collected by a digital twin offer challenges in handling, processing and storage. The paper aims to report on the development of a new framework that combines the digital twin and digital thread for better data management in order to drive innovation, improve the production process and performance and ensure continuity and traceability of information. The digital twin/thread framework incorporates behavior simulation and physical control components, in which these two components rely on the connectivity between the twin and thread for information flow and exchange to drive innovation. The twin/thread framework encompasses specifications that include organizational architecture layout, security, user access, databases and hardware and software requirements. It is envisaged that the framework will be applicable to enhancing the optimization of operational processes and traceability of information in the physical world, especially in an Industry Shipyard 4.0.

Keywords: digital twin; digital thread; framework; shipyard; industry 4.0

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1. Introduction

Digital twin (DTW) technology is the cornerstone of digital transformation, which we are currently witnessing in the new industry 4.0 revolution. DTW is accessible now more than ever and many reputable and innovative companies such as Tesla and Siemens have adopted it with varying success. Siemens [1] has integrated DTW into its three major sections of product lifecycle: product, production and performance. The virtual representation of the product is created and tested to validate performance under expected use conditions. Production is optimized through manufacturing process simulations where any sources of error or failure can be identified and prevented before proceeding to physical production. Subsequently, DTW has potential to improve performance by producing high-quality products at lowest logical cost by integrating manufacturing processes and enhancing production planning in manufacturing implementation [2].

In addition to companies in the business of manufacturing products, companies in other sectors such as the National Aeronautics and Space Administration (NASA), a pioneer of the DTW, used this technology to develop ultra-high fidelity simulation models of aerospace vehicles. These simulations enabled NASA's engineering team to predict the future performance and status of their vehicles accurately in the form of the "factors-of-safety" during design and certification phases. It also enabled mission managers to make informed decisions based on historical and real-time data to improvise possible in-flight changes to a vehicle's mission [3].

The global medical industry has been utilizing DTW to test medical devices virtually before introducing them into the physical world. For example, the Living Heart Project has adapted DTW for cardiovascular surgeons in diagnosis, education and training [4]. This project is not limited to cardiovascular surgeons but has positive implications for medical device design, clinical diagnosis and regulatory science. The fundamentals of this project involve the use of both pacemakers in live participants and virtual patients with the goal of increasing industry innovation in tackling heart diseases.

Further practical use of DTW in the medical industry relates to tailoring health care to individuals. In South Korea, DTW is being utilized in combination with Medical Artificial Intelligence to tailor healthcare plans to individual patients [5]. This, in conjunction with information on tracked health and lifestyle data from wearable devices, could eventually result in a "virtual patient." Virtual patient models allow medical personnel to perform continuous remote monitoring on patients at low-cost and provide health predictions and prescribe preventive treatments promptly. Through such interventions, South Koreans have benefitted from significant health improvements, reductions in healthcare costs and increased personal freedom in dealing with their own health.

Beyond healthcare, DTW is employed on a large scale in urban planning. For example, Virtual Singapore is a dynamic 3D city model [6] that consists of a detailed 3D map of Singapore and contains information such as texture and material representations of geometrical objects, terrain attributes and infrastructure and so forth. This 3D model is useful in virtual experimentation, virtual test-bedding, planning and decision-making and research and development.

Despite DTW being accessible now to most companies and governments, the adoption and uptake in Australian small- and medium-sized enterprise (SME) is still very slow. For most SMEs, tackling industry 4.0 problems requires a number of enabling technologies such as Product Lifecycle Management (PLM) software, enterprise resource planning (ERP) packages, the Internet of Things (IoT) and Cyber-Physical Systems (CPS), which communicate and cooperate with each other in real time. Unfortunately, it can be difficult for SMEs to integrate data into these systems when they have been developed by separate firms. Hence, the foundational knowledge, experience and potential of DTW has yet to become mainstream. There also exists a gap in understanding the requirements, applicability, security and sustainability of such technologies.

There are many studies in the field of DTW but very few studies have reported combined DTW and digital thread (DTH) technology in industrial transformations. The purpose of this paper is to report on the development of a new framework that combines the DTW and DTH for better data management in order to drive innovation, time to market and improve the production process and performance. First, we review the concept of DTW. Secondly, we consider its applicability in the entire product life cycle context. Thirdly, we describe the DTH and its entities. Fourthly, we discuss the development and integration of a DTW and DTH in a new framework and look at the necessary components for industry to embrace it. Finally, we are providing an example of combining DTW and DTH in industry 4.0 Shipyard to demonstrate how this new framework is going to work, particularly in Australian context.

2. The Digital Twin

A DTW is commonly known as a connection of data between a physical entity and its virtual representation that is made for the purpose of improving the performance of the physical part using computational simulations and techniques [7]. The concept of DTW was first introduced more than a decade ago at the University of Michigan and was further developed by Michael Grieves [8]. Grieves described the DTW as a cycle of data between three components, that is, a physical object, its virtual model and the information processing hub that links the physical object and its virtual model. Grieves envisaged this new concept as the possible foundation of PLM and a new product-manufacturing method to fulfil desired design specifications [8]. Figure 1 depicts these three components (virtual representation, information hub and physical objects) of DTW in an industry application.

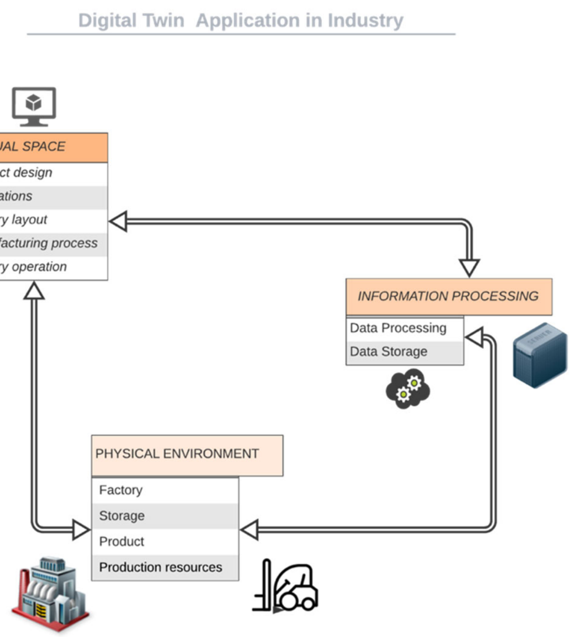

Figure 1. An example of the application of digital twin in industry.

2.1. Physical Environment

The physical environment is the basis for developing the DTW [9,10]. Generally, the objects included in most of the studies are manufactured products such as vehicles, aircraft or 3D printers. Of key importance is the fact that the DTW is not solely limited to an object itself but often considers the environment and interactions with it. If the DTW is created for the optimization of the manufacturing process, then the purpose of the DTW in the product lifecycle must be specified [7,11–13].

2.2. Virtual Space

Virtual space is the first phase of creating a DTW and incorporates a 3D model representation of the physical object, containing the geometric modelling of the physical object, the virtual workers and the virtual environment in which the product is contained. The user should model and analyze that of the 3D product in the physical space and simulate this in the virtual space, including movements of workers and the products and how they interact. The user also needs to define the attributes and properties of the product and corresponding rules of operation in the physical world and then simulate these in the virtual space. Once all these aspects have been successfully integrated into the DTW environment, the full virtual representation is considered complete.

2.3. Information Integration

Information that is collected from physical sources (from suppliers, the product itself, organizational changes) will be analyzed and integrated into the DTW during the data-integration phase. These data need to be analyzed and integrated into the DTW seamlessly. For example, a stock-taking DTW would need to understand the amount of stock left in the shop floor as physical objects and be able to translate this information to ensure up-to-date stock tracking. This is the step where the real-world data are integrated with virtual representations to create a DTW.

2.4. Current Digital Twin Application in the Industry

DTWs attract interest from different industries' operations areas such as product design, logistics, manufacturing and maintenance. Also, DTWs can be used to increase the efficiency and automation levels of the manufacturing, maintenance and after-sales service (as shown in Figure 2) [7,14,15].

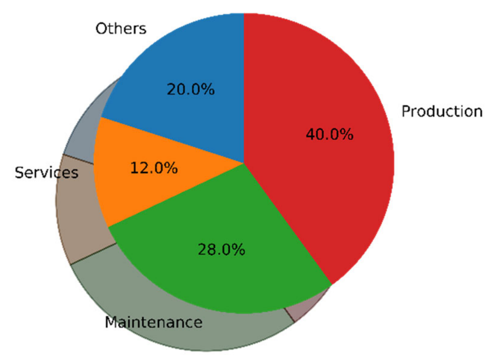

Figure 2. Application areas of Digital Twins according to Melesse et al. (reproduced from [15], Elsevier, 2020).

In the product concept, design and production phases, DTW can be a very useful tool in the manufacturing system. Studies show that DTWs have been used successfully to understand the performance and behavior of individual machines, making it easier to integrate the production line [16,17]. By leveraging the advantages of DTW, small manufacturing companies have achieved better performance in automation and adaptability to changes in customer orders or material properties such as hardness, strength and elasticity. These successes show that DTW can be used as a tool to increase efficiency in the production planning and optimization of the manufacturing implementation [16,17]. DTW has also revealed potential in the predictive maintenance area where, based on the information collected from the physical component, multi-physics simulations and data analysis are performed to predict future performance and possible future failures. These can be used to generate early warnings and to feed into the maintenance plan continuously, thereby reducing the costs of unplanned disruption. However, these kinds of applications have not yet been widely adopted and further research is needed to generalize them for wider use [9,15,18].

In the services area, such as after-sale service, DTW can be used as an information tool to provide added value to the customers by being able to produce better predictions of the future behavior and the remaining lifetime of an asset and its components. DTWs can also be used to collect useful data to drive design modification, improve product performance and improve the overall production planning cycle [15,16,19]. Despite some successful applications, the methods and tools to implement DTW in industry are still in their early stages of development and need more research. Also, many of the physical phenomena involved in the manufacturing of several products such as aircraft, vehicles and machining tools are complex and hard to simulate. Hence, these issues need more research to develop better models. Additionally, the large amount of data that can be collected by a DTW introduces new challenges in data handling, processing and storage

[20,21] and hence, a framework to build DTWs should address these challenges [9,14,15,22–25].

2.5. Enabling Tools for Digital Twin

In the literature [2,26], the enabling tools for DTW can be broken down into five categories: 1. tools for controlling the physical world; 2. tools for DTW modeling; 3. tools for DTW data management; 4. tools for DTW services applications; and 5. tools for connections in a DTW environment. There are a number of commercial application platforms that have various enabling DTW technologies provided by global companies, for example, Predix (General Electric Company, Boston, MA, USA), Thingworx (PTC Inc., Boston, MA, USA), Mindsphare (Siemens, Munich, Germany), ANSYS (ANSYS Inc., Canonsburg, PA, USA), 3D Experience (Dassault Systèmes®, Vélizy-Villacoublay, France), Altair (Altair Engineering, Inc., Troy, MI, USA), Oracle (©ORACLE, Austin, TX, USA), HEXAGON (MSC Software, Newport Beach, CA, USA) and SAP (Weinheim, Germany) [26].

3. Traditional Product Lifecycle Management Approach

In the traditional PLM approaches to product development, there are many user groups and stakeholders involved in creating and sharing information during the planning, design, production and service phases (Figure 3). Hence, many documents and a large amount of data are created to capture the decisions and results of PLM activities.

Therefore, the engineers in any one team in the PLM will continually work independently by importing files locally for modification and them exporting them for storage and future use. If subsequent user groups use different data manage systems and software, the net result is that these iterations can be slow and time consuming. The overall cost required for data conversion from one part of the system to the other becomes large and reduces overall value for money.

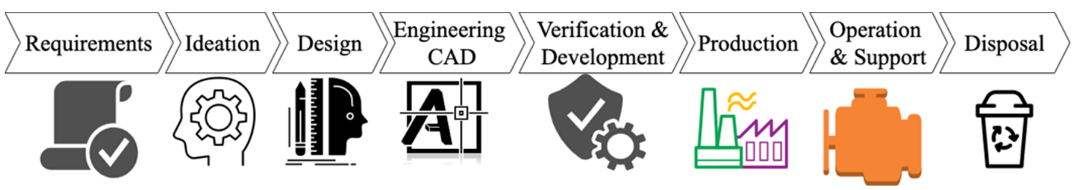

Figure 3. Traditional product life cycle management process.

3.1. Data Silos and Fragmented Information

For decades, organizations have optimized each product life cycle phase separate from others. Hence, highly fragmented information and knowledge exchange exists between life-cycle phases [27,28]. As a result, valuable information and knowledge is often lost and not used as context for decision-making in the transition phases and, hence, there are information gaps in the product life cycle, especially in the design-to-manufacturing and design-to-service and maintenance stages. We know that PLM is an iterative activity. Therefore, the management and exchange of information becomes crucial to ensure continuity of work flow to support innovation-based models of competitiveness and to reduce the risks of failure [27,29–31].

3.2. Digital Twins in Product Lifecycle Management

In engineering PLM, integration of DTW is a paradigm shift that can help companies set up for better processes of managing all product lifecycle stages starting from ideation, to design, testing, certification, manufacture, operations, maintenance and, finally, disposal (Figure 4) [32,33]. With a DTW, thousands of processes and modifications can be modelled for all lifecycle phases of a product. Users can test for different "what if" scenarios for changes in the design, materials, manufacturing parameters, logistics and operational conditions, among others. Furthermore, the effects of the modifications to the other phases of the life cycle can also be assessed [34].

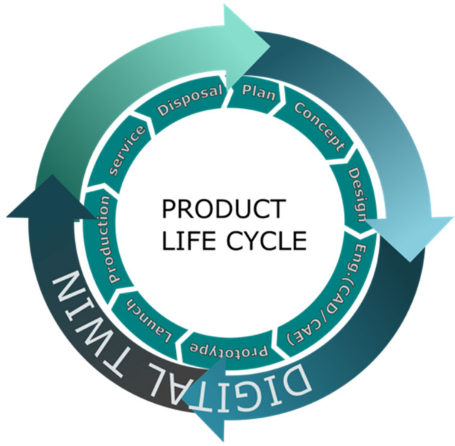

Figure 4. Integration of Digital Twin application with the Product Life Cycle management.

For example, some aspects that can be achieved with DTW are a detailed recording and storage of process data from the manufacturing stages, immediate use of information from manufacturing difficulties or errors and parts defects to identify critical manufacturing steps. Also, clients can be offered customization to their needs, repair processes can be scheduled based on the knowledge of the entire product operation history throughout the product life cycle and higher machine availability, considerably lower downtimes and faster attention times following predictive maintenance of machine tools can be available [1,6].

4. The Digital Thread

A DTH refers to a data-driven architecture that links all information generated and stored within the DTW enabling it to flow seamlessly through the entire PLM phase from invention to disposal [10,35–37]. Mies et al. [38] described the process of a DTH in the context of additive manufacturing technologies. The DTH enabled data to be integrated into one platform, allowing seamless use of and ease of access to all data. Mies et al. hypothesized that additive manufacturing processes offer ideal opportunities to apply DTH as they rely heavily on new data-driven technologies.

Siedlak et al. [39] performed a case study on a DTH that was integrated into traditional aircraft design metrics. The use of DTH enabled the necessary multidisciplinary trades to link their data through common inputs and data flows, which facilitated integrated models and design analyses. It allowed the sharing of information between usually isolated organizations to enable a more time- and cost-efficient design process.

DTH is a multi-step process that complements DTW over the entire lifecycle of the physical entity. It contains all the information necessary to generate and provide update to a DTW [35]. It relies heavily on the correct development of a framework that creates homogeneity and easy access to data through three main data chains: 1. the product innovation chain; 2. the enterprise value chain; and 3. the field and services chain (Figure 5).

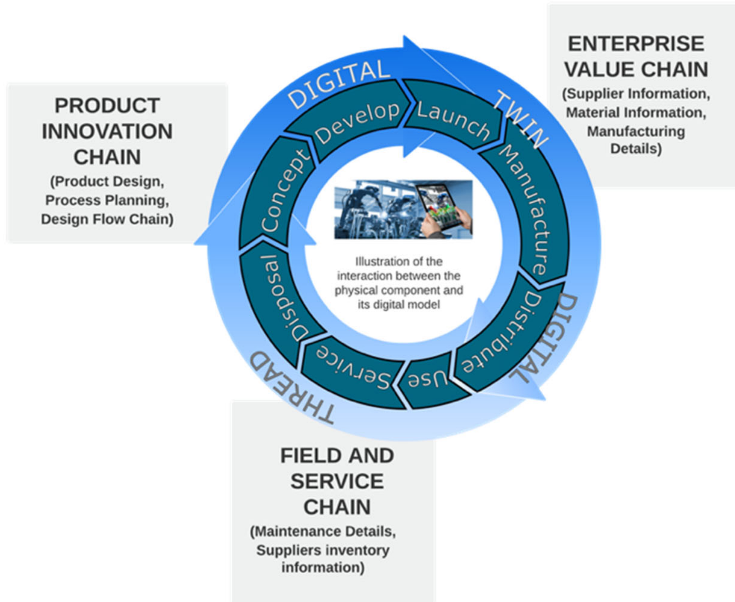

Figure 5. The concept of digital thread to complement digital twin.

4.1. Product Innovation Chain

The product innovation chain is the first step in the initialization of the DTH. This is where the lifecycle of the product is created and stored for future needs. The product designs, process planning and design flow are integrated into the thread, which outlines any suppliers and the information that were created during the first development of the physical product.

4.2. Enterprise Value Chain

The enterprise value chain is the second step in the creation of the DTH and incorporates more sophisticated details in the production of the product. This is where supplier information is integrated into the thread and on how the supplier might have produced the parts, batch numbers and so forth. Other information on the parts, including materials used and manufacturing details, would also be added. For this part of the thread, as much information can be added as the user requires. If required, all the information, including individuals who manufactured the parts, where the original materials were from and how they were obtained, can be added if this is what is required by the end-users.

4.3. Field and Service Chain

Information related to maintenance and parts is found within the field and service section of the DTH. Information that would be useful to the maintenance team and various suppliers can be seen in this section, with maintenance manuals and part availability from suppliers being incorporated into the DTH.

4.4. Key Technologies for Digital Thread

The key technologies that support implementing DTH in the three main data chains have been challenged by the difficulty in aggregating disparate data in various formats from different systems and organizations throughout the product lifecycle [36]. There exist commercial software tools that support inter-operability and enable the DTH applications. For example, the ModelCenter (Phoenix Integration, Blacksburg, VA, USA), TeamCenter (Siemens, Plano, TX, USA), ThingWorx (PTC Inc.), 3DExperience (Dassault

Systèmes®), Aras Innovator® (Aras, Andover, MA, USA) and Autodesk Fusion Lifecycle (Autodesk Inc., San Rafael, CA, USA) are various commercial software tools for managing centralized data storage and the integration of simulation models for optimizing product and system designs [40–42].

5. New Digital Twin and Digital Thread Framework Development

The importance of DTW and DTH is highlighted by academe and industry due to its virtual/real-world integration [9]. As DTWs can integrate data collected from physical models with data from computational models and processes with advanced prediction methods, the results can be used to improve the performance of the existing product or to produce improved versions in the future [7]. Also, product design, assembly, production planning and workspace layouts have been found to be potential fields for twin/thread framework application [17,43].

The development of a new DTW and DTH framework (hereafter, the twin/thread framework) is an integration of DTW and DTH step and often requires more resources than when building a DTW for the first time. The twin-thread framework has multi-layered stages (Figure 6), which require the developer to follow a loop-style iterative approach to develop it.

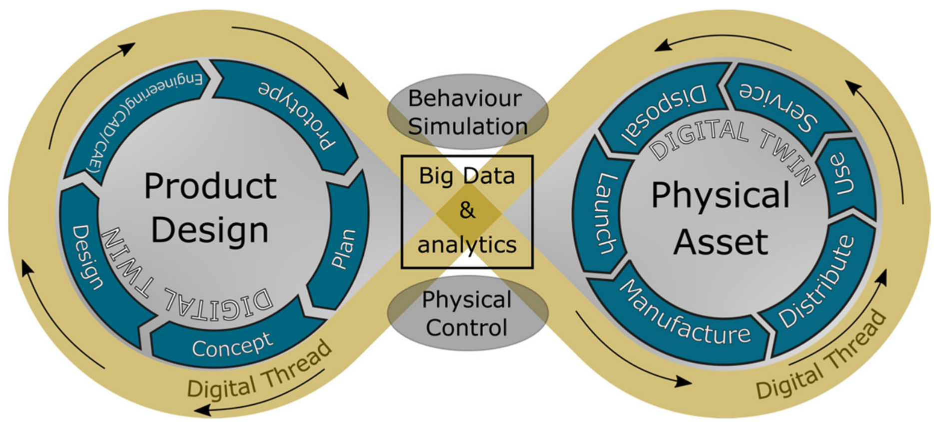

Figure 6. Digital Twin and Digital Thread framework for efficient product data management.

The new twin/thread framework comprises product design and physical asset components that are building blocks for establishing a centralized product data management (PDM) system. A PDM system will ensure the inter-operability of services and platforms involved in a project and help to standardize file formats, adopt common data storage and representation approaches and impose version control on data files across platforms. In addition, the PDM system will not only save time for engineers and designers in importing files from one platform and exporting them into another but also allows them to communicate and collaborate constantly with other stakeholders (i.e., a non-linear style approach) via a unified and consistent data representation framework, with the aim to delivering relevant data to the right person at the right time and in real time.

The advantage of the new twin/thread framework is that the users can use DTW to set up virtual models to test out scenarios to investigate where problems might have occurred and help them to predict what they might do to rectify the problems. DTH is an added benefit where it enables all stakeholders to effectively communicate and share big data bi-directionally up and down stream throughout the entire product life cycle.

5.1. Integration of a Model-Based Systems Engineering (MBSE) Approach to Support PLM

Given the increasing model-driven data across many industries, a new Model-Based System Engineering (MBSE) approach was introduced. MBSE uses a unified platform to support the requirements of design, analysis, verification, production and maintenance within the entire PLM activities [29]. MBSE aims to use a models-oriented approach (instead of document-based approach) to support the exchange of information. Figure 7 provides an overview of the common tiers of MBSE architecture. The lowest tier in the architecture contains data that are to be accessed and potentially used for analysis. Systems within the middle and top tiers provide functions and services that manage the translation and/or transaction of data between different organizations [36].

The decision-makers can also use MBSE to manage risks by defining proactive and reactive resilience strategies and contingency plans using the historical and real-time disruption data analytics to ensure business continuity [44].

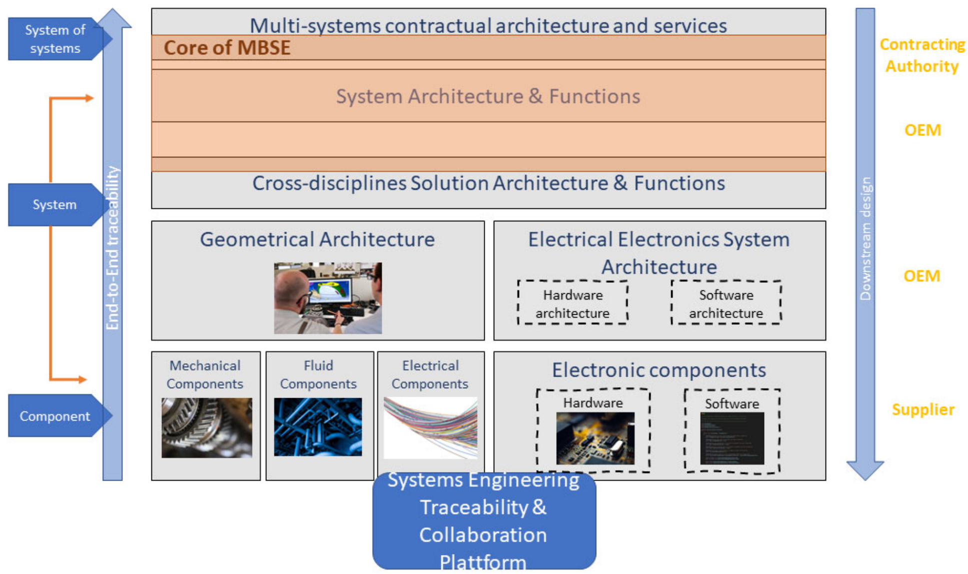

Figure 7. Model-Based Systems Engineering framework to support the consistency of exchanging model-data.

5.2. Behaviour Simulation

An operation of a process is required for the behavior simulation step to simulate a physical product in a virtual space. Key functions of the physical model will be simulated and the response of the virtual product will be examined. For example, in a stock-take model, the virtual model could be simulated to represent a real-life scenario of lost stock, the virtual model would then be required to find the supplier and order new stock to replenish the resources automatically, keeping the flow and function of overall product. Behavior simulation needs inputs from the DTH with respect to supplier information to be integrated into the DTW. Once the behavior is simulated virtually, the system can move to the physical control and complete the twin/thread cycle.

5.3. Physical Control

Physical control is the last stage in the twin/thread framework and involves controlling and changing the physical system. The physical control brings the other steps together and produces a fully functioning DTW that can change and interact with the physical model. By incorporating sensing and controlling systems and linking them with the communication infrastructure, the physical model will be able to be manipulated and changed within a virtual space. The behavior and structure of the physical world can be controlled manually or automatically through the DTW and real-world changes can be analyzed and optimized through simulations. After the physical control has been executed, the DTW will update instantly to simulate the new physical model. For example, for a stock-take delivery on-time set-up, the use of sensors would identify a low stock levels of a product and the product would be ordered through the supplier information based in DTH and the DTW would be updated with the amount of stock. Once delivered, the stock would then revert to 'normal' supply levels and the DTW will need to be updated immediately to reflect this change.

Once physical control is completed, the next iteration of the cycle begins and the DTW will need to be constantly updated in order to keep up with the workforce and the demanding needs of the new industry 4.0.

The twin/thread framework also encompasses different aspects including organizational architecture layout, security, user access, data storage and hardware and software requirements, which will be addressed in the following sections.

5.4. Organisational Architectures

First, the organizational architecture needs to be developed in the system. This may be set up by the supplier of the software or can be set up in-house depending on the users' needs. This includes the organization set-up, logos and context behind the DTW before starting the process, setting up a clear outline of what the organization needs and the needs of the users.

5.5. Data Storage Requirements

The software requirements for the twin/thread framework also need to be established for the data to be easily managed and imported into the various systems. Ideally, the software would allow for all the functions required in the DTW including 3D modelling, product design chain flow, manufacturing details and service information. Whichever software is chosen by the user should also include a service agreement with that company to ensure any complications and issues can be resolved, enabling maximum efficiency and use of the software.

A large volume of data will be collected from a variety of sources during the entire PLM process. These data can be classified into three sets: 1. structured (i.e., data with specific formats such as digits, symbols, tables, etc.); 2. semi-structured (e.g., trees, graphs, XML documents, etc.); and 3. unstructured (e.g., texts, audios, videos, images, etc.) [45] These data need to be stored in databases for further processing, analysis and decision-making. Big data storage technologies, such as distributed file storage (DFS), standard Structured Query Language (SQL) databases, NoSQL database, NewSQL database and cloud storage, can be applied according to the nature of the data [26,45].

The DTW model can be updated continuously with the newest data stored in the database via SQL queries or online application programming interface (API). Interactive dashboards and other visualization tools, such as AR/VR goggles, can extract and consume data using the same mechanism.

5.6. Hardware Requirements

The hardware requirements for the software also need to be established before developing the twin/thread framework. These requirements are based on what software the users will be running for the DTW (examples of software include 3DExprience) and the type of activities they will be undertaking with the software. For CPU-exhaustive tasks (such as design tools or CAD creation), premium hardware is needed to run the required software. As there are a number of companies that offer the enabling software and technologies for DTW, users are recommended to refer to the vendor's certified hardware specifications. For example, Dassault Systèmes' has its specific certification process for workstations and laptops from various manufacturers, models, operating systems, graphic cards and drivers. This is to ensure reliable operation and seamless integration of the DTW enabling software and removes any hardware issues in running the software. It is also recommended that the hardware be upgraded periodically to ensure smooth operating and functionality for all users. By investing time in development, the twin/thread framework will run effectively by eliminating compatibility and scalability issues. Without investing time in the framework, users might experience poor software instability run time and will lack productivity due to a non-sustainable software environment in the long-term use of the twin/thread framework.

5.7. Cyber Security Framework

The next vital step is to set up and control cybersecurity for the twin/thread framework to ensure cyber resilience (Figure 8). The cybersecurity protocol contains three essential elements: 1. robust policies to maintain safeguard; 2. technologies that comply with security control; and 3. training of staff to support organizational awareness [46]. Data security could be industry-specific and some industries might require more rigorous security measures than others. A measure that would ensure the safety of the information in the twin/thread framework would be the implementation of ISO27001 [47]. ISO27001 is an international security standard developed to provide a model for establishing, implementing, operating, monitoring, reviewing, maintaining and improving an information security management system. These security measures could be implemented to all users who have access to the DTW on the server. Additional training is recommended to all users to ensure the utmost safety of the organizations and the information stored within the twin/thread framework. This is an integral stage in the framework's development, as this is what protects both the users and the suppliers from potential danger and IT crime [46].

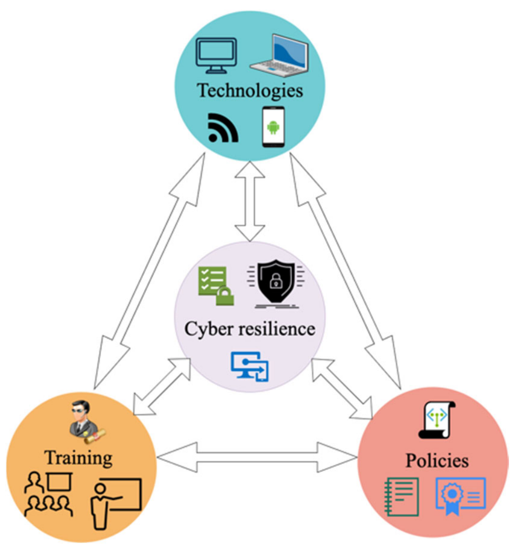

Figure 8. Cybersecurity framework for the digital twin/thread system.

Identifying correct user access and the creation of an identity and access management protocol (IAM) for the user are the next stages of the framework's development. This involves setting up correct access and roles for the right users, ensuring that only the information and recourses that are needed by that user is accessed [48,49]. User authorization needs a further authentication step to ensure the security of the data. This could be achieved through adapting strong or multi-factor authentication options such as the use of security questions or through email authorizations [48].

5.8. Proposed Architechture of Enabling Digital Twin/Thread Application

Despite DTH spanning the entire product life cycle, digital data continuity from the design to maintenance stage, as well as between Original Equipment Manufacturers (OEMs) and suppliers is limited. 'Discontinuity' of digital data and fragmentation of supply chain information might be the result from the use of many CAD software and/or PLM systems by OEMs, cyber security and data sharing control requirements and the lack of the required technology and digital skills among OEMs and suppliers.

A new enabling framework is, therefore, needed to link all information within the DTW to flow seamlessly through the entire product life cycle to support downstream processes in real-time and to address the challenges from design to manufacturing transition. The new enabling framework should have sufficient functionality, scalability and connectivity with customers and suppliers to ensure digital continuity and be easily integrated into the twin/thread framework.

In order to achieve digital continuity in the entire PLM, a platform and a set of software applications dedicated specifically to engineering design, verification and manufacturing are required. As noted in the literature [50,51], standardized design software, databases, tools and processes are a key to success for big and complex projects that involve many stakeholders from many countries to ensure digital continuity and traceability without causing costly mistakes and delay. Figure 9 provides an overview of the proposed architecture of a twin/thread system, which comprises organization/technical specifications, associated interface tools, PLM components, data analytics and the operation of the model-oriented MBSE approach. Each aspect of the proposed architecture is discussed in the following sub-sections.

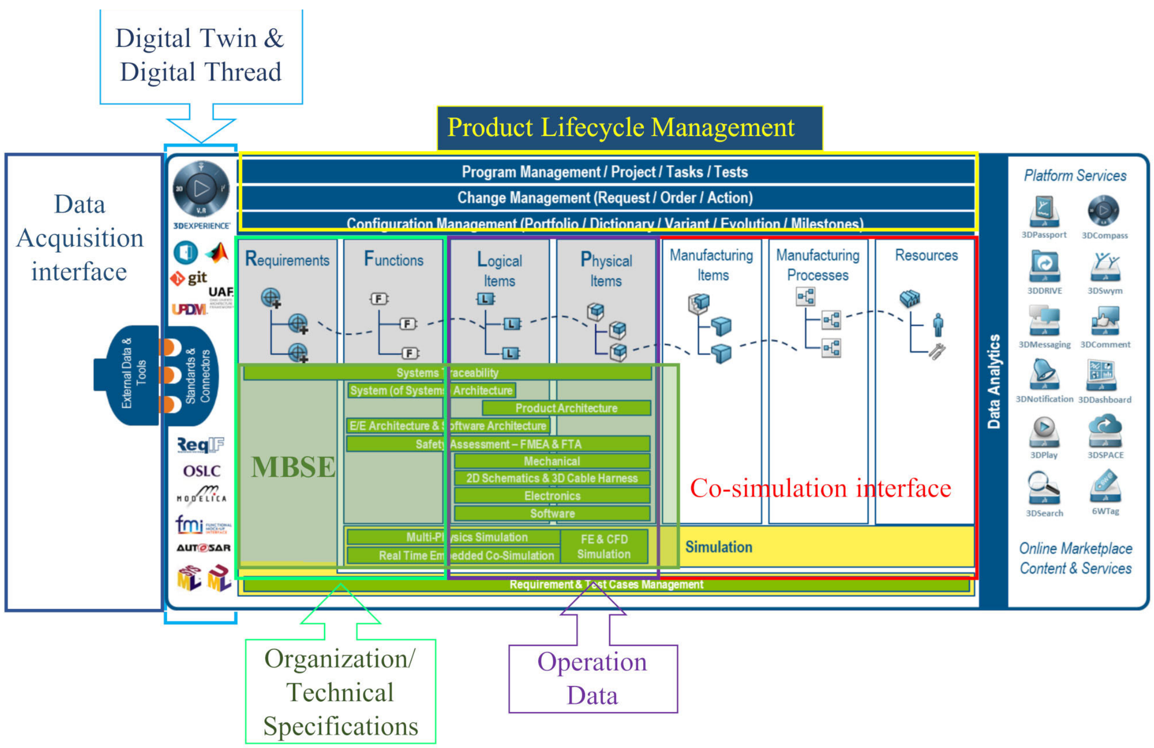

Figure 9. Proposed architecture for enabling digital twin/thread application to enhance digital continuity and traceability.

5.8.1. Digital Twin and Thread Application Suites

The top section of the framework includes a database, an application server and thick client (i.e., software such as 3DExperience). The application server provides the interface between the database and access to internal and external clients [36]. The database contains interdisciplinary models, for example, CAD models, functional models and simulation models. Each of these models are created during the engineering process of a DTW using specific tools. The connectors such as 1. Open Services for Lifecycle Collaboration (OSLC) links, which establish traceability and analyze relationships between the requirements, functions, resources, manufacturing and processes, 2. AUTomotive Open System ARchitecture (AUTOSAR)—a standard for system specification and exchange that helps to improve the reusability of vehicle software architectures, and 3. Unified Profile for Department of Defense Architecture Framework (DoDAF) and the UK Ministry of Defence Architecture Framework (MODAF) (UPDM)—a common software language to describe defense architectures, are used to connect data and achieve the DTH across domains, applications, organizations, systems and systems-of-systems. The DTW and DTH are connected to the PLM data repository via the data acquisition interface.

5.8.2. Product Lifecyle Management Components

Users can employ the PLM features to configure the collaborative creation and management dissemination of information related to product. These features allow users from different locations to work concurrently in real time on the same data, via a simple web connection to the twin/thread application suites. The integration of such features within the twin/thread suites allows users to optimize the change management processes as well as minimize the impact on every stage of the lifecycle [52].

5.8.3. Model-Based Systems Engineering (MBSE)

MBSE provides a common guideline on the management concept, system-to-system architecture and operational scenarios to promote concurrent model development and enhance re-usability of model data. It aggregates the model data from engineering and manufacturing items and processes or from different organizations in the supply chain. With MBSE, users can employ modelling and simulation data to create DTW of the physical assets in each step of the lifecycle journey. Then, the DTH will link its corresponding DTW to the design of the physical systems to ensure traceability links [52]. See Section 5.1 for details.

5.8.4. Data Acquisition Interface

The data acquisition interface will capture and store data collected by sensors and operational data from the real world. Through this interface, sensor and operational data can be transferred to DTW and this, subsequently, allows users to perform dynamic behavior simulation in parallel with the real-world data. Technologies that can implement a data acquisition interface are, inter alia, Predix (General Electric Company), Thingworx (PTC Inc.), Mindsphare (Siemens) and 3D Experience (Dassault Systèmes®) [26].

5.8.5. Organization and Technical Data

These data contain information about the physical asset itself. All documentations (e.g., requirements, specifications, design layouts, service manuals, maintenance reports etc.) that are generated by all stakeholders throughout the entire product life cycle can be stored here [52].

5.8.6. Operational Data

Real-world operational data can also be stored here using the data acquisition interface [53], such as: 1. sensor data, which is continuously streamed and recorded the current operation of an asset; 2. control data, which determines the current status of the real component; and 3. Radio-Frequency Identification (RFID) scanner data, which capture the current physical location of physical assets.

5.8.7. Co-Simulation Interface

The co-simulation interface can be used to simulate the flow of the entire production system and manufacturing processes in the real world [53]. For example, a user can utilize a factory layout program in the application suite to create a DTW of an existing physical factory floor and then use the factory flow simulation interface to create the factory flow process, starting from the supply of raw materials to the final dispatch of end products. The user can begin the simulation by choosing a start location, the required resources (e.g., 3D objects used in simulation, raw materials, worker manikins, etc.) and manufacturing processes (e.g., conveyor belts, numerical control machines, robotic arms, etc.) for the designated tasks. While the simulation is running, the current state, utilization percentage, current capacity and total of activities completed can be tracked. A system performance monitor in the simulation interface can be used to display live information for the whole factory floor and all resources. The live information, which includes utilization, total activities completed, average bottleneck of resources and current operational state of machinery, can provide unique and important support to customers and shareholders in implementing strategic planning and optimization.

5.8.8. Big Data and Analytics

There is a necessity for a platform for reliable 'big data' storage and to perform data analytics for decision-making. A large amount of data is generated and processed at any stage of the product lifecycle [54]. Large datasets can also come from various sources (e.g., computers, mobile devices, sensing technologies) [55,56]. Data analytics provides the capacity to analyze large and complex datasets and project/process managers can gain greater insight to make informed decisions and implement actions by searching, discovering and processing patterns in big data [55]. When a product is manufactured, all relevant data, such as status data from machines or energy consumption data from manufacturing systems, are stored and accessible in the DTW via the data acquisition interface. As a result, energy consumption optimization and better operational efficiency can be achieved. Such data also provide actionable insights for future decision-making.

5.9. Intellectual Property (IP)

In a globalized environment where innovation is crucial, the main competitive advantage of organizations lies in the development of new ideas and intellectual property (IP). Throughout the phases in a product's lifecycle, many change iterations (e.g., changes in customer demands or amendments in design and optimization) and the exchange of many highly sensitive information (e.g., IP products and services or personal information) will take place between various user-groups and stakeholders [57]. Historically, organizations faced a lack of integrated systems to manage their IP and heavy reliance on spreadsheets/manual documents. Thus, managing IP protection raises numerous challenges for organizations. The following sections elaborate on how the proposed approach can help to ensure IP continuity and protection.

5.9.1. Intellectual Property Continuity

Traditionally, organizations use the "throw it over the wall" approach, where different teams work in insolation from each other. Once a task is completed, they will hand over documents and 3D models to the next team. This approach does not address data silo issues and information that is often lost or lacks traceability [10]. The proposed twin/thread framework can play a significant role in modern product development and management. It provides a single, shared PDM platform to connect various user-groups and stakeholders throughout the entire product lifecycle from concept to disposal. The PDM platform will: 1. allow users to have easy, quick and secure access to data in a central repository during the product design process and 2. enable users to support product development and management processes by sharing, updating and controlling the way users create, modify and monitor the flow of product-related information. Such processes occur during the entire the product lifecycle and each stage involves dynamic interactions between entities that use the available information to generate new information and IPs and share them further [57,58]. As such, the proposed twin/thread framework will transform the way organizations manage their information and IP more efficiently by harmonizing all sources and types of data (of different formats, stored using different means and in different locations) to ensure digital continuity and traceability (Figure 10).

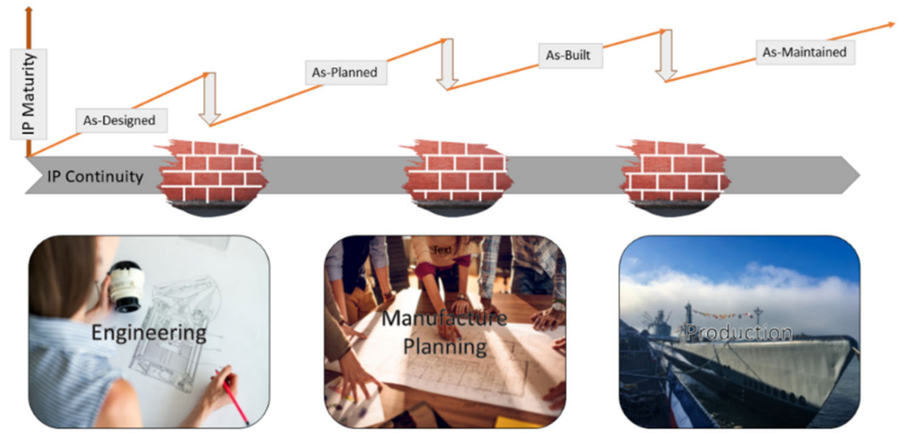

Figure 10. Management of intellectual property to ensure its continuity and filling the missing gaps.

As IP management maturity increases, companies can identify gaps related to engineering design, manufacturing planning, steps of a production process and service and maintenance over the lifecycle. With the ease of tracible information and knowledge, organizations can fill in the missing gaps for generating real growth possibilities [59].

5.9.2. Intellectual Property Security and Protection

One issue is how to protect IP effectively from loss, leak and theft. Through the adoption of a model oriented MBSE approach with the twin/thread framework and with proper cyber-security measures in place, organizations can provide segregated access to internal and external clients (e.g., OEMs and suppliers). In this regard, a number of appropriate organizational and technical concepts to exchange, manage and control access to information securely will be considered [49,60]:

1. Role-based access control. This allows organizations to manage a user's role and access to documents and directories. Once the user has authenticated his or her personal information against the system using a username and password, the system will grant access based on the defined role,
2. Digital watermarks. These provide a unique identification of origin for a document that can easily be traced when it is made accessible to internal and external stakeholders,
3. Data Leakage Prevention (DLP). This blocks extracting files by external, non-authorized devices such as USB sticks and keep track of e-mail traffic and the flow of information and its use, with whom it is shared and what actions are applied to it [57], and
4. Enterprise Rights Management (ERM). This integrates the know-how in suitable CAD and non-CAD (e.g., pdf-documents, MS Office documents) templates, which are encrypted using ERM-templates during the creation process and can be decrypted only after authentication against the decryption key received from the ERM server [60].

Depending on the business model and the needs of the organization, commercial software providers (as identified in Section 2.5) can provide consultation, implementation, integration, hosting and training services for potential control of access to information from PDM and PLM platforms and from a shared folder to companies with different scales. This secure access can ensure the protection of IP and other proprietary lifecycle data [36], for example, the IP and the design of the product being fabricated, batch 'Bill of Materials' components and any processes being developed to fabricate the product [36,61].

6. Industry 4.0 Shipyard

The differences between implementing a DTW in the manufacturing and maritime domains have been recently studied [56]. The study showed that very few implementation frameworks for the maritime domain have been developed but found one promising framework with the basic requirements for a DTH solution. The study concluded that both domains are developing open platforms for DTW implementation and present some useful real-world implementation examples of DTW [56].

DTW has also been proposed as a natural step from MBSE, with great possibilities of improvement in the production of highly complex products such as cruise ships. Some of the advantages highlighted are the ease in collaboration amongst all teams involved in the process of ship design [62–65]. Also, the possibility to access information and manage it efficiently using an advanced interface could help develop efficient maintenance and training programs that, in time, can lead to higher operational performance levels [66,67].

Additionally, DTH has been identified as a different way from the traditional 2D drawings for shipbuilders to design and build their ships faster and better. DTH offers shipbuilders the possibility of having their employees and suppliers connected to and synchronized with their shipyard, production planning, customer orders and requirements, 3D models and every aspect of design [68].

However, the current DTW models applied in the ship building industry show that only some of the components of the ship are being represented in the DTW, which is understandable due to the considerable number of sub-assets included in a modern ocean vessel. Including such a huge number of parts and their properties, interactions and performances in a model imposes great challenges. As DTH technology continues to mature, it will help the industry improve several aspects of their production processes through collaboration and constant communication of information [69].

6.1. Proposing Digital a Twin/Thread Framework in Australian Shipyard

As a result of the progressive implementation of smart and autonomous systems of Industry 4.0, the shipbuilding industry has developed a new, radical paradigm in its manufacturing systems by integrating automated tools and processes, creating new demands for more lean production processes, while increasing production efficiency, improving ship safety and reducing environmental impacts.

Furthermore, in a very complex shipyard site that contains large areas for fabrication of the ships, dry docks, slipways, warehouses, painting facilities and so forth, there exists many moving goods and many parts may look alike during the entire ship building life cycle. Hence, there is a need for ship operators to develop a relatively energy efficient way of moving goods and to accurately identify and trace moving goods to minimize impacts and to improve productivity and safety in the shipbuilding process.

In developing Shipyard 4.0, we believe a right framework are required to assist in designing a virtual work environment using highly detailed DTW, which could optimize the entire shipbuilding process by delivering the right information at the right time to avoid mistakes and increase productivity.

The concept of the DTH is typically defined as the flow of information that informs how a product moves through its design and production lifecycle (Figure 11). The implementation of DTH allows the monitoring of production in shipyard facilities and of the suppliers' production in their own plants. This provides greater product and process visibility to the ship builders, as well as greater transparency for the customer throughout the building process.

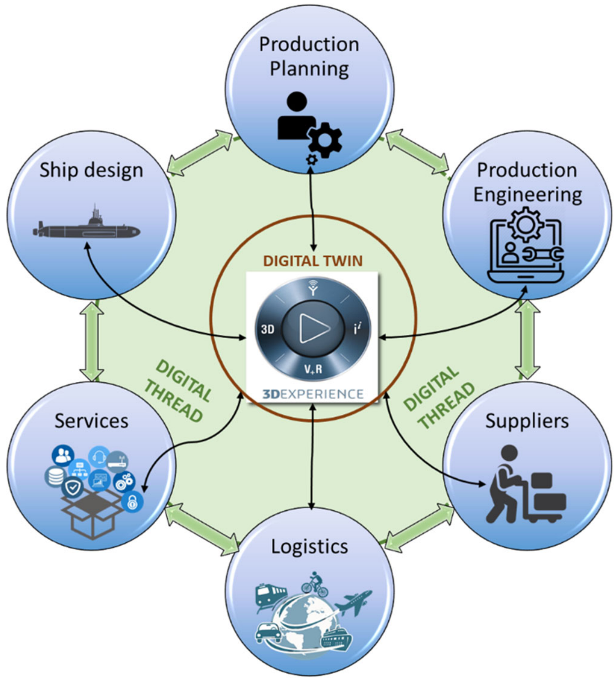

Figure 11. Digital Twin and thread implementation scheme for a shipyard.

A DTW of the shipyard will improve the efficiency of the factory flow when data can be extracted via behavior simulations of an operation process, such as machining time. Extracted data can be connected via DTH and fed into the DTW to identify bottlenecks. Furthermore, having a twin/thread framework where the DTW resides offers benefits in time management in scheduling and delivery. This relates to the inclusion of supply-chain data in the DTW. A fully integrated supply chain allows users to access the full spectrum of information available. A twin/thread framework could improve decision-making thanks to its single source of information.

In addition to improving manufacturing and design stages, DTW and DTH could enhance managerial decision-making processes. Provided that a true DTW of the shipyard is created, the information generated from all areas would be conducive to optimizing and achieving key performance indicators. Additionally, if the supply chain was integrated into the DTW, this information would give management information on what to expect, potential future issues and time to adjust to unforeseen circumstances.

Ships are normally built to last for up to thirty or more years. Therefore, it is important to ensure the continuity and traceability of design-to-service and design-to-maintenance information until their final dismantling. After its construction ships will continue to operate in the seas and will have impacts on the environment throughout their operational lives. The use of the twin/thread framework with the integrated MBSE and big data will be able to help providing a way of more effectively dealing with environmental and other issues.

According to the Australian Naval Group's SEA 1000 program [70], a total of 12 submarines will be built and all expected to be in operation by the mid-2050s. When considering future design aspects, over the next 30 years, the DTW offers the opportunity to test and reiterate designs via virtual testing, such as thermal and structural analysis, for improvement through its feedback loop processes. Legacy, historical and real-time data (maintained history, sensors data, test results etc.) connected via DTH through the physical ship can be subsequently fed back into the design process and used to improve design in case there are unforeseen circumstances or realized areas of improvement.

6.2. Roadmap for the Implementation of the Proposed Twin/Thread Framework

The implementation of the twin/thread framework can be challenging for an organization. A clear understanding of the framework and careful planning are essential to deploy its applications effectively to meet the organization's requirements and needs and to prevent costly mistakes. There are a few global companies that provide 'out-of-the-box' software applications and PLM solution suites for both DTW and DTH, including PTC Inc., Siemens, ANSYS Inc., Dassault Systèmes® and Autodesk Inc. For organizations interested in implementing the twin/thread suites as a mean to improve efficiency, software providers would normally offer consulting, implementing and support services that align with the customers' business requirements. While every implementation journey is unique, businesses can obtain the best results by following an industry 'best practice' and the methodology roadmap shown in Figure 12. The common phases for implementing out-of-the-box twin/thread solution are divided into: 1. access and definition; 2. design and build; and 3. deployment and support.

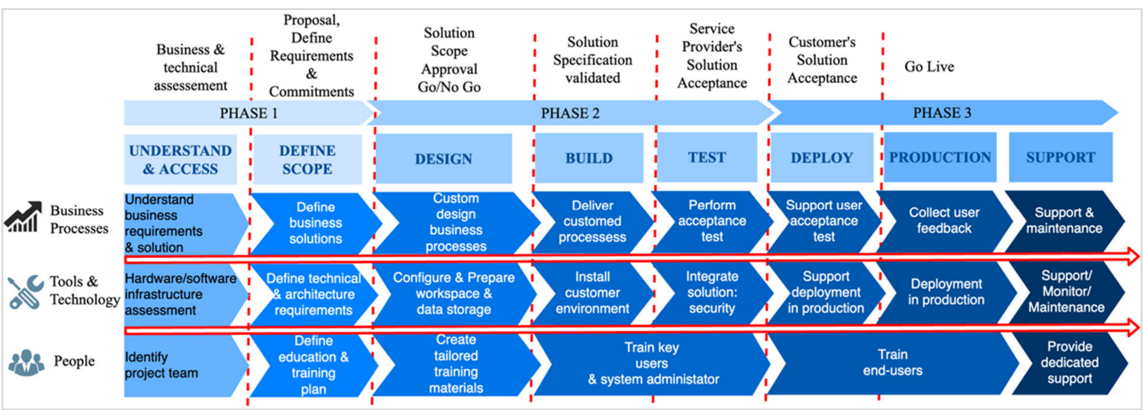

Figure 12. Design, build and implementation of the 'out-of-the-box' digital twin/thread product roadmap (modified from [71]).

The very first step is for businesses identifying the requirements and needs for the twin/thread suites within the enterprise. A comprehensive understanding of an organization's own business processes and requirements can provide insight into how to set up the necessary organizational architectures to ensure the seamless flow of information outlined in Section 5.4. Once the requirements have been identified, it is time to engage a potential software provider and system integrator to put the plan into action by identifying the hardware, software and data storage requirements (Sections 5.5 and 5.6) and nominating the project team to champion the roles. Prior to full roll-out, it is important to design and build the distinct architectures of the twin/thread applications that are aligned to the organization's requirements. The proposed architecture (Section 5.8) can be used to guide implementation.

While the twin/thread suites have effective hardware and software security processes, it is critical for organizations to consider the additional security measures outlined in Sections 5.7 and 5.9.2, especially in cases that involve IPs and new innovations when the twin is replicating their physical counterparts throughout the entire lifecycle [72]. Early participation from executive leadership and a well-trained and educated workforce in the twin/thread suites is a key attribute to ensure successful implementation in an organization. Finally, regular database-integrity checks and maintenance need to be considered before the application goes live and beyond to ensure that any problems are detected and administrators can either restore from a backup or conduct repair options.

6.3. Operation and Sustainment of Twin/Thread Framework in Australia Shipyard

With the adoption of the twin/thread framework, the shipyard industry can utilize DTW to transform the whole production lifecycle to ensure sustainability and to improve the performance of future programs [10,55]. For example, design engineers can leverage MBSE to work together with manufacturing engineers to create 3D models and simulations that link to real-time visualization for digital and physical production processes and instructions throughout the entire product value chain. The DTH will provide a platform to aggerate big data from disparate systems throughout the product lifecycle into actionable information through data analytics. With this deep insight from diagnostic analytics, descriptive analytics and predictive analytics, engineers, managerial teams and technician can use the data to support decision-making [55].

The twin/thread framework has been proposed and, in order to make it work, contracting authorities in the shipyard industry need to have the necessary hardware and software systems to facilitate multi-OEM participation in the DTH to ensure the connectivity of data. The sustaining of twin/thread frameworks will depend on continuing digital transformation, the endorsement of standardize tools and data exchange and better understanding of and agreements for upstream lifecycle functions to accommodate needs in downstream functions [10].

7. Conclusions

DTW and DTH are two promising technologies that will allow the manufacturing industry to optimize of their operational processes and traceability of information in the physical and virtual worlds. However, from the literature reviewed in this article, it can be concluded that these technologies are still in their early stages and further research related to implementation is needed, especially in framework development and in data processing, storage and security.

At present, existing frameworks can perform only limited aspects of what a true DTW and DTH should be able to achieve. While a DTW is designed to include the entire lifecycle of a physical part from design to use and then disposal, existing frameworks are largely focused on the design and creation stages only. Though some papers have referred to PLM in relation to DTH, which to ensure the connectivity of data silos and isolated information and elements to improve communication and collaboration, the existing DTH technology that integrates seamlessly with DTW has yet to be successfully implemented.

The proposed twin/thread framework, which uses DTW to represent the enterprise chains (i.e., product innovation chain, enterprise value chain and asset chain) and uses DTH to connect the enterprise data together to create digital continuity and accessibility. The advantage of the new twin/thread framework is that the users can use DTW to set up virtual models to simulate possible scenarios to predict future performance and the possible future failures. DTH is an added benefit where it enables all stakeholders to effectively communicate and share big data bi-directionally up and down stream throughout the entire product life cycle.

In order to adopt the twin/thread framework, OEMs need to define and adopt suitable technologies for product, process and resource modelling and validation, then maintain a digital repository for the deposition of the numerous products, processes and resources information within a single platform, of which the Model based System Engineering (MBSE) approach was introduced. The MBSE approach allows user-groups and stakeholders to collaborate on a unified system, where they can share data, perform simulation and visualization of a highly detailed model of a future physical product and exchange information in the form of models instead of document.

This will open avenues for accurate identification and easier traceability of information that will lead to improved efficiency and productivity. More significant is the possibility of iterative designs through feedback processes, which can shorten production lead times. This feedback is made possible through the DTH connecting the physical environment and DTW and is created through data extractions from both the physical and digital worlds. The same information that improves future design is used for management decisions.

In the context of the shipyard, the benefits of integrating a twin/thread framework into the established shipyard process span improved productivity and performance. Design engineers can leverage on the DTW to test and reiterate designs via virtual testing, such as thermal and structural analysis, for improvement through its feedback loop processes. The DTH will provide a platform to aggerate big data from multiple sources, such as maintained history, sensors data, test results and so forth, throughout the product lifecycle into actionable information through data analytics to improve the performance of future programs.

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References

1. Barrios, P.; Eynard, B.; Danjou, C. Towards a Digital Thread Between Industrial Internet of Things and Product Lifecycle Management: Experimental Work for Prototype Implementation. In Proceedings of the 16th IFIP International Conference on Product Lifecycle Management (PLM 2019), Moscow, Russia, 8–12 July 2019; Springer: Cham, Switzerland, 2019; pp. 273–282.
2. Qi, Q.; Tao, F.; Zuo, Y.; Zhao, D. Digital Twin Service towards Smart Manufacturing. *Procedia CIRP* **2018**, *72*, 237–242, doi:10.1016/j.procir.2018.03.103.
3. Glaessgen, E.; Stargel, D. The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, USA, 23–26 April 2012, doi:10.2514/6.2012-1818.
4. Scoles, S. A Digital Twin of Your Body Could Become a Critical Part of Your Health Care. Availabe online: https://slate.com/technology/2016/02/dassaults-living-heart-project-and-the-future-of-digital-twins-in-health-care.html (accessed on 20 June 2020).
5. Shin, S.Y. Current status and future direction of digital health in Korea. *Korean J. Physiol. Pharmacol.* **2019**, *23*, 311–315, doi:10.4196/kjpp.2019.23.5.311.
6. Goto, S.; Yoshie, O.; Fujimura, S. Empirical Study of Multi-Party Workshop Facilitation in Strategy Planning Phase for Product Lifecycle Management System. In Proceedings of the 16th IFIP International Conference on Product Lifecycle Management (PLM 2019), Moscow, Russia, 8–12 July 2019; Springer: Cham, Switzerland, 2019; pp. 82–93.
7. Jones, D.; Snider, C.; Nassehi, A.; Yon, J.; Hicks, B. Characterising the Digital Twin: A systematic literature review. *CIRP J. Manuf. Sci. Technol.* **2020**, *29*, 36–52, doi:10.1016/j.cirpj.2020.02.002.
8. Grieves, M. Digital twin: Manufacturing excellence through virtual factory replication. *White Pap.* **2014**, *1*, 1–7.
9. Tao, F.; Zhang, H.; Liu, A.; Nee, A.Y.C. Digital Twin in Industry: State-of-the-Art. *IEEE Trans. Ind. Inform.* **2019**, *15*, 2405–2415, doi:10.1109/tii.2018.2873186.
10. Leiva, C. Demystifying the Digital Thread and Digital Twin Concepts. *Ind. Week* **2016**. Availabe online: https://www.industryweek.com/technology-and-iiot/systems-integration/article/22007865/demystifying-the-digital-thread-and-digital-twin-concepts (accessed on 18 August 2020)
11. Hofmann, T. Integrating Nature, People, and Technology to Tackle the Global Agri-Food Challenge. *J. Agric. Food Chem* **2017**, *65*, 4007–4008, doi:10.1021/acs.jafc.7b01780
12. Mohammadi, A.; Jahromi, M.G.; Khademi, H.; Alighanbari, A.; Hamzavi, B.; Ghanizadeh, M.; Horriat, H.; Khabiri, M.M.; Jahromi, A.J. Understanding Kid's Digital Twin. In Proceedings of the 17th International Conference on Information and Knowledge Engineering (IKE), Las Vegas, NV, USA, 30 July–2 August 2018; CSREA Press: Las Vegas, NV, USA, 2018; pp. 41–46.

13. Verdouw, C.; Kruize, J. Digital Twins in Farm Management: Illustrations from the FIWARE Accelerators SmartAgriFood and Fractals. In Proceedings of 7th Asian-Australasian Conference on Precision Agriculture Digital, Hamilton, New Zealand, 16–18 October 2017; Procesion Agriculture Association New Zealand: Hamilton, New Zealand, 2017; pp. 1–5, doi:10.5281/zenodo.1006670.
14. Lu, Y.; Liu, C.; Wang, K.I.K.; Huang, H.; Xu, X. Digital Twin-driven smart manufacturing: Connotation, reference model, applications and research issues. *Robot. Comput. Manuf.* **2020**, *61*, doi:10.1016/j.rcim.2019.101837.
15. Melesse, T.Y.; Di Pasquale, V.; Riemma, S. Digital Twin Models in Industrial Operations: A Systematic Literature Review. *Procedia Manuf.* **2020**, *42*, 267–272.
16. Roy, R.B.; Mishra, D.; Pal, S.K.; Chakravarty, T.; Panda, S.; Chandra, M.G.; Pal, A.; Misra, P.; Chakravarty, D.; Misra, S. Digital twin: Current scenario and a case study on a manufacturing process. *Int. J. Adv. Manuf. Technol.* **2020**, *107*, 3691–3714, doi:10.1007/s00170-020-05306-w.
17. Schleich, B.; Anwer, N.; Mathieu, L.; Wartzack, S. Shaping the digital twin for design and production engineering. *CIRP Ann.* **2017**, *66*, 141–144, doi:10.1016/j.cirp.2017.04.040.
18. He, B.; Bai, K.-J. Digital twin-based sustainable intelligent manufacturing: A review. *Adv. Manuf.* **2020**, 1–21, doi:10.1007/s40436-020-00302-5.
19. Vachálek, J.; Bartalský, L.; Rovný, O.; Šišmišová, D.; Morháč, M.; Lokšík, M. The Digital Twin of an Industrial Production Line within the Industry 4.0 Concept. In Proceedings of the 21st International Conference on Process Control (PC), Štrbské Pleso, Slovakia, 6–9 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 258–262.
20. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, doi:10.1016/j.autcon.2020.103179.
21. Wang, B. The Future of Manufacturing: A New Perspective. *Engineering* **2018**, *4*, 722–728, doi:10.1016/j.eng.2018.07.020.
22. Scott-Emuakpor, O.; George, T.; Beck, J.; Schwartz, J.; Holycross, C.; Shen, M.H.H.; Slater, J. Material Property Determination of Vibration Fatigued DMLS and Cold-Rolled Nickel Alloys. In Proceedings of the ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, Düsseldorf, Germany, 16–20 June 2014; ASME: New York, NY, USA, 2014; Volume 7A.
23. DebRoy, T.; Zhang, W.; Turner, J.; Babu, S.S. Building digital twins of 3D printing machines. *Scr. Mater.* **2017**, *135*, 119–124, doi:10.1016/j.scriptamat.2016.12.005.
24. Majumdar, P.K.; FaisalHaider, M.; Reifsnider, K. Multi-Physics Response of Structural Composites and Framework for Modeling Using Material Geometry. In Proceedings of the 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, MA, USA, 8–11 April 2013.
25. Ricks, T.M.; Lacy, T.; Pineda, E.J.; Bednarcyk, B.A.; Arnold, S.M. Computationally efficient solution of the high-fidelity generalized method of cells micromechanics relations. In Proceedings of the American Society for Composites 30th Annual Technical Conference, East Lansing, MI, USA, 28–30 September 2015.
26. Qi, Q.; Tao, F.; Hu, T.; Anwer, N.; Liu, A.; Wei, Y.; Wang, L.; Nee, A.Y.C. Enabling technologies and tools for digital twin. *J. Manuf. Syst.* **2019**, doi:10.1016/j.jmsy.2019.10.001.
27. Hoeber, H.; Alsem, D. Life-cycle information management using open-standard BIM. *Eng. Constr. Arch. Manag.* **2016**, *23*, 696–708.
28. Chen, Y.; Jupp, J. Model-Based Systems Engineering and Through-Life Information Management in Complex Construction. Product Lifecycle Management to Support Industry 4.0. In Proceedings of the 15th IFIP International Conference on Product Lifecycle Management (PLM 2018), Turin, Italy, 2–4 July 2018; Springer: Cham, Switzerland, 2018; pp. 80–92.
29. Fernández Pérez, J.L.; Hernandez, C. *Practical Model-Based Systems Engineering*; Artech House: Boston, MA, USA, 2019.
30. Peters, S.; Fortin, C.; McSorley, G. A Novel Approach to Product Lifecycle Management and Engineering Using Behavioural Models for the Conceptual Design Phase. In Proceedings of the 16th IFIP International Conference on Product Lifecycle Management (PLM 2019), Moscow, Russia, 8–12 July 2019; Springer: Cham, Switzerland, 2019; pp. 159–169.
31. Mabkhot, M.M.; Al-Ahmari, A.M.; Salah, B.; Alkhalefah, H. Requirements of the smart factory system: A survey and perspective. *Machines* **2018**, *6*, 23.
32. Nasir, M.F.M.; Hamzah, H.S. Supply chain management framework development for new multiple life cycle product development. In Proceedings of the 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bali, Indonesia, 5–7 December 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 812–816.
33. Lim, K.Y.H.; Zheng, P.; Chen, C.-H. A State-of-the-Art Survey of Digital Twin: Techniques, Engineering Product Lifecycle Management and Business Innovation Perspectives. *J. Intell. Manuf.* **2019**, *1–25*, 1313–1337, doi:10.1007/s10845-019-01512-w.
34. Awouda, A.; Aliev, K.; Chiabert, P.; Antonelli, D. Practical Implementation of Industry 4.0 Based on Open Access Tools and Technologies. In Proceedings of the 16th IFIP International Conference on Product Lifecycle Management (PLM 2019), Moscow, Russia, 8–12 July 2019; Springer: Cham, Switzerland, 2019; pp. 94–103.
35. Singh, V.; Willcox, K.E. Engineering Design with Digital Thread. *AIAA J.* **2018**, *56*, 4515–4528, doi:10.2514/1.J057255.
36. Helu, M.; Hedberg, T.; Barnard Feeney, A. Reference architecture to integrate heterogeneous manufacturing systems for the digital thread. *CIRP J. Manuf. Sci. Technol.* **2017**, *19*, 191–195, doi:10.1016/j.cirpj.2017.04.002.
37. Hedberg, T., Jr.; Feeney, A.B.; Helu, M.; Camelio, J.A. Toward a Lifecycle Information Framework and Technology in Manufacturing. *J. Comput. Inf. Sci. Eng.* **2017**, *17*, doi:10.1115/1.4034132.
38. Mies, D.; Marsden, W.; Warde, S. Overview of Additive Manufacturing Informatics: "A Digital Thread". *Integr. Mater. Manuf. Innov.* **2016**, *5*, 114–142, doi:10.1186/s40192-016-0050-7.

39. Siedlak, D.J.L.; Pinon, O.J.; Schlais, P.R.; Schmidt, T.M.; Mavris, D.N. A digital thread approach to support manufacturing-influenced conceptual aircraft design. *Res. Eng. Des.* **2017**, *29*, 285–308, doi:10.1007/s00163-017-0269-0.
40. Bone, M.; Blackburn, M.; Kruse, B.; Dzielski, J.; Hagedorn, T.; Grosse, I. Toward an Interoperability and Integration Framework to Enable Digital Thread. *Systems* **2018**, *6*, 46, doi:10.3390/systems6040046.
41. Phoenix Integration. Model Center MBSE. Availabe online: https://www.phoenix-int.com/product/mbse/ (accessed on 11 January 2021).
42. Finocchiaro, M. Demystifying Digital Thread and Digital Twin. 2017. Available online: https://www.linkedin.com/pulse/demystifying-digital-dilemmas-michael-finocchiaro (accessed on 7 January 2021).
43. Zheng, Y.; Yang, S.; Cheng, H. An application framework of digital twin and its case study. *J. Ambient. Intell. Humaniz. Comput.* **2018**, *10*, 1141–1153, doi:10.1007/s12652-018-0911-3.
44. Ivanov, D.; Dolgui, A. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Prod. Plan. Control* **2020**, 1–14, doi:10.1080/09537287.2020.1768450.
45. Tao, F.; Qi, Q.; Liu, A.; Kusiak, A. Data-driven smart manufacturing. *J. Manuf. Syst.* **2018**, *48*, 157–169, doi:10.1016/j.jmsy.2018.01.006.
46. Borky, J.M.; Bradley, T.H. (Eds.) Protecting Information with Cybersecurity. In *Effective Model-Based Systems Engineering*; BSpringer International Publishing: Cham, Switzerland, 2019; pp. 345–404, doi:10.1007/978-3-319-95669-5_10.
47. Calder, A.; Watkins, S.G. *Information Security Risk Management for ISO27001/ISO27002*, 2nd ed.; IT Governance Publishing: Cambridgeshire, UK, 2010.
48. Katsikogiannis, G.; Mitropoulos, S.; Douligeris, C. An Identity and Access Management Approach for SOA. In Proceedings of the 2016 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT), Ajman, UAE, 12–14 December 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 126–131.
49. Detlef, G.; Gert, R.; Alexander, K.; Richard, L. Information Management in Product Development Workflows—A Novel Approach on the basis of Pseudonymization of Product Information. *Procedia CIRP* **2014**, *21*, 467–472, doi:10.1016/j.procir.2014.03.180.
50. Curran, A. How Computer Design Software Delayed The Airbus A380. Availabe online: https://simpleflying.com/airbus-a380-computer-design-delay/ (accessed on 14 January 2021).
51. Kingsley-Jones, M. Farnborough First News: The Race to Rewire the Airbus A380. Availabe online: https://www.flightglobal.com/farnborough-first-news-the-race-to-rewire-the-airbus-a380/68529.article (accessed on 14 January 2021).
52. Fourgeau, E.; Gomez, E.; Hagege, M. Managing the Embedded Systems Development Process with Product Life Cycle Management. In *Complex Systems Design & Management Asia. Advances in Intelligent Systems and Computing*; Springer: Cham, Switzerland, 2016; Volume 426, pp. 147–158.
53. Ashtari Talkhestani, B.; Jung, T.; Lindemann, B.; Sahlab, N.; Jazdi, N.; Schloegl, W.; Weyrich, M. An architecture of an Intelligent Digital Twin in a Cyber-Physical Production System. *Automatisierungstechnik* **2019**, *67*, 762–782, doi:10.1515/auto-2019-0039.
54. Tao, F.; Cheng, J.; Qi, Q.; Zhang, M.; Zhang, H.; Sui, F. Digital twin-driven product design, manufacturing and service with big data. *Int. J. Adv. Manuf. Technol.* **2018**, *94*, 3563–3576, doi:10.1007/s00170-017-0233-1.
55. Zimmerman, P.; Gilbert, T.; Salvatore, F. Digital engineering transformation across the Department of Defense. *J. Def. Model. Simul.* **2017**, *16*, 325–338, doi:10.1177/1548512917747050.
56. Taylor, N.; Human, C.; Kruger, K.; Bekker, A.; Basson, A.; Taylor, N.; Human, C.; Kruger, K.; Bekker, A.; Basson, A. Comparison of Digital Twin Development in Manufacturing and Maritime Domains. In *International Workshop on Service Orientation in Holonic and Multi-Agent Manufacturing SOHOMA 2019*; Borangiu, T., Trentesaux, D., Leitão, P., Giret Boggino, A., Botti, V., Eds.; Springer: Cham, Switzerland, 2019; pp. 158–170, doi:10.1007/978-3-030-27477-1_12.
57. Ranchal, R.; Bhargava, B. Protecting PLM Data Throughout Their Lifecycle. Quality, Reliability, Security and Robustness in Heterogeneous Networks. In Proceedings of the 9th International Conference (QShine 2013), Greader Noida, India, 11–12 January 2013; Springer: Berlin/Heidelberg, Germany, 2013; pp. 633–642.
58. Ameri, F.; Dutta, D. Product Lifecycle Management: Closing the Knowledge Loops. *Comput. Des. Appl.* **2005**, *2*, 577–590, doi:10.1080/16864360.2005.10738322.
59. Vaz, C.R.; Selig, P.M.; Viegas, C.V. A proposal of intellectual capital maturity model (ICMM) evaluation. *J. Intellect. Cap.* **2019**, *20*, 208–234, doi:10.1108/jic-12-2016-0130.
60. Biahmou, A.; Stjepandić, J. Towards agile enterprise rights management in engineering collaboration. *Int. J. Agil. Syst. Manag.* **2016**, *9*, 302–325, doi:10.1504/IJASM.2016.081564.
61. Mason, A. Protection of Intellectual Property of the Plant Continuity through IT/OT Cyber Security Measures and Governance into Industrial Automation & Control Systems. Master's Thesis, The George Washington University, Washington, DC, USA, 2018.
62. Recamán Rivas, Á. Navantia's Shipyard 4.0 model overview. *Cienc. Tecnol. Buques* **2018**, *11*, doi:10.25043/19098642.165.
63. Fraga-Lamas, P.; Fernandez-Carames, T.M.; Blanco-Novoa, O.; Vilar-Montesinos, M.A. A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard. *IEEE Access* **2018**, *6*, 13358–13375, doi:10.1109/access.2018.2808326.
64. Fernandez-Carames, T.M.; Fraga-Lamas, P.; Suarez-Albela, M.; Vilar-Montesinos, M. A Fog Computing and Cloudlet Based Augmented Reality System for the Industry 4.0 Shipyard. *Sensors* **2018**, *18*, 1798, doi:10.3390/s18061798.
65. Ramirez-Pena, M.; Abad Fraga, F.J.; Sanchez Sotano, A.J.; Batista, M. Shipbuilding 4.0 Index Approaching Supply Chain. *Materials* **2019**, *12*, 4129, doi:10.3390/ma12244129.

66. Arrichiello, V.; Gualeni, P. Systems engineering and digital twin: A vision for the future of cruise ships design, production and operations. *Int. J. Interact. Des. Manuf.* **2019**, *14*, 115–122, doi:10.1007/s12008-019-00621-3.
67. Stanić, V.; Hadjina, M.; Fafandjel, N.; Matulja, T. Toward Shipbuilding 4.0—An Industry 4.0 Changing the Face of the Shipbuilding Industry. *Brodogradnja* **2018**, *69*, 111–128, doi:10.21278/brod69307.
68. Čelar, D. Augmented Reality for Naval Applications. *Nav. Eng. J.* **2017**, *129*, 55–57.
69. Morais, D.; Goulanian, G.; Danese, N. The Future Reality of the Digital Twin as a Cross-Enterprise Marine Asset. In Proceedings of the 19th International Conference on Computer Applications in Shipbuilding 2019, Rotterdam, The Netherlands, 24–26 September 2019; The Royal Institution of Naval Architects: London, UK, 2019; pp. 24–26.
70. Kuper, S. Top 5 for 2018: Defence Connect's Best SEA 1000 Stories. Availabe online: https://www.defenceconnect.com.au/maritime-antisub/3359-top-5-for-2018-defence-connect-s-best-sea-1000-stories (accessed on 29 June 2019).
71. 3DEXPERIENCE. *Industry Services Transition Factory: A Smooth Transition to the 3DEXPERIENCE*; Dassault Systèmes: Waltham, MA, USA, 2016. Available online: https://www.3ds.com/fileadmin/Products/Services/pdfs/services-Transition-Factory-flyer.pdf (accessed on 10 January 2021).
72. Hearn, M.; Rix, S. Cybersecurity Considerations for Digital Twin Implementations. *IIC J. Innov.* **2019**, 107–113. Available online: https://www.iiconsortium.org/news/journal-of-innovation-2019-nov.htm (accessed on 12 January 2021).