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SWLC-DT: An Architecture for Ship Whole Life Cycle Digital Twin Based on Vertical–Horizontal Design

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Abstract: With the development of IoT technology, the digital twin has been applied in many fields. It is the key to realizing the integration of physical information space and an effective means for intelligent upgrading of products, providing a novel idea for the whole life cycle management of complex products. As a pillar industry at the national strategic level, the shipbuilding industry is in the stage of informatization transformation and upgrading and needs to improve its own competitiveness. The ship whole life cycle includes design, construction, operation, and maintenance, as well as scrapping and recycling, but each stage has a certain independence, which makes it prone to the problem of information islands. However, the current research on the product full lifecycle digital twin has not yet considered the impact of historical data of successive generation products on each stage of the current product lifecycle. To address the above issues, this paper firstly proposes the vertical–horizontal design idea from the perspective of the product whole life cycle and combining historical experience (vertical) with real-time data (horizontal) to realize the construction and evolution of digital twin models at all stages of the life cycle. Then, on the basis of the vertical–horizontal design idea, a framework for the ship whole life cycle digital twin is proposed. Finally, the operation mechanism of the framework is elaborated from the four stages of the ship life cycle, with a view to providing a reference for the transformation and upgrading of the future ship industry.

Keywords: whole lifecycle digital twin; ship digital twin; vertical–horizontal design idea; digital twin framework; operation mechanism

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1. Introduction

The globally growing digitalization and interconnection of processes and businesses is leading toward a closer gearing of the various stages of the product lifecycle (PLC) in the industry [1]. As a pillar industry at the national strategic level, the shipbuilding industry has the characteristics of high product complexity, low level of digitalization, long life cycle, and low degree of information integration [2]. It is facing the transformation and upgrading of informatization and intelligence [3]. The ship life cycle (SLC) includes design, construction, and operation, as well as scrapping and recycling, with each stage lasting a long time and involving a large number of people. However, there is a certain degree of independence in each stage of SLC, and the problem of information silos easily arises between each stage, bringing challenges to the transformation and upgrading of ship informatization and intelligence.

With the proposal and advancement of the "Industry 4.0" strategy [4], all industries are developing toward digitization, integration, and intelligence, and the fourth industrial revolution led by intelligent manufacturing has come [5]. Unlike traditional manufacturing, intelligent manufacturing focuses more on the entire process of PLC [6]. The traditional stages of product design, manufacturing, and service are independent of each other and have low information integration, while product design, manufacturing and service are key elements of PLC [7]. As an enabling technology for the fusion of physical information space [8], the digital twin is an effective means to realize the transformation and upgrading of complex products in terms of digitization, networking, intelligence, and service [9], and provides a new idea for the full life cycle management of complex products.

Grieves [10] describes the application of the digital twin in PLC. With in-depth research on digital twin, it plays an important role in product design [11], product manufacturing [12], product service [13], fault prediction [14], etc. However, less research has been conducted on the product whole life cycle (PWLC). Miao [15] gave the connotation of the digital-twin-based PLC and analyzed the way digital twin was applied in typical scenarios of PLC stages such as product development, manufacturing, maintenance, and scrapping. Zhuang and Kaewunruen [16–20] used digital twin technology to solve the problems of independence among the various stages of PLC and the lack of consistent data models throughout the engineering cycle but did not consider the interactions among the various stages of the lifecycle. In response to the problem that the research and application of digital twin technology focus mainly on shop floor operation and product maintenance, Thomas [21] proposed a digital-twin-based ring design framework for complex products, which fully considered the relationship between product design and manufacturing but did not involve the entire life cycle of complex products and did not consider the influence of product history data. Xie and Chen [22–24] fully considered the interactions among the various stages of PLC and used historical data of previous generation products to achieve design optimization and innovation for the contemporary product, but such a method used only historical data to optimize product design and did not consider the impact of historical product data on the various stages of the current product.

In recent years, the digital twin has been widely used in shop floor manufacturing, aerospace, medical, urban construction, ships, automobiles, and other fields [8], but there is less research on digital twin for the ship whole life cycle (SWLC). In the ship manufacturing stage, Wu [25] used digital twin technology to achieve the intelligent manufacturing of ships and validated it with a pipe-processing line; Li [26] adopted digital twin technology to realize the prediction and control of ship group product quality. In the ship maintenance stage, VanDerHorn and Anyfantis [27,28] proposed a digital-twin-based method for predicting the structural state and life of a ship to support the maintenance plan and operational decision of the ship. Giering and Yang [1,29] proposed the research idea of a digital twin of SWLC but did not consider the connection among the various stages of the life cycle and the impact of historical data on each stage. In comparison with the existing research, the main contributions of this paper are as follows:

1. This paper proposes the vertical–horizontal design (V-H) idea from the perspective of the product whole life cycle to address the problem that the current digital twin does not refine the historical data of previous generations of products to each stage of the contemporary the product lifecycle.
2. This paper proposes the connotation of the ship whole life cycle digital twin (SWLC-DT) in combination with the V-H idea in view of the fact that there is no systematic definition of SWLC-DT.
3. Aiming at the lack of effective information exchange among the various stages of the current the ship life cycle, which is not conducive to the digital transformation of the shipbuilding industry and the development of intelligent ships, this paper proposes an architecture for SWLC-DT based on the V-H idea.

2. Literature Review

The concept of the digital twin first originated from the information mirror model proposed by Grieves [30]. In 2012, the US Air Force Research Laboratory and the National Space Administration proposed to build a virtual model in virtual space that is the same as the physical space vehicle and defined the digital twin for the first time—A digital twin is an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin [31]. Since then, the digital twin has received extensive attention, and numerous results have been achieved in domestic and international research on the digital twin. Tao proposed a five-dimensional conceptual model of the digital twin [32] on the basis of the three-dimensional model and proposed the digital twin standard system [33], digital twin enabling technology tools [34], and the model construction theory [35] on the basis of the five-dimensional model.

The digital twin is a key enabling technology to realize cyber–physical space fusion [8], and it has now been applied to various stages of PLC [36]. Regarding the research on digital twin in PLC, Xiang [37] analyzed the applications in the fields of product green material selection, green dismantling, green recycling, green remanufacturing, and reverse supply chain on the basis of the five-dimensional model; Liu [38] explored the application of digital twin satellites in various stages of satellite overall design, detailed design, manufacturing, on-orbit service and health management, and network operation and maintenance management from a whole life cycle perspective. Tao [39] proposed the concept of a digital twin network and gave the system architecture design from the perspective of the whole life cycle of the network. Ding [40] described the technical framework of digital twin high-speed trains in terms of the construction of digital twin models and functional services for the whole life cycle of high-speed trains, respectively. Zhang [7] used digital twin technology to integrate the three stages of product design, manufacturing, and service to achieve intelligent manufacturing of products.

With the development of the new generation of information technology, the digital twin has been applied in the fields of electric vehicles [41], healthcare [42], networks [43], power grids [44], and ships [45]. In the marine sector, most of the research on digital twin at home and abroad focuses on a certain stage of ship design, manufacturing [25], and maintenance [27] or the research on a certain component of the ship, such as the ship propulsion system [46] and the ship electrical system [45]. The digital twin has been initially applied in the marine sector, but less research has been done on SWLC.

In recent years, the digital twin has been widely researched in the whole life cycle of various products, but there are still many deficiencies. In the field of ships, there are also few relevant studies. At present, the world major shipbuilding countries are vigorously promoting the intelligent manufacturing of ships. Different from traditional manufacturing, intelligent manufacturing focuses more on the entire process of PLC. The digital twin is a key to realizing the integration of physical information space and provides a new idea for the management of complex products whole life cycle; therefore, SWLC-DT has broad research prospects.

3. The V-H Idea for PWLC Digital Twin

In the current research on PWLC digital twin, the product design, manufacturing, operation and maintenance, and scrapping form a complete closed loop of optimized product design. It applies product historical data to the product design optimization stage but has not yet refined the data from the various stages of the historical PLC to the various stages of the contemporary PLC. This results in a poor correlation among the virtual models at each stage and inaccurate and costly services based on the virtual models. To address the shortcomings of research on PLC digital twin, this paper divides PLC into four stages: product design, product manufacturing, product operation, and product maintenance and proposes the V-H idea for PWLC digital twin, as shown in Figure 1.

In Figure 1, the V-H idea of PWLC digital twin realizes the construction and integration of the product entire lifecycle digital twin model (DTM) from the vertical and horizontal directions. The vertical dimension is the historical data of each stage of the previous generation PLC, and the horizontal dimension is the real-time data of each stage of the contemporary PLC.

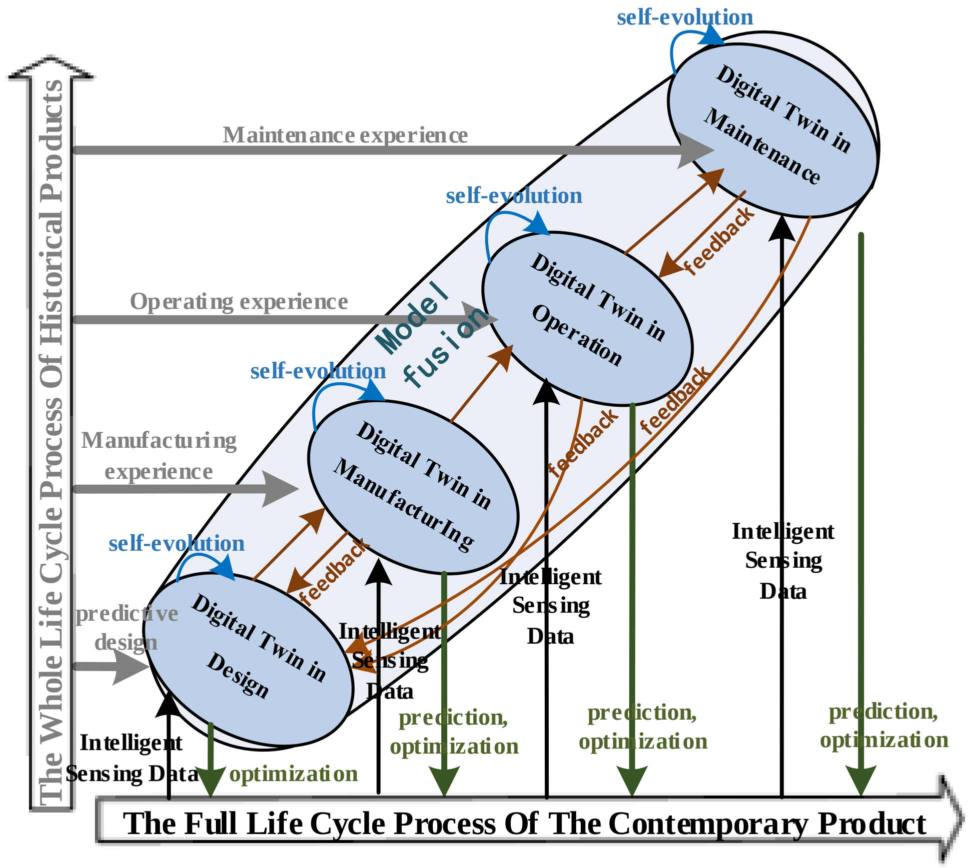

Figure 1. The V-H for PWLC digital twin.

3.1. The Vertical Historical Data

In the vertical direction, before constructing the DTM, according to the division of PLC stages, the historical data of each stage of previous generation products lifecycle provides design, manufacturing, operation, and maintenance experience for the contemporary products, forming a preliminary DTM corresponding to each stage. With the help of existing historical data, it provides prior knowledge for the construction of the DTM of contemporary products and optimizes the generation process of the product DTM. For example, in the product design phase, the use of a large amount of whole lifecycle data from previous generations of products provides a reference for the design of current products, forming a preliminary design DTM and enabling the predictive design of products.

3.2. The Horizontal Real-Time Data

In the horizontal direction, during the model construction and evolution, real-time intelligent sensing data are provided at each stage of the contemporary PLC to facilitate the self-evolution of the DTM corresponding to each stage, so that the DTM is highly consistent with the physical space entity and ultimately realizes virtual–real mapping. For example, in the manufacturing stage, on the basis of real-time data from the manufacturing workshop, the manufacturing DTM evolves itself and remains largely consistent with the actual manufacturing process. Before the fault occurs, the manufacturing DTM enables the prediction of the state of the equipment in the manufacturing workshop and generates an improvement plan, which can be optimized through the validation of the virtual model. In addition, PLC digital twin interacts among the various stages, such as in the design and manufacturing phases. In the manufacturing process, the design deficiencies are verified through the virtual manufacturing of the digital twin, thus enabling the optimization of the design DTM.

3.3. The Vertical–Horizontal Design Idea

The V-H idea for PWLC digital twin applies the data from various stages of the historical product to the implementation of the DTM. Before building the DTM for each stage of PLC, the data from each stage of the historical product (vertical) provides historical experience for each stage of the contemporary PLC to form a preliminary DTM. In the model construction and evolution stage, the self-evolution of the DTM in each stage is realized by sensing the real-time data at each stage of PLC, thereby ensuring the consistency of the DTM with the physical entity. At the same time, according to real-time data, with the help of high-fidelity DTM, the prediction and optimization of each stage of the actual PLC is realized.

By combining the historical data of previous generation products with real-time data from contemporary products, the V-H idea for PLC digital twin solves the problems in the current research on the digital twin of PWLC and enables the predictive generation of digital twin models for each stage of PLC, shortening the time experienced throughout the lifecycle of current products, while improving the economic efficiency of products with the help of high-fidelity twin models.

4. An Architecture for SWLC-DT Based on V-H

4.1. SWLC-DT

The SWLC is divided into four stages: design, construction, operation, and maintenance. At present, most of the research on the ship digital twin focuses on one of these stages, and there is still a lack of research on SWLC digital twin, and a systematic definition of the digital twin of SWLC has not yet been formed. Therefore, this paper proposes the connotation of SWLC-DT in combination with the V-H idea:

SWLC-DT is oriented toward the four stages of the SLC. It realizes the construction and fusion of virtual models for each stage of SLC from both the historical data (vertical) of previous generation ships and the real-time data (horizontal) of contemporary ships and provides intelligent services for the SWLC on the basis of the virtual models.

4.2. The System Architecture of SWLC-DT

Traditionally, the stages of SLC are independent of each other. Researchers have not given enough consideration to the interactions among the various stages of the ship, resulting in a lack of effective information interaction among ship design, manufacturing, operation, and maintenance, which is highly prone to the formation of information silos and is not conducive to the digital transformation and upgrading of the ship industry. In response to the inadequacy of the current research on digital twin in the PLC, Section 2 proposed the V-H idea of PWLC digital twin. On the basis of the previous section, this subsection proposes an architecture for SWLC-DT, as shown in Figure 2.

The architecture for SWLC-DT consists of physical space, virtual space, knowledge space, a virtual control platform, and a data transmission interface layer. The physical space corresponds to the actual SWLC; the virtual space is a virtual mapping of the physical space, which consists of the twin layer and the intelligent service layer; the knowledge space includes two parts: the data layer and the knowledge layer; the virtual control platform is divided into the system build time and the system run time, providing control services for the construction and operation of the whole system. In the architecture for SWLC-DT, the physical space is the foundation of the entire system; the virtual space is the core of the system; the data transmission interface layer is the bridge to realize the information interaction between various parts; the virtual control platform is the key, supporting the construction and operation of each part; and the knowledge space is the brain of the system, providing knowledge services for the virtual space and the virtual control platform.

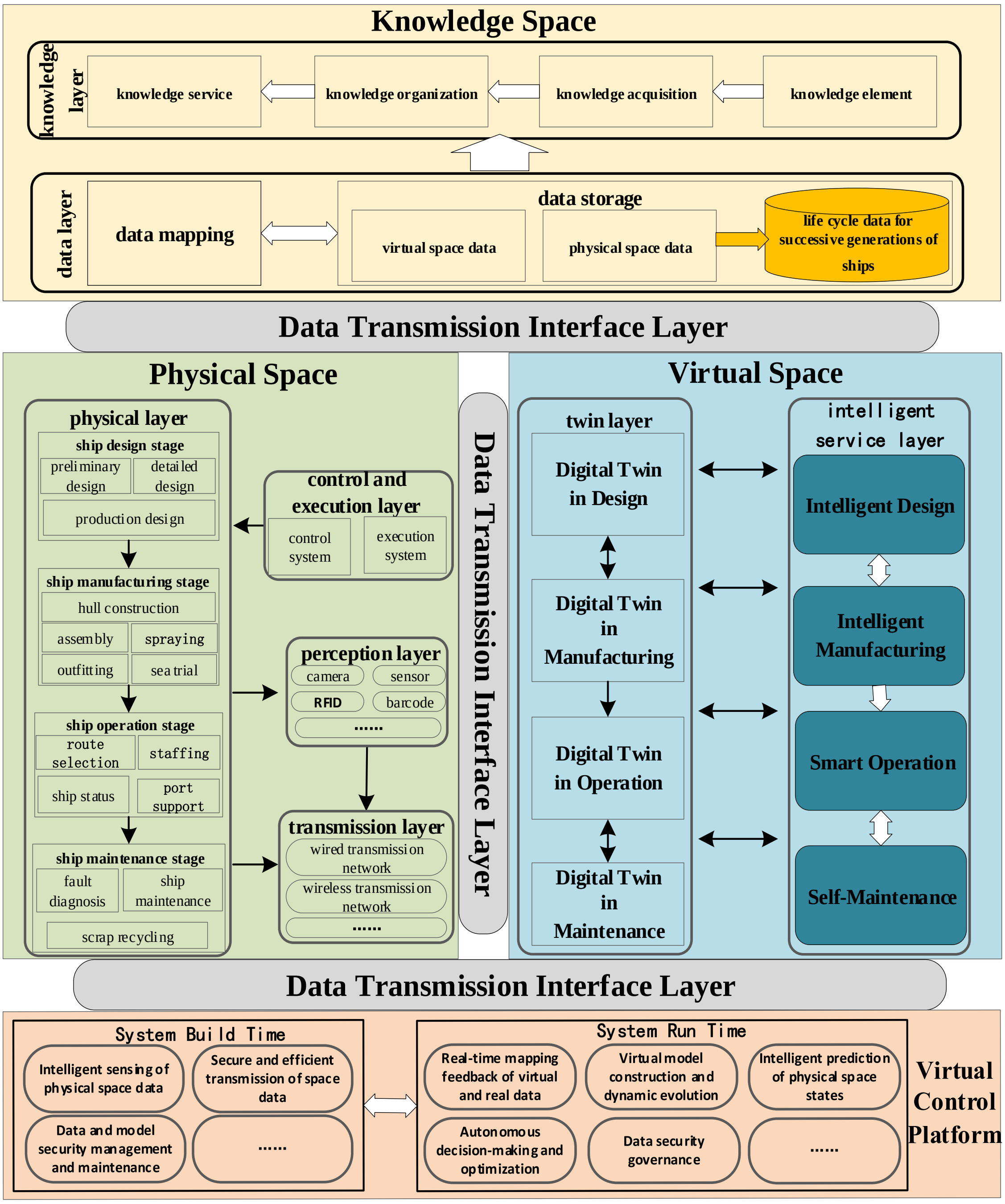

Figure 2. The architecture of SWLC-DT.

4.2.1. Physical Space

The physical space is a dynamic and complex real ship world that is the basis of the whole system, which includes the physical layer, the control and execution layer, the perception layer, and the transmission layer.

The physical layer corresponds to SWLC, including four stages: the design, manufacturing, operation, and maintenance stage, and each stage corresponds to a series of actual operations on the physical ship. For example, the manufacturing phase includes mainly hull construction, assembly, outfitting, spraying, and sea trials. The control and execution layer enables the control of the virtual space over the physical space, which includes the control system and the execution system. In the physical layer, the control and execution layer prompt the physical equipment to operate following the instructions from the virtual space. The core of the physical space construction is the perception of all-element information in the physical layer. Since the corresponding physical departments are distributed off-site at different stages, to obtain real-time data in the physical space, the sensors in the perception layer and the transmission network in the transmission layer are required to achieve real-time acquisition and transmission of all elements of data in the physical layer.

4.2.2. Virtual Space

The virtual space is mapped to the physical space and serves SWLC. It is the core of the system and consists of two main components, the twin layer and the intelligent service layer, as shown in Figure 3.

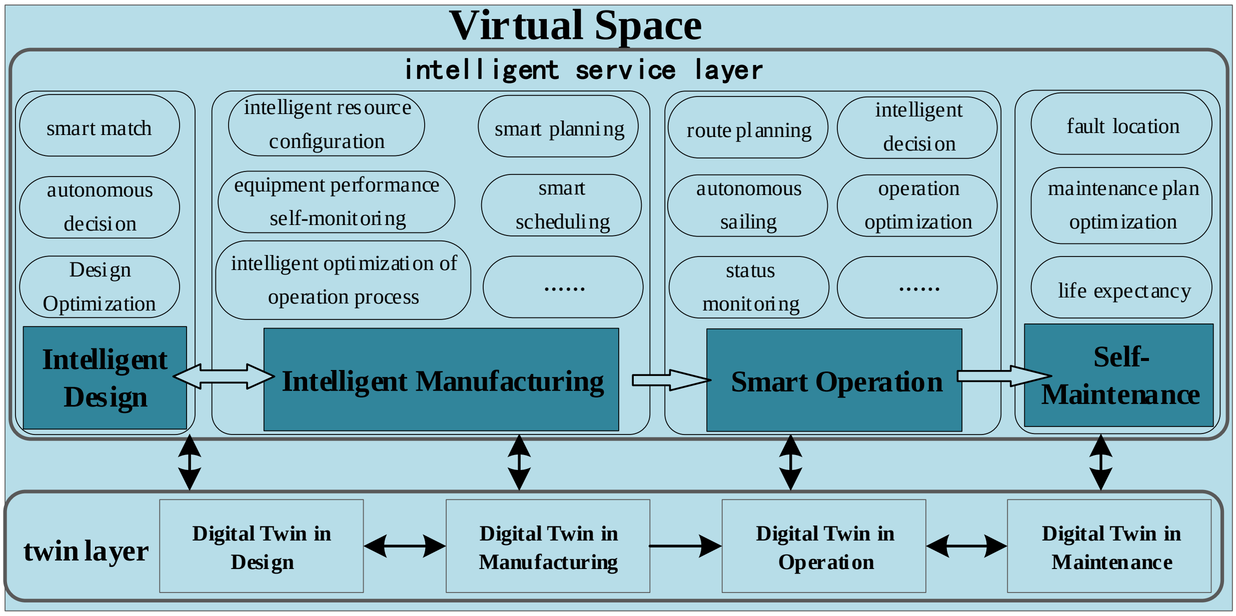

Figure 3. The structure of the virtual space.

On the basis of the V-H idea, the twin layer generates a preliminary DTM through the historical data of various stages of previous generation ships, and then realizes the self-evolution of the virtual model on th basis of the real-time data from intelligent perception in each stage of the physical layer. The twin layer consists of digital twin models corresponding to each stage of SLC, including design DTM, manufacturing DTM, operation DTM, and maintenance DTM. In the twin layer, historical ship data and real-time data from each phase are combined to fuse and correlate the twin models at each stage of SLC, thus eliminating barriers to information interaction throughout the SWLC.

The intelligent service layer provides intelligent services for each stage of the physical space on the basis of the real-time data from the twin layer and the physical space, realizing intelligent design, intelligent manufacturing, smart operation, and self-maintenance of the ship. For example, in the ship maintenance stage, based on the ship maintenance DTM, historical maintenance data, ship equipment attributes and real-time data, the predictive maintenance and life prediction of the ship are realized.

4.2.3. Knowledge Space

The knowledge space is the brain of the system, enabling the storage and processing of data in both physical and virtual space. The knowledge space consists of the data layer and the knowledge layer, as shown in Figure 4.

The data layer is composed of data storage and data mapping. It contains the historical data of previous generation ships and real-time data from each stage of the physical space, respectively corresponding to the vertical and horizontal directions of the V-H idea. The data storage module realizes the storage of lifecycle data of the previous generation of ships, physical space data, and virtual space data. The data from the physical space include mainly design data, equipment data, ship production process data, and real-time ship operation data of the physical layer. The virtual spatial data include simulation data from the twin layer, model data, and decision data from the service layer. When the contemporary ship is scrapped and recycled, the corresponding physical space data are automatically stored in the life cycle data for successive generations of ships. To achieve the rapid mapping of the virtual and physical space data, the data generated in the four stages of the physical layer and twin layer are stored separately. The data mapping realizes the synchronous mapping between physical space and virtual space, which consists of three parts: data fusion, data association, and data synchronization.

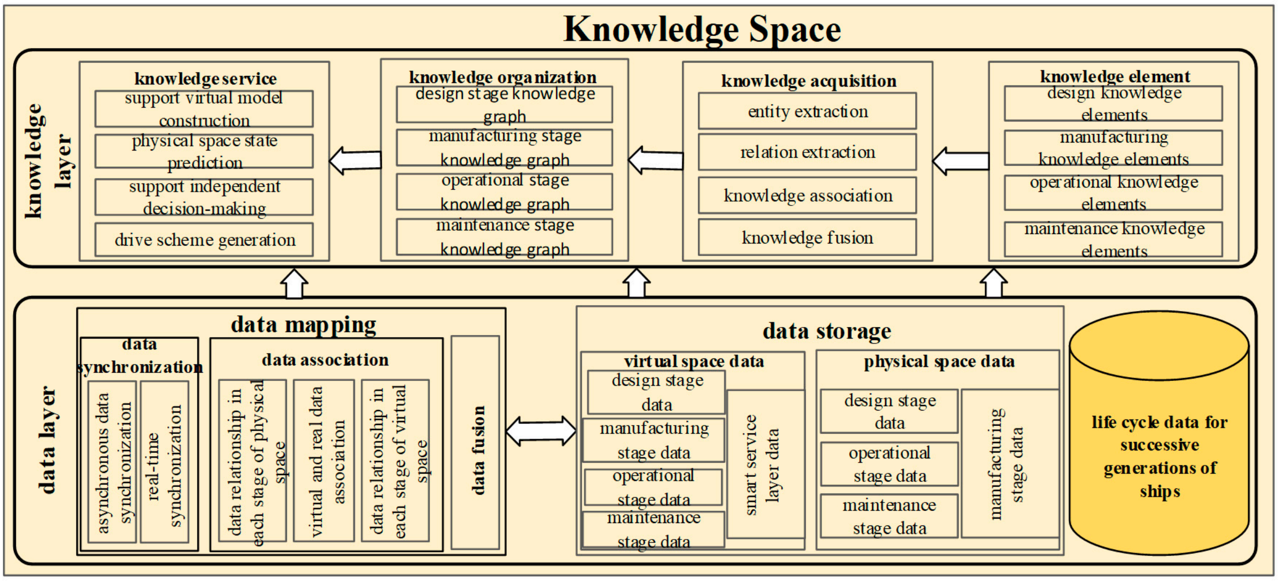

Figure 4. The structure of the knowledge space.

The knowledge layer includes the extraction of knowledge elements in each stage of SLC, the acquisition of knowledge, the organization of knowledge, and the provision of knowledge services. Firstly, knowledge elements are extracted according to each stage of the ship to complete the acquisition of knowledge. Then, the knowledge is correlated and fused, and the knowledge is organized for each stage of SLC using the knowledge graph. Finally, it provides knowledge services for the construction of virtual space models, the prediction of physical space states, and the generation and optimization of physical space decisions.

4.2.4. Virtual Control Platform

The virtual control platform realizes the management and maintenance of the physical space, virtual space, knowledge space, and data transmission interface layer. It consists of two views: the system build time (SBT) and the system run time (SRT).

SBT realizes the organization of the system, which includes the organization of physical entities and devices in the physical space, the intelligent perception of real-time data, the construction of virtual models in the virtual space regarding the data of each stage of historical ships, the secure and efficient transmission of data in the three major spaces, and the secure management and maintenance of the data and virtual models.

SRT provides management and maintenance for the system operation. It includes real-time mapping and feedback of data in virtual space and physical space, dynamic evolution of virtual models in virtual space, intelligent prediction of physical entities states in physical space, autonomous decision-making, scheme optimization in case of sudden fault of physical equipment, and security governance of system data. During the system operation, the virtual control platform provides different decision views for prediction and decision optimization tasks in different stages and scenarios.

4.2.5. Data Transmission Interface Layer

The data transmission interface layer enables the transmission and interaction of data among physical space, virtual space, knowledge space, and virtual control platform. Due to the different sources and structures of data in physical space, virtual space, knowledge space and control platform, data processing and protocol conversion are required to realize data transmission.

The data transmission interface layer establishes a consistent perception interface and communication protocol so as to realize the unified encapsulation of multi-source heterogeneous data. In addition, the data transmission interface layer includes simple preprocessing operations on the transmitted data, such as data cleaning, to finally realize the direct interaction of data among physical space, virtual space, knowledge space, and virtual control platform.

5. Case Study: Digital Twin Application in SWLC

This section introduces the operation mechanism of SWLC-DT in detail for the physical objects corresponding to each stage of the ship, as shown in Figure 5.

In the digital twin for SWLC, each stage corresponds to a DTM: the design DTM, the manufacturing DTM, the operations DTM, and the maintenance DTM. In Figure 5, the ship digital twin also contains a digital model for storing and processing data, which includes historical data of the previous generation ships entire life cycle, the knowledge related to the ship, and the real-time data generated at various stages. The operation mechanism of each stage of SWLC-DT will be described next.

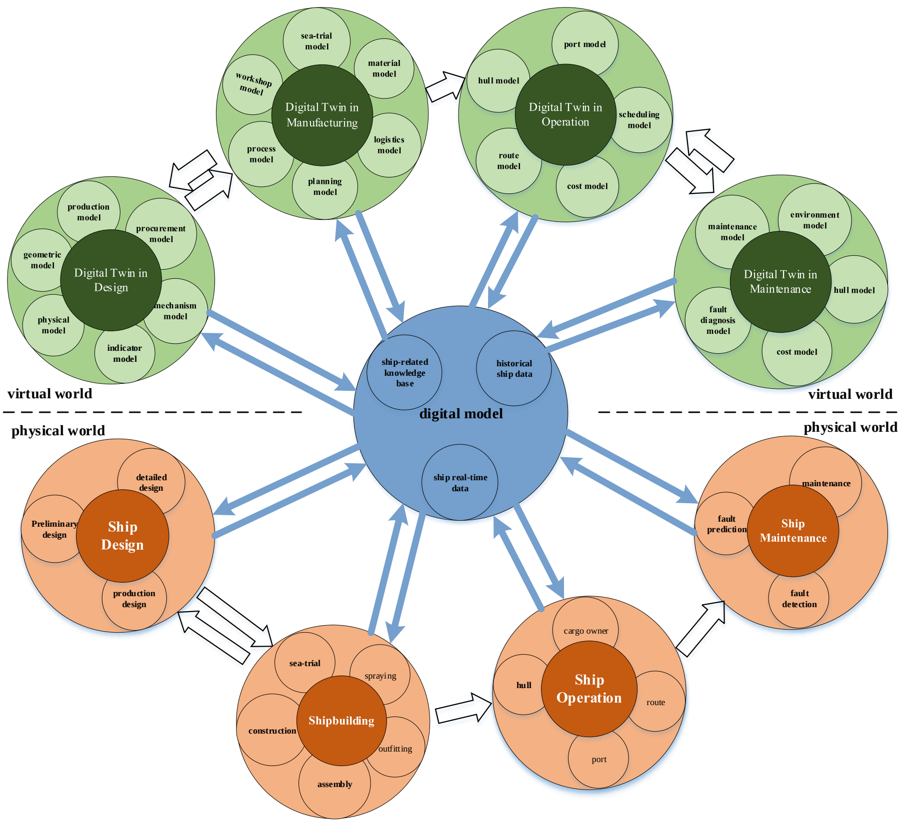

Figure 5. The operation mechanism of ship digital twin.

5.1. Digital Twin in Ship Design Stage

The ship design is divided into three stages: preliminary design, detailed design, and production design. The process of ship design is the construction process of the design DTM.

1. Preliminary design stage:

The preliminary design realizes the design of the overall structure of the ship, including the design of the overall performance of the ship, the selection of the ship equipment, the design of the ship layout, and parameters. On the basis of the ship design knowledge and the historical data of previous generation ships including design, manufacture, operation, and maintenance, the overall design of the ship is quickly formed according to the ship owner's requirements. In this process, the preliminary design model of the ship is formed quickly by intelligent matching of historical ship type, historical ship equipment parameters, and ship owner's requirements in the virtual space. The preliminary design model includes a geometric model, physical model, and indicator model. The geometric model is used to describe the geometry of the ship, including the overall structure of the ship and the shape of the ship's equipment. The physical model describes the main physical parameters of the ship, such as the storage capacity and displacement. The indicator model is used to describe the overall technical indicators of the ship. After completing the preliminary design, the preliminary design model is optimized by comparing the actual data differences after the simulation verification of the virtual model.

2. Detailed design stage:

The detailed design stage is based on the preliminary design to finalize the hull structure of the ship, the selection of equipment, and the ordering of materials. The detailed design model of the ship is formed in the virtual space, including the mechanism model and the procurement model. The mechanism model is used to describe the operation and mapping mechanism of the ship. The procurement model describes the ordering of main materials. In the detailed design stage, the simulation of the mechanism model is used to verify the overall performance of the ship and whether the hull structure meets the requirements so as to realize the iterative optimization in the detailed design stage of the ship. The procurement model realizes the virtual procurement of relevant materials in the design stage and verifies the design plan according to the actual parameters of raw materials.

3. Production design stage:

The production design stage determines the ship construction plan according to the actual construction capability and process level of the shipyard. The production design model used to describe the ship production requirements is formed in the virtual space, while the production design is verified virtually, and the optimization of the production design is ultimately realized.

After three design stages, the virtual models of the three stages are fused to finally form a DTM of the ship design in virtual space that meets the needs of shipowners.

5.2. Digital Twin in Manufacturing Stage

The manufacturing stage includes the processing of materials, the assembly of hull parts and components, the outfitting and painting of the general section, the hull gathering together, and the sea trial. In the virtual space, the ship manufacturing DTM is composed of the ship and the ship manufacturing workshop, including the workshop model, the process model, the planning model, the material model, the logistics model, and the sea-trial model.

The workshop model corresponds to the physical workshop ship manufacturing. Before the actual manufacture of the ship, the workshop model completes virtual manufacturing in the virtual space according to the design DTM generated in the design stage. By comparing the differences between the virtual manufacturing data and the expected data in the design stage, feedback on the design stage is formed before the actual manufacturing, enabling the optimization of the ship design and avoiding losses in the actual manufacturing process.

In the process of ship processing and manufacturing, the construction of individual hull components has the characteristic of being distributed off-site, creating the problem of information silos in the physical space. By integrating the information flow of various production departments, the workshop model eliminates the barriers of information dissemination among various departments, thus realizing the integration of ship hull, outfitting, and spraying. In addition, with the real-time perception of workshop equipment data, the workshop model monitors the status of manufacturing equipment to avoid equipment damage during processing from affecting the ship manufacturing schedule. The workshop model achieves feedback on the ship design during the manufacturing process and optimizes the ship design by perceiving the actual data of the hull component manufacturing and comparing the difference with the design data.

The process model corresponds to the ship construction process. In the manufacturing process, the ship is processed and manufactured according to the process model, and combined with the real-time operation status of the workshop model, the optimization of the ship construction process is realized.

The planning model corresponds to the production schedule of the ship and ensures the delivery of the ship within the schedule. In the actual manufacturing process, the overall delivery time of the ship will be affected due to the factors of the materials logistics, workshop equipment, and the quality of the parts processed during the manufacturing process. The planning model realizes the dynamic update and optimization of the ship production plan by synthesizing the transportation of materials, the maintenance of workshop equipment, and the use of materials.

The logistics model is constructed on the basis of the transportation status of the purchased materials, and the purpose is to reasonably plan the construction of each component of the ship by controlling the logistics timeliness of the materials. The material model corresponds to the actual material situation. Due to the complexity of the ship, the materials are numerous and complex, and the location and usage of materials cannot be obtained in time. By constructing the material model of the ship, the real-time situation of the material is described, thus ensuring the efficiency of ship construction.

The sea-trial model corresponds to the sea trial process of the ship. Before the actual launch of the ship for sea trials, the virtual launch of the trial-model is verified to solve the possible problems of the ship. In the actual process of sea trial at the dock, by comparing the difference between the actual data and the simulation data, the repair and optimization of the hull are realized, ultimately forming the manufacturing DTM of the ship.

In order to realize the intelligent manufacturing of ships, the ship manufacturing process and ship processing plan are quickly formed in the virtual space on the basis of the ship manufacturing history data and related knowledge from the digital model, and the evolution of the process model and planning model is completed through the perceived actual manufacturing data. In addition, the workshop model closely connects each processing workshop, substitute processing workshop, and each production department to avoid the formation of information islands in the process of ship processing and to realize information sharing in the manufacturing process. The workshop model realizes the virtual manufacturing of ships in the virtual space, shortens the time experienced throughout the cycle of whole design and construction, and reduces the losses caused by the traditional manufacturing process. It also serves as a bridge to realize the communication between ship design and manufacturing, thus achieving the integration of ship design and manufacturing.

5.3. Digital Twin in Manufacturing Stage

In the process of ship operation, the ship DTM operation is constructed in the virtual space according to the actual operation. The DTM includes the hull model, the route model, the cost model, the scheduling model, and the port model.

The hull model is the overall model of the ship after design and manufacture, which describes all functional properties and relevant equipment parameters of the ship. During the operation of the ship, the hull model is consistent with the actual hull, such as the specific operation conditions of the ship. The hull model enables the shipowner to keep track of the actual operation status of the ship and the fuel consumption to ensure the optimal transportation of the ship.

The route model intelligently selects the route on the basis of the historical operation data of ships and the deadline required by the cargo owner. In addition, the autonomous navigation of the ship is realized based on the hull model, the route model, and the historical data of the ship's navigation.

The cost model helps shipowners to gain a comprehensive understanding of the main consumption of the ship during its operation, such as ship fuel and charter. It also intelligently adjusts costs in combination with capital demand. In addition, it combines with the hull model to obtain real-time fuel consumption of the ship, describe the economic status of the ship, optimize the ship operations, reduce the costs, and maximize economic efficiency.

The scheduling model combines the cost model, the route model, and the hull model to realize intelligent scheduling of the ship on the basis of the actual condition of the ship. For example, when an early warning of the ship state occurs, the ship scheduling model intelligently generates the maintenance scheduling plan on the basis of historical maintenance data. At the same time, the hull model simulates and verifies the generated scheduling plan and optimizes the scheduling plan according to the simulation results. The port model guarantees the interaction between the ship and the port. During the voyage, the interaction between the ship and the port is crucial. Through the port model, the port provides remote technical support for the ship to ensure the safe navigation of the ship.

5.4. Digital Twin in Ship Maintenance Stage

The ship maintenance stage enables predictive maintenance of the ship and the generation of a maintenance plan after the fault occurred. In the virtual space, the ship maintenance DTM is quickly generated on the basis of the ship historical maintenance data, ship maintenance knowledge and ship intelligent perception data. The ship maintenance DTM consists of the hull model, the environmental model, the cost model, the fault diagnosis model, and the maintenance model.

The environmental model parameterizes the environmental data of ship operation, describes the factors affecting the performance of the ship equipment and ensures that the hull model can be largely consistent with the actual operating conditions of the ship.

The fault diagnosis model is based on the historical data of ship maintenance, the real-time operation data of the ship and the physical characteristics of the ship equipment to monitor the health of the ship, ensure the efficient operation of the ship, and realize the scrapping and recycling of the ship. Different from the traditional fault diagnosis based on historical data, the fault diagnosis model integrates physical factors of the equipment and the environment of the ship to achieve a more accurate fault diagnosis of the ship.

The maintenance model is aimed at two situations, one is to generate a maintenance plan for the fault predicted by the fault diagnosis model, and the other is to generate a maintenance plan for the regular maintenance of the ship.

The cost model considers the cost in the process of ship maintenance. It promotes the maintenance model to optimize the ship maintenance plan by analyzing the cost of the maintenance plan to ensure that the ship maintenance has the greatest economic efficiency.

The hull model is consistent with the actual physical ship in the virtual space. Due to the variability of the environment, the hull model evolves dynamically according to the actual perception data of the ship. When the ship breaks down, the hull model performs virtual verification on the maintenance plan generated by the maintenance model to realize the intelligent optimization of the plan. During the ship maintenance process, the hull model updates the corresponding equipment attribute information according to the maintenance plan to ensure consistency between the virtual ship and the physical ship.

Meanwhile, the maintenance DTM forms feedback on the operation DTM, coordinates the ship operation, and ensures the consistency between ship operation and maintenance.

6. Discussion

This paper firstly reviews the application of digital twin in the field of ships and the research on digital twin in the whole life cycle of products. Aimed at the problems existing in the research of digital twin in the complex PWLC and the lack of research in the field of ships, we firstly propose the V-H idea for PWLC digital twin, in which the vertical direction is the historical data of each stage of the previous generation products lifecycle, and the horizontal direction is the real-time data of each stage of the contemporary PLC. The construction of PWLC digital twin is realized from both the vertical and horizontal directions. Then, combined with the V-H idea, we elaborate the connotation of SWLC-DT and propose SWLC-DT architecture. The proposed framework is expounded from five aspects, including physical space, virtual space, knowledge space, data transmission interface layer, and virtual control platform. Finally, the operation mechanism of SWLC-DT is analyzed. It is hoped that the research in this paper can provide a reference for the application scenarios of digital twins in PWLC and the transformation and upgrading of smart ships in the future.

In the future, we will further improve and optimize the theoretical framework of the SWLC-DT, conduct in-depth research on the construction and dynamic evolution of the virtual model in the virtual space, realize autonomous reconstruction of virtual models, promote a high dynamic consistency between the virtual model and the physical space entity, and guarantee the effectiveness of state prediction and optimization of physical entities based on virtual models.

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