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Review

Digital twin for ship life-cycle: A critical systematic review

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ABSTRACT

The focus on digitalisation in manufacturing is spreading to other industry fields, including large and complex objects like ships. Such interest introduces the concept of Digital Twins in supporting designers and operators through the whole ship-life cycle. However, the term Digital Twin is typically abused in the shipping industry, many times erroneously referring to any virtual version of a model-based system as a Digital Twin of the ship. The mutual data exchange between the physical and virtual environment, which is the basis of a true Digital Twin, is mostly missing, confusing a virtual model with a sophisticated living virtual environment. Few reviews are available in the literature for Digital Twins on ships. This systematic review proposes the identification of weaknesses and correlations between current Digital Twin applications in the maritime industry and other industry fields. Furthermore, the methodology applied here may be repeated in future studies to provide a fair and objective overview of the research advancements in the topic. The study highlighted how literature scarcely addresses the design and decommissioning phases, indicating that research should focus on these topics, especially concerning the design of future ships.

1. Introduction

The digitalisation of industrial manufacturing has been a process ongoing for the last ten years. The availability of new information technologies, such as cloud computing (Wang et al., 2018), Internet of Things (IoT) (Chen et al., 2018), Artificial Intelligence (AI) (Ludwig et al., 2018), wireless sensor networks (Syafrudin et al., 2018), and big data (Kusiak, 2017), allows for digital advancement in the industry, known as Industry 4.0 (Schwab, 2017). All these new technologies are rapidly developing across multiple sectors and aspects of the industry, showing growing potential to improve the entire product life-cycle (Stark, 2015) instead of the sole manufacturing process. In particular, these information technologies facilitate the integration between the physical and digital world, promoting extensive employment of the Digital Twin (DT) concept (Grieves, 2015; Tao and Zhang, 2017). Such a trend is emphasised by industry and academia, leading to a spread of DT-related works in the open literature, especially in the last few years (Liu et al., 2021b). Emphasising this, Fig. 1 shows the publication per year, including "Digital Twin" in the title or keywords according to the Scopus and Web of Science (WoS) databases from 2013 to August 2022.

The digital transition, intended as a DT-assisted life-cycle management of a complex system (Grieves and Vickers, 2017), also involves sectors not directly related to industrial production only (Tao et al., 2017), as in the case of transport sectors and, consequently, maritime industry (Erikstad, 2017). However, compared to the application in manufacturing or energy-related fields, published works in the transport sector remain a step behind, with the maritime industry registering lower levels than aerospace or automotive engineering. Fig. 2 shows the results of unfiltered research on these main topics on the Scopus and WoS databases, highlighting the differences between the mentioned sectors. However, before discussing considerations specific to the maritime and ship industry, a general description of the DT is provided first.

1.1. The DT concept and its relation to product life-cycle

The Digital Twin is a virtual representation of a physical entity or process, potentially during its entire life-cycle. The virtual entity is capable of representing the actual status of the physical entity including a relevant recording of historically collected data. Additionally, the Digital Twin can evaluate the future behaviour of the physical entity, modifying some control actions up to optimising a complete operation.

Fig. 3 shows the conceptual model of a general Digital Twin, highlighting the possible interactions between virtual, physical environments and an operator. The specific interactions or tasks, as reported in the figure, between the three entities can be interpreted as follows:

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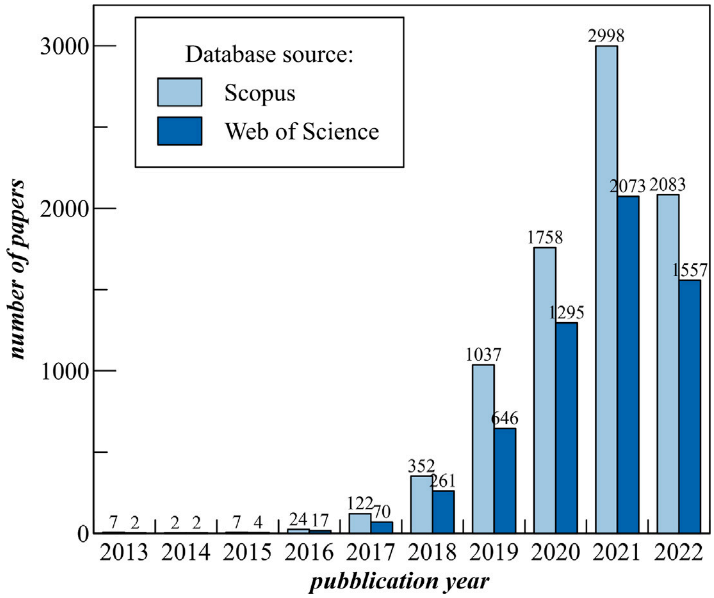

Fig. 1. Published works per year including "Digital Twin" in the title or keywords indexed on Scopus and WoS databases (2013-August 2022).

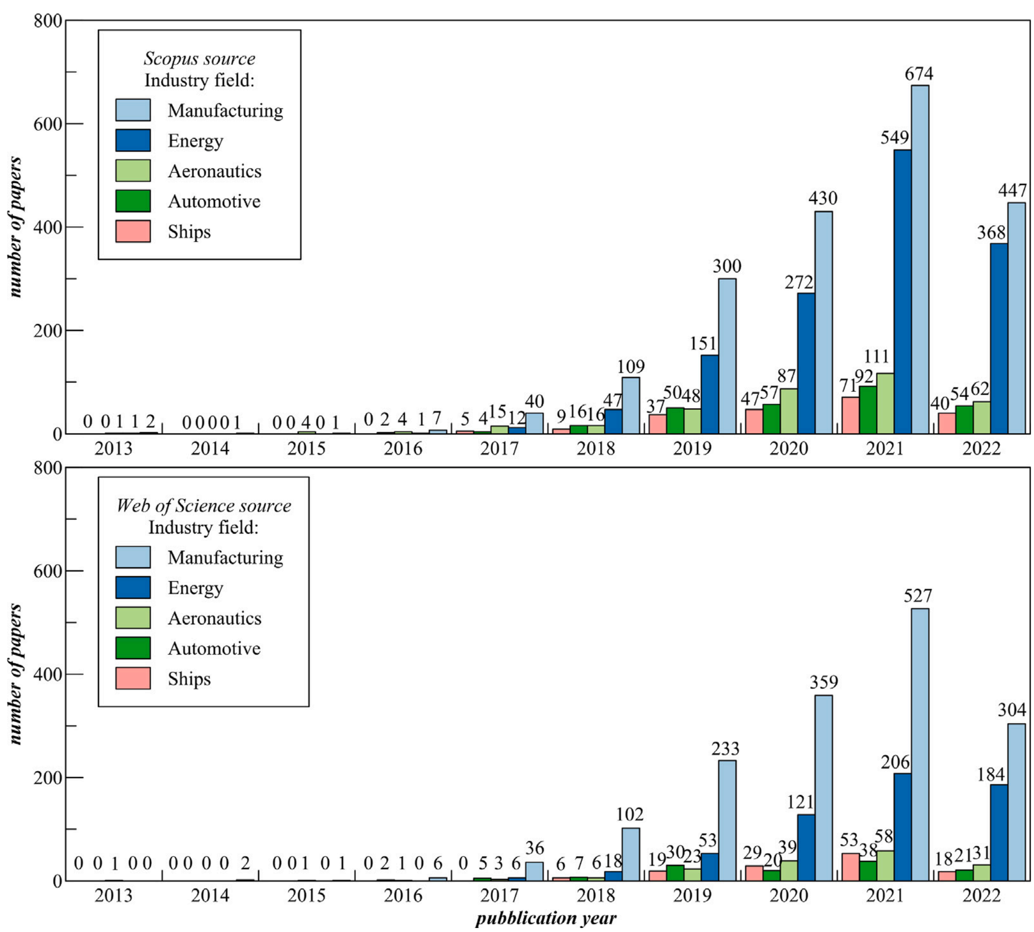

Fig. 2. Published works per year on different industrial sectors indexed on Scopus (*top*) and WoS (*bottom*) databases (2013-August 2022).

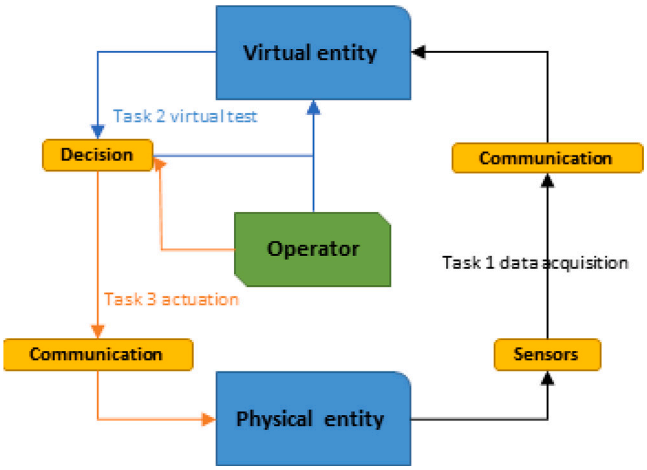

Fig. 3. Schematic representation of a Digital Twin with the interconnection between virtual and physical entities.

Task 1 : acquisition of data from the physical to the virtual entity, employing sensors (in the physical entity) that communicate data to the virtual environment at a specific rate and with a given protocol.

Task 2 : execution of virtual test or optimisation processes to improve physical object performances or reduce risk of malfunctions or failures.

Task 3 : actuation of corrective actions on the physical entity by sending data to the physical entity actuators with a given protocol.

The actuation of the specific tasks can be effectively driven by the operator or performed autonomously, depending on the structure of the virtual entity and decision support systems (Moghadam et al., 2021). Therefore, being able to perform multiple tasks concurrently, the virtual entity can also be composed of a set of virtual sub-entities (Grieves, 2015).

1.1.1. Relevant Digital Twin descriptions and definitions

The original description of Digital Twin is comprised of an entity composed of three environments: (1) a physical product containing information about the product itself, (2) a virtual representation of that product, and (3) a bi-directional connection of data flowing in both directions. That means data flows from the physical to the virtual environment, and instructions, processes and information go back from the virtual to the physical environment (Grieves, 2015). According to Grieves, this generates the so-called twinning or mirroring between physical and virtual environments, intended as a communication cycle between the two states. The virtual space can then be divided into several sub-spaces enabling different operations, like modelling, testing, optimisation or validation. To properly perform such tasks, the DT should be provided with appropriate models that can be comprehensive of the whole system, or by a set of communicating models of sub-systems composing the global virtual space. The nature of the models can be different, varying from physics-based models up to statistical ones (Liu et al., 2021b). The nature of the models does not necessarily change the integration between the two DT spaces. Literature examples do not always report the level of integration between virtual and physical spaces required by the DT concept. Therefore, Kritzinger et al. (2018) propose the following classification for reported use cases:

– *Digital Model*: no automatic communication between virtual and physical states.
– *Digital Shadow*: there is unilateral data communication from physical to virtual states.
– *Digital Twin*: bilateral communication between physical and virtual entities.

This subdivision is schematically presented in Fig. 4, showing the different interaction levels and information flows between the physical and virtual environment. This classification is used throughout the paper, even though different complementary definitions of the DT concept may be found in the literature. The other definitions are used within different engineering fields or outside the industrial environment. To give an overview, the most common alternative nomenclatures are briefly reported and described:

– *Product Avatar*: such a definition is antecedent to the Digital Twin concept, where Hribernik et al. (2006) define a *hybrid world* in which material product instances in the real world are represented by digital counterparts called Avatars in virtual reality. Avatars are not intended as static objects but as active, intelligent entities capable of autonomous decision-making, thus introducing analogies also with life-cycle product management (Hribernik et al., 2013). Ríos et al. (2015) provide a detailed comparison between the Avatar and the Digital Twin concepts.
– *Virtual Twin*: this terminology introduced by Kritzler et al. (2017) describes a data representation of instances collected by a Digital Twin. Such interpretation intrinsically describes the Digital Twin as a digital entity collecting data and high-level specific knowledge of a physical system. Therefore, Virtual Twin supports the accessibility to Digital Twin data.
– *Digital Surrogate*: this concept introduced by Shao and Kibra (2018) aims to give a less abstract but nevertheless interchangeable definition of Digital Twin. The Surrogate is conceived as an integrated model, representing, connecting, and synchronising a part of, or the whole, physical manufacturing process or system through historical or real-time data of the physical process/system.
– *Digital Shadow*: the adoption of such a term is somewhat contradictory with the definition provided before and used throughout the paper. The adoption of such terminology is mainly restricted to German-language authors. The shadow has been introduced by Schuh et al. (2018) and defined as a sufficiently accurate information supply system containing the set of digital representations of assets (Bauernhansl et al., 2018a,b). Afterwards, the concept has since been aligned with the previously-provided definition, making the Digital Twin a concept complementary to the Digital Shadow.
– *Virtual Twin Data Space*: this terminology defines a virtual environment that combines interdisciplinary models that are synchronised with the respective physical twin (Abramovici et al., 2017). The concept is similar to the above-mentioned Digital Shadow with the same correlation to the Digital Twin terminology as expressed for the alternative Shadow nomenclature.
– *Digital Triplet*: such a concept is developing together with the appearance of the Digital Twin one. The main idea is to insert an additional level between virtual and physical environments. The first paradigm was provided by Umeda et al. (2017) augmenting an *intelligent activity world* emphasising the transfer of insight from human knowledge into a digital system. Such a concept has been developed also by other authors (Lutters et al., 2019) postulating the necessity of a temporary *what-if* model between physical and virtual space.

1.1.2. Digital Twin collocation across product life-cycle

Another relevant aspect of a DT is its collocation across the product life-cycle, which means considering its definition during the design, production, operation, and decommissioning or retire phases. Grieves and Vickers (2017) define different development stages and environments to adapt the DT to the product life-cycle:

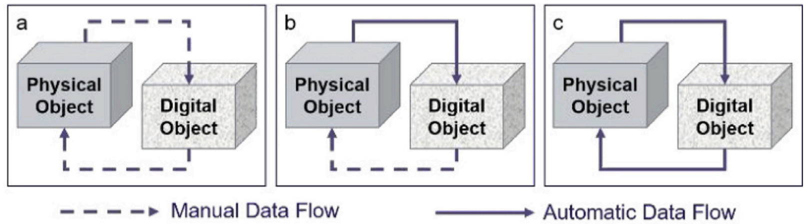

Fig. 4. Integration levels between virtual and physical environment for Digital Models (a.), Digital Shadows (b.), and Digital Twins (c.) Kritzinger et al. (2018).

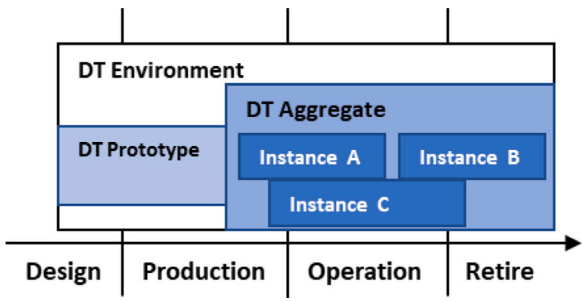

Fig. 5. Collocation of digital twin stages and environment across the product life-cycle.

- *Digital Twin Prototype*: is the virtual description of the product in the design phase, containing all the information needed to build the physical product.
- *Digital Twin Instance*: is a specific instance of the physical product that remains linked to it for the whole product life.
- *Digital Twin Aggregate*: the combination of all the instances.
- *Digital Twin Environment*: a multi-physics domain and application space for Digital Twins. It includes performance prediction, data collection and information/process management.

Fig. 5 gives an overview of the mentioned DT stages and environment across the product life-cycle.

Such definitions are typical within the manufacturing industry and subsequently used in other industrial fields. It is then necessary to analyse in detail the status of DTs for the maritime industry, reviewing the currently employed concepts, technologies, and applications specific to the sector.

1.2. DT review works related to ships and existing DT frameworks for ships

The literature presents a few cases of DT reviews specific to the maritime industry, providing four studies as keynote examples (Taylor et al., 2019; Chen et al., 2021; Fonseca and Gaspar, 2021; Assani et al., 2022). Other investigations pertain to the offshore sector (Sivalingam et al., 2018; Ciuriuc et al., 2022) and are more oriented to the energy field. As this study is focused specifically on the ship sector, offshore-specific works do not fit this review.

The review provided by Taylor et al. (2019) analyses the developments of DT in the maritime industry, comparing the needs of ship's oriented DTs against the manufacturing environment. Only conceptual papers are reviewed together with some applications derived from industry, resulting in a set of less than 30 DT-related works. The main finding is the unbalance between framework implementations for DT between manufacturing and maritime environment. Chen et al. (2021) provide a generic overview of the applications and challenges in the application of DT on ships and offshore structures, providing general guidelines for the design, calibration and preparation of Digital Models. Therefore, the review is not 100% linked with the whole DT but to a single part of the twin component (Grieves, 2015). Fonseca and Gaspar (2021) provide a review focused on the data handling, integration and modelling in a hypothetical DT application for ships, highlighting challenges and future objectives for this specific subject. The work of Assani et al. (2022) is more structured than the other three, proposing the classification of 19 papers related to Ship DTs according to a criterion involving 4 points: (1) the purpose of the model, (2) the data acquisition and processing, (3) the modelling methods, and (4) the model validation. Even though the classification is more specific than in Chen et al. (2021), there is still inconsistency concerning the description of a Digital Twin or a Digital Model, thus neglecting the mutual data communication between the physical and digital environment, which is the core point of DTs. Furthermore, the classification of models employed by the different authors in their virtual environments does not follow the nomenclature that is currently being used extensively in the field of data engineering and that will be discussed later specifically for the operational phase (See Section 4). From these reviews, it is evident that the ships industry frequently considers a DT as a digital version of model-based system engineering, which is incorrect.

Such a misinterpretation between Digital Twins, Digital Shadows, and Digital Models is not advisable in works characterising the DT from a manufacturing perspective. Several reviews are available for the characterisation of the DT concept in the industry (Holler et al., 2016; Negri et al., 2017; Kritzinger et al., 2018; Tao et al., 2019; Liu et al., 2019b; Enders and Hoßbach, 2019; Jones et al., 2020; Sjarov et al., 2020; Liu et al., 2021b), all providing a structured and systematic revision of the topic that helped researchers to identify new research topics or practitioners comprehend and understand the DT concept (Liu et al., 2021b). Such an approach to DT reviews is currently missing for ship applications.

Besides scientific works that can be found adopting the above-mentioned databases, the Digital Twin application on ships has a parallel application path outside the academic world. As the introduction of new technologies generally helps the reduction of risks and liabilities through the production and operational phase, the shipping industry is looking forward to the incorporation of real-time monitoring and optimisation of processes, using sensor-based data to optimise decisions. Therefore, software companies and classification societies are starting to provide dedicated solutions based on DT technologies. Such kinds of aids are more related to advanced stages of design or during production, where integration between different systems in CAD-integrated environments with sensing and simulation technology allows for building a DT-based model.

Table 1 provides an overview of the main providers of DT applications for the ship industry. As there is no detailed information besides the information leaflets and websites about the effective technologies and methods implemented in the mentioned platforms, these DT options cannot be effectively analysed in the systematic analysis performed in the following sections. Furthermore, it is also the expectation of principal Classification Societies that effectively true Digital Twins examples on complex assets as ships will only appear between 2025 and 2030 (Siegfried and Smogeli, 2022). However, classification societies like RINA (2022) have started to quantify possible margins of costs reduction. Large reductions in ship operating expenditure, up to 40%, are possible and reduced port time up to 30% as well. Equally

Table 1
Main Digital Twin platform providers for the ship industry.

References	Provider	Application
Han et al. (2021b)	AVEVA	DT platform for operational awareness and decision support system onboard, collection of data on daily ship activities and processes
Siqiang (2019)	China Classification Society (CCS)	DT application to monitor the status of system onboard ships
Systemes (2022)	Dassault Systèmes	DT platform enabling a closed-loop connection between the virtual and physical environment allowing for testing products and processes.
Wärtsilä (2020)	Eniram–Wärtsilä	DT models for energy efficiency management. Engine consumption and pollutant emission reduction
Wang et al. (2021)	Ericson	DT application for cargo handle on different ship types
Kongsberg (2022)	Kongsberg	DT environment to monitor and simulate the ship in operation
Jimenez et al. (2020)	Navantia	DT models to identify failure possibilities providing decision support for predictive maintenance
Li et al. (2020)	Shadong Shipping Corporation (SDSC)	DT models to verify ship structures
(RINA) (2021)	Sertica (RINA)	DT models to identify failure possibilities providing decision support for predictive maintenance
Cozmiuc (2021)	Siemens	DT models to monitor the ship maintenance cycles

important, the enhanced shipping company capabilities are expected to produce increased volumes handled, revenue and profitability. Shipbuilding costs are expected to decrease by 15%–20%. Creating and maintaining digital twins can be an expensive endeavour.

1.3. Paper objectives and structure

The previous section highlighted the lack of a systematic review of DTs for ship applications. Even though the employment of DTs arose across different industries and the first tentative frameworks and protocols began to appear, in the maritime sector, the development of a complete DT concept is still in an embryonic form, without definitive frameworks or protocols. Previous research works focus on specific subtasks of a DT without a comprehensive and in-depth analysis of the concepts and technologies needed to employ DT through the whole ship life-cycle. Therefore, this paper intends to perform a systematic review to achieve the following objectives:

– Analyse the status of digital twin research for ships.
– Identify the main application of DTs through the ship's life-cycle.
– Identify the gaps between ship application and other industry fields.
– Propose a potential solution to fill the detected gaps.
– Recommend future directions for DT applications on ships.

The paper is structured as followed: Section 2 reports the review methodology adopted to classify the DT-related works on ships indexed between 2013 and August 2022. Section 3 provides the results of the literature analysis, which means the status of the DT research in the maritime sector. Section 4 analyses the application of the DT concept through the ship's life cycle, identifying the gaps with other industries. The work concludes with observations and indications of future research direction in Section 5, drawing the concluding remarks in Section 6.

2. Literature review approach

The analysis of available reviews in the maritime sector highlights the lack of a systematic and rigorous approach to DTs. This paper follows the process of a literature review proposed by Kietchenham et al. (2009) by identifying main research questions (RQs), specifying suitable criteria (C), and a quality index (QI). With such an approach, the resulting study complies with relevant works on DTs for other industry segments. Such an approach is also needed to filter out the initial search presented in the introduction papers that only mention DT in the title or abstract without giving a proper insight into the topic.

2.1. Main research questions

The possible questions arising for the DT technologies and application review in an industrial sector may be multiple and could cover a range from global to specific tasks. The following four questions help provide answers to defining the state-of-the-art in DTs in the maritime industry and identify gaps with other sectors:

RQ-1 What is the status of DT applications in the shipping industry?
RQ-2 What are the phases of the ship life-cycle involved in DT applications?
RQ-3 What is the twinning level (i.e. level of information flow between the physical and virtual environment) used in relevant applications?
RQ-4 Is the approach adopted in line with other industry sectors?

The analysis of DT development in the maritime sector will then follow these four pillars to draw a complete overview of DT application in ship life-cycle in Section 4.

2.2. Inclusion and relevance criteria

A preliminary search on Scopus and WoS databases focused on the inclusion of keywords in the title and abstract of indexed scientific contributions. Such a search approach is not accurate enough for a proper review and needs valid refinement to filter the effectively relevant works on the topic of digital twins for the maritime industry. The following criteria of inclusion/exclusion drive a first preliminary screening of a rough database:

C-1 Argument is pertinent to the marine sector (*inclusion*).
C-2 Full text in English is available(*inclusion*).
C-3 The article is a primary study (*inclusion*).
C-4 The study is a duplicate (*exclusion*).

After analysing the review for the maritime sector in Section 1.2, the review articles have been filtered to focus on technical content only.

The introduction of quality assessment criteria is then needed to assess the technical content of the papers. Also, in this case, the process should be systematic and reproducible, in line with relevant reviews on DTs. To this end, the quality assessment proposed by Kietchenham and Charters (2007) and Gurbuz and Tekinerdogan (2018) is a suitable example, requiring answering the following quality index (QI):

QI-1 Are the aims of the study clearly stated?
QI-2 Are the scope, context and experimental design clearly identified?
QI-3 Are the variables in the study likely to be reliable and valid?

QI-4 Is the research methodology adequately reported?
QI-5 Are the studies' RQs adequately answered?
QI-6 Are negative findings, and identified weaknesses presented?
QI-7 Are the main findings assessed concerning credibility, validity and reliability?
QI-8 Are the conclusions linked with the study's scope? Are they reliable?

Then, as suggested by Tummers et al. (2019), 1 point is given if the index is fully satisfied, 0.5 points if partially, and 0 points if not satisfied. Then, applying this strategy, a paper may score a maximum of 8 points and pass the QI screening by having at least 4. Such a process ensures keeping only high-quality papers as input for the review.

2.3. Content classification

The above-described process delivers a final database of high-quality papers related to DT in the maritime industry. It is then necessary to classify the resulting works' content to suitably answer the RQs. This study proposes five categorisations, four primarily related to the DT topic described and one on the paper editorial collocation. Concerning the DT-related categorisation, the first criterion covers the life cycle, the second covers the twinning level, the third the type of content, and the fourth the ship-specific topic. The *life-cycle phases* considered here are the general ones for a ship (and generally for an industrial product), namely design, production, operation and retire. In addition, a specific category covers papers dealing with the whole ship's life cycle. Summarising:

- *Design*: in this category early and advanced design stages are included. Since detail design is typically concurrent with the production phase in the ships industry, they are not included here.
- *Production*: includes the detailed design phase and the construction of the ship.
- *Operation*: this category includes all the aspects of the operational life of the ship, from specific operations at sea to maintenance and repair.
- *Retire*: this phase includes the effective decommissioning of the ship or a potential substantial retrofitting.
- *Life cycle*: this category includes works dealing with more than one of the above-mentioned phases or making general considerations on the whole ship life cycle.

The *twinning level* follows the classification provided in Section 1.1, thus distinguishing between Digital Model, Digital Shadow, and Digital Twin. The third categorisation describes the *type of content* in the paper, considering the research depth and presence and detail levels of provided examples, distinguishing between:

- *Concept*: the work prioritises the concepts, definitions and capabilities of DT in the maritime industry.
- *Technology*: the paper describes or details DT's enabling technologies.
- *Paradigm*: the study provides a general description of the DT application in the marine field, with no in-depth analysis or case study.
- *Framework*: the study starts with a general description of the DT, providing a framework implementation and a rather-detailed case study.
- *Application*: after a detailed description of DT application in the maritime field, the paper also provides technical details and a detailed case study.

Besides the type of content, it is appropriate to distinguish between the different topics covering maritime applications of DT. As such subjects spread from naval architecture-specific problems, like resistance or motions, to more data-related arguments, such as data communication or the Internet of Things (IoT), it is impossible to provide an appropriate list before the screening. Therefore the topic categorisation relates to the final data set of papers and will be introduced in Section 3.

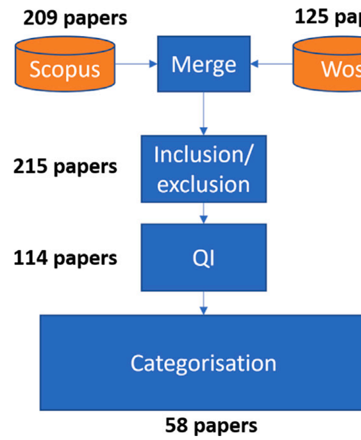

Fig. 6. Systematic literature review scheme.

3. Analysis of Digital twin research

The initial research on Scopus and WoS databases, including only the keywords according to the description in Section 1, identified a starting set of 209 publications on Scopus and 125 on WoS. The authors note here that focusing this review on literature available in these databases may miss maritime research that has happened in research projects that have not disseminated their digital twin research in such venues. Such projects may include eSHyIPS (2021), VITAL5G (2021), or NAVAIS (2017), who have opted for other dissemination avenues.

Applying the methodology described in Section 2 and sketched in Fig. 6, the starting set has been merged, leading to a total of 215 publications to be assessed first with the inclusion/exclusion criteria C-1 to C-4. After the first screening process, 114 publications remain for the quality index (QI) assessment. The QI assessment further restricts the final number of papers to 58. Fig. 7 shows the QI screening output. The ratio between filtered and unfiltered papers is high in this stage compared to other DT reviews adopting the same screening (as in van Dinter et al. (2022)) because here, the evaluation of the full text is introduced at this stage, while the inclusion criteria refer to the abstract.

The content categorisation started on the final subset of 58 manuscripts, subdividing the papers according to the provided categories given in Section 2.3. Categorisation also comprehends the topic category, which, as previously mentioned, has not been defined a priori due to the vastness of possible topics in the shipping industry. Having restricted the research to the final 58 papers, the following 12 topics (in alphabetical order) suit the final subset of works:

- *Auxiliary systems*: includes all the systems onboard ships not related to the power system.
- *CAD modelling*: relates to the generation of a 3D graphic environment for detail design and production purposes.
- *Control/motions*: includes topics related to ship motion prediction and vessel motions control.
- *Data/sensors*: associated with data communication within virtual and physical environments and the usage of sensors onboard.
- *Decommissioning*: employment of the DT technologies to study the retire phase of the ship.
- *DT architecture*: issues associated with the global architecture of the DT environment.

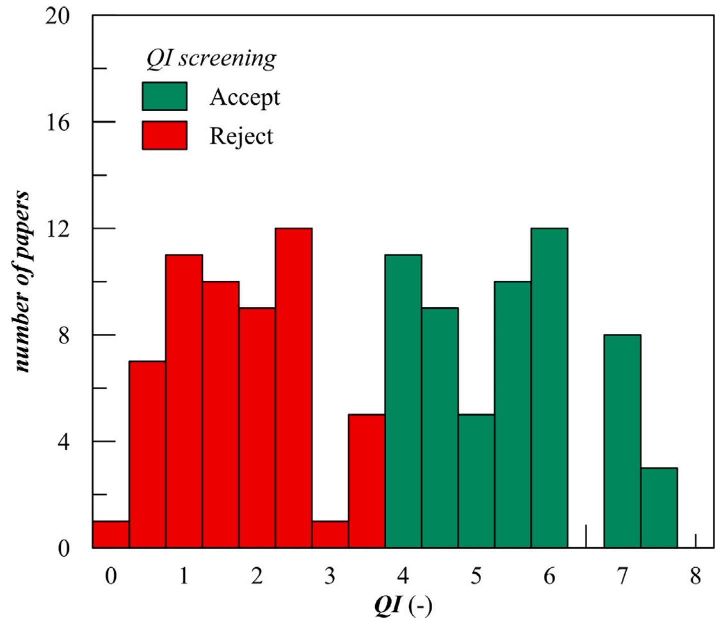

Fig. 7. QI evaluation scores.

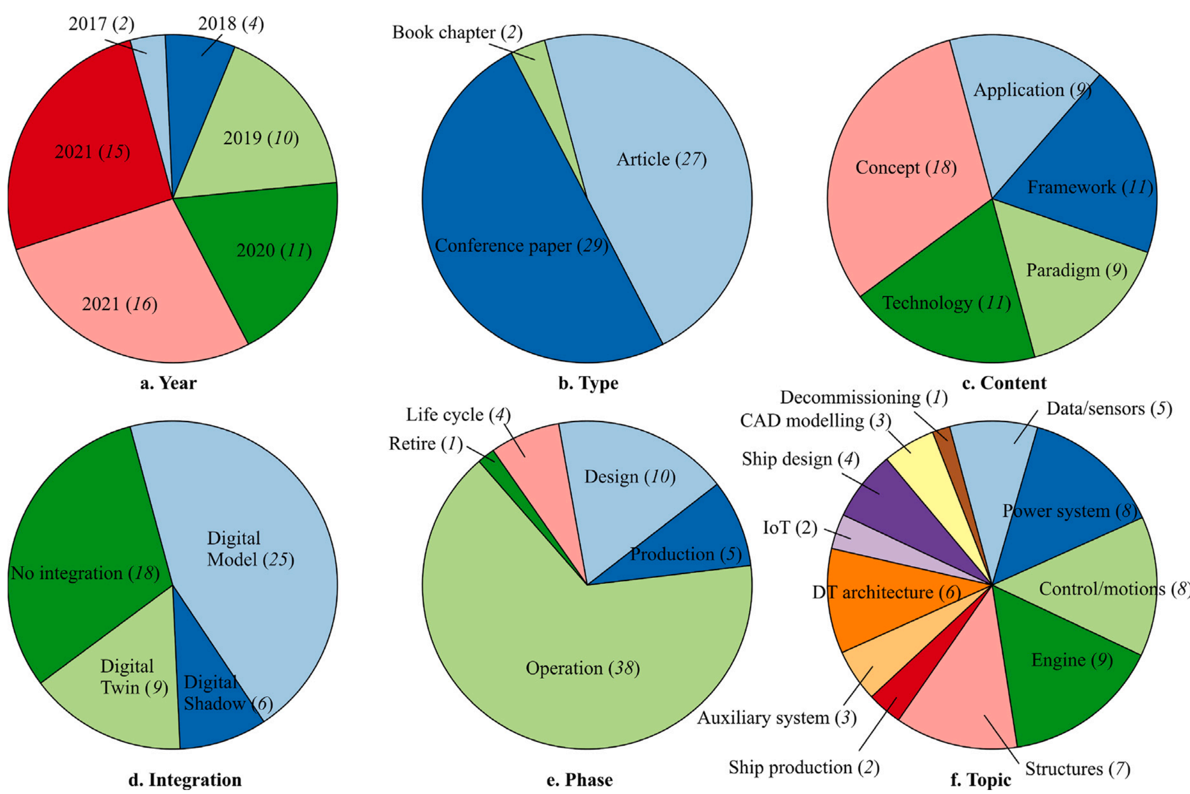

Fig. 8. Global division of the filtered papers for reviews per year (a.), type (b.), content (c.), integration (d.), phase (e.) and topic (f.) categories.

– *Engine*: issues related to the main propulsive engine or diesel generators onboard (as an individual object).
– *IoT*: topics related to the internet interconnection between virtual and real environments.
– *Power systems*: issues including the whole propulsive or power generation system mounted onboard (not only the engine object).
– *Ship design*: topics related to the early or advanced stage of the ship design, intended as using DT as a part of the designer decision process.
– *Ship production*: implementation and usage of DT technologies in the production sites of the ship.
– *Structures*: issues associated with the estimation of structural loads on the ship or on a single part of the ship.

Table 2 presents the filtered papers with the final complete categorisation, including topics. These topics cover a wide spectrum of applications in the maritime field, including traditional naval architecture disciplines, like ship design, hydrodynamics or structures, and more

Table 2
Categorisation of the set of selected papers for review.

ID	Paper reference	Type	Content	Integration	Phase	Field
#1	Wang et al. (2022b)	Article	Application	Digital Shadow	Operation	Data/sensors
#2	Wang et al. (2022a)	Conference paper	Framework	Digital Shadow	Operation	Power system
#3	Fonseca et al. (2022)	Article	Paradigm	Digital Shadow	Operation	Control/motions
#4	Coraddu et al. (2022)	Book chapter	Framework	Digital Model	Operation	Engine
#5	Hautala et al. (2022)	Article	Paradigm	Digital Model	Operation	Engine
#6	Stoumpos and Theotokatos (2022)	Article	Paradigm	Digital Model	Operation	Engine
#7	Rogers and Ebrahimi (2022)	Conference paper	Technology	Digital Twin	Operation	Data/sensors
#8	Stoumpos et al. (2022)	Article	Framework	Digital Shadow	Operation	Engine
#9	Van Der Horn et al. (2022)	Article	Framework	Digital Model	Operation	Structures
#10	Fang et al. (2022)	Article	Application	Digital Model	Operation	Structures
#11	Schirmann et al. (2022)	Article	Framework	Digital Model	Operation	Control/motions
#12	Vidal-Balea et al. (2022)	Conference paper	Concept	–	Production	Ship production
#13	Huang et al. (2022)	Conference paper	Paradigm	Digital Twin	Operation	Data/sensors
#14	Nielsen et al. (2022)	Article	Application	Digital Model	Operation	Control/motions
#15	Haikonen et al. (2022)	Conference paper	Paradigm	Digital Model	Operation	Engine
#16	Wu et al. (2021a)	Article	Concept	–	Production	Ship production
#17	Wu et al. (2021b)	Conference paper	Paradigm	Digital Twin	Operation	Auxiliary systems
#18	Hu et al. (2021)	Article	Technology	Digital Twin	Production	Engine
#19	Sapkota et al. (2021)	Article	Framework	Digital Model	Design	Structures
#20	Kutzke et al. (2021)	Article	Technology	Digital Model	Life cycle	DT architecture
#21	Coraddu et al. (2021)	Article	Framework	Digital Model	Operation	Engine
#22	Han et al. (2021a)	Conference paper	Framework	Digital Model	Operation	Structures
#23	Major et al. (2021)	Conference paper	Application	Digital Model	Operation	Control/motions
#24	Chu et al. (2021)	Article	Framework	Digital Model	Operation	Control/motions
#25	Giering and Dyck (2021)	Article	Concept	–	Life cycle	DT architecture
#26	Schirmann et al. (2021)	Conference paper	Framework	Digital Model	Operation	Control/motions
#27	Jagusch et al. (2021)	Conference paper	Technology	Digital Twin	Production	Data/sensors
#28	Fernandez (2021)	Conference paper	Concept	–	Design	CAD modelling
#29	Taskar and Andersen (2021)	Article	Framework	Digital Model	Operation	Control/motions
#30	Liu et al. (2021a)	Article	Technology	Digital Twin	Operation	IoT
#31	Ko et al. (2021)	Conference paper	Technology	Digital Twin	Operation	IoT
#32	Cheng et al. (2020)	Article	Technology	Digital Twin	Operation	Engine
#33	Bondarenko and Fukuda (2020)	Article	Framework	Digital Model	Operation	Power system
#34	Stoumpos et al. (2020)	Article	Concept	–	Operation	Engine
#35	Zhang et al. (2020)	Conference paper	Technology	Digital Twin	Operation	Data/sensors
#36	Hatledal et al. (2020)	Article	Paradigm	Digital Model	Operation	Power system
#37	Chu et al. (2020)	Conference paper	Paradigm	Digital Model	Operation	Control/motions
#38	Perabo et al. (2020)	Conference paper	Application	Digital Model	Operation	Power system
#39	Nikula et al. (2020)	Article	Technology	Digital Shadow	Operation	Data/sensors
#40	Arrichiello and Gualeni (2020)	Article	Concept	–	Design	Ship Design
#41	Pedersen et al. (2020)	Article	Application	Digital Model	Operation	Power system
#42	Nikolopoulos and Boulougouris (2020)	Article	Paradigm	Digital Model	Design	Ship Design
#43	Coraddu et al. (2019)	Article	Application	Digital Model	Operation	Power system
#44	Johansen and Nejad (2019)	Conference paper	Application	Digital Model	Operation	Power system
#45	Ibrion et al. (2019)	Conference paper	Concept	–	Life cycle	DT architecture
#46	Mondoro and Grisso (2019)	Conference paper	Paradigm	Digital Model	Design	Structures
#47	Schirmann et al. (2019)	Conference paper	Concept	–	Operation	Structures
#48	England (2019)	Conference paper	Concept	–	Production	DT architecture
#49	Munoz and Ramirez (2019)	Conference paper	Concept	–	Design	CAD modelling
#50	Munoz and Fernandez (2019)	Conference paper	Concept	–	Design	CAD modelling
#51	Kamath et al. (2019)	Conference paper	Concept	–	Retire	Decommissioning
#52	Esteve (2019)	Conference paper	Concept	–	Life cycle	DT architecture
#53	Tygesen et al. (2018)	Conference paper	Concept	–	Operation	Structures
#54	Van Os (2018)	Conference paper	Concept	–	Life cycle	DT architecture
#55	Bekker (2018)	Conference paper	Application	Digital Model	Operation	Auxiliary systems
#56	Dimopoulos et al. (2018)	Book chapter	Technology	Digital Model	Design	Auxiliary systems
#57	Ferguson (2017)	Conference paper	Concept	–	Design	Ship Design
#58	Stachowski and Kjeilen (2017)	Conference paper	Concept	–	Design	Ship Design

information technology-specific issues. Fig. 8 provides an overview of the global number of papers according to the different categories identified in this study.

As this review deals with the application of DT technologies through the ship life cycle, it is worth giving a more detailed insight into the papers concerning phase categorisation. Figs. 9 to 12 show the correspondence between the relevant categories for publication year and design phase, excluding the retire one, where the database research identified only a single paper. Fig. 9 shows the type categorisation, which means the editorial distinction of the works between journal articles, conferences and book chapters. The analysis highlights how the dissemination choice of the authors for all the life cycle phases is transitioning from live events to journals. An explanation could be due to COVID issues or a higher quality of the research, especially concerning the operation phase, where most of the papers are centred. Fig. 10 shows the content categorisation. Here, a transition is evident from the early concept papers to more recent examples of frameworks and applications of DT. The integration categorisation (Fig. 11), (i.e. between Digital Model, Shadow and Twins), confirms the trend observed for the content category, as the transition from conceptual to application papers gives more focus on different integration forms for the analysed instances. Fig. 12 shows the topics categorisation among the different life cycle phases, highlighting how the increase of publications after 2020 spread the number of topics covered by different works. Such behaviour is evident in papers related to specific topics related to subsystems of the ship (e.g. engine, Power system, etc...). Topics like ship design, including a global vision of the ship ensemble, appear in early

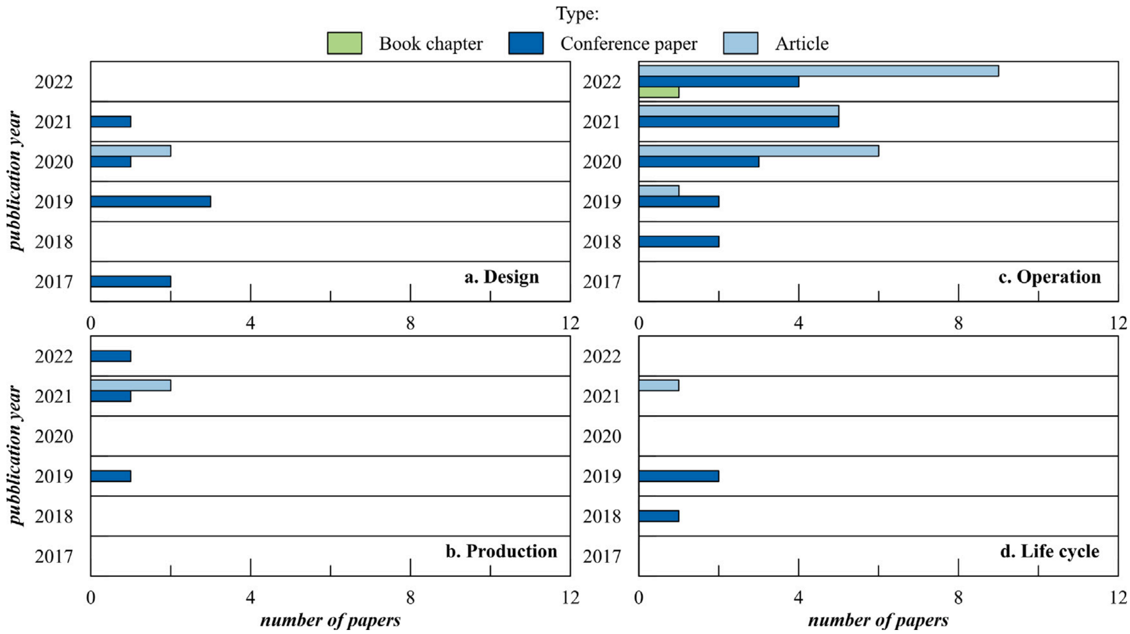

Fig. 9. Type categorisation per year among different phases: (a.) design, (b.) production, (c.) operation and (d.) life cycle.

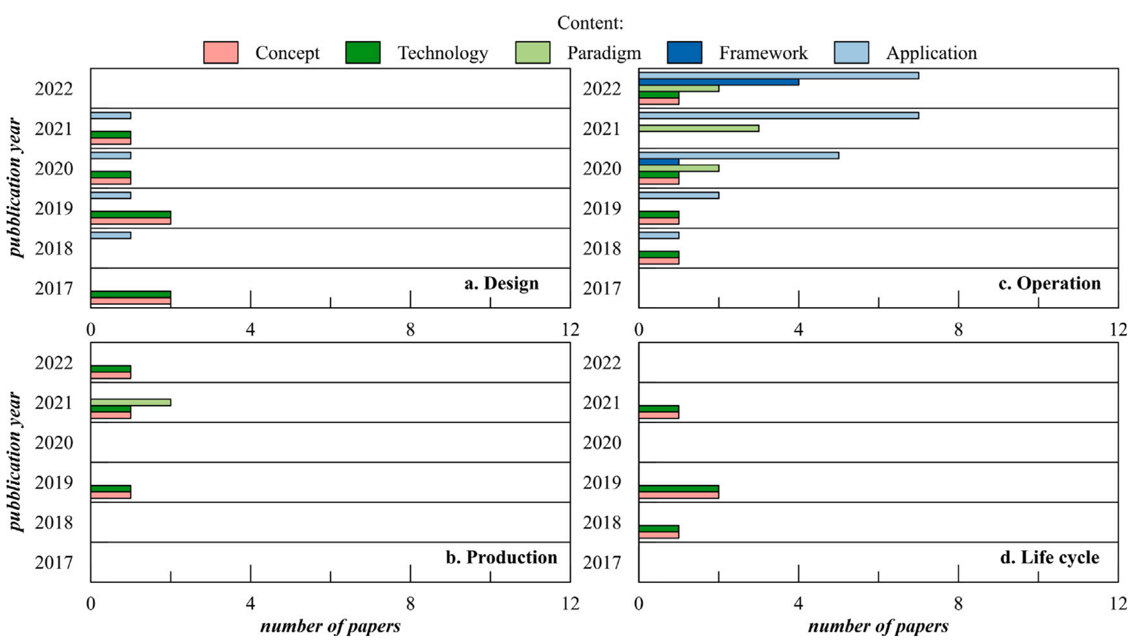

Fig. 10. Content categorisation per year among different phases: (a.) design, (b.) production, (c.) operation and (d.) life cycle.

concept papers only, missing the transition to application in the last years.

As previously mentioned, the operational phase presents the main bulk of peer-reviewed works on Digital Twins for ships. For such works an additional categorisation is possible. This is done to help fill the last gap identified by analysing the existing reviews on Digital Twins in the shipping industry presented in Section 1.2 by means of a data-science oriented classification of the models.

The following distinctions of models is the standard data-science definition given in the literature (Brause, 2010; Khan and Farmeena, 2012):

– *White-box* models: this approach consists of the creation of an analytical or numerical model based on the first principle physical description of the attribute to be predicted. The relationship between variables is fully represented by theoretically derived mathematical models validated with experimental or empirical data. A white-box model provides insight into the correlation and interconnection of different variables and attributes of interest for the simulated system, thanks to a transparent and well-defined set of equations. White-box models allow for different levels of fidelity, providing complex high-level numerical methods, that could be simplified into low-fidelity analytical models to speed up simulations in real-time, as required by a DT process.
– *Black-box* models: contrary to white-box models, black-box approaches employ statistical techniques to derive a direct correlation between a set of inputs and desired outputs, purely based on empirical data (observations) without reliance on an established physical model. There are different methods inside the wide group of black box models available in the literature, such as:

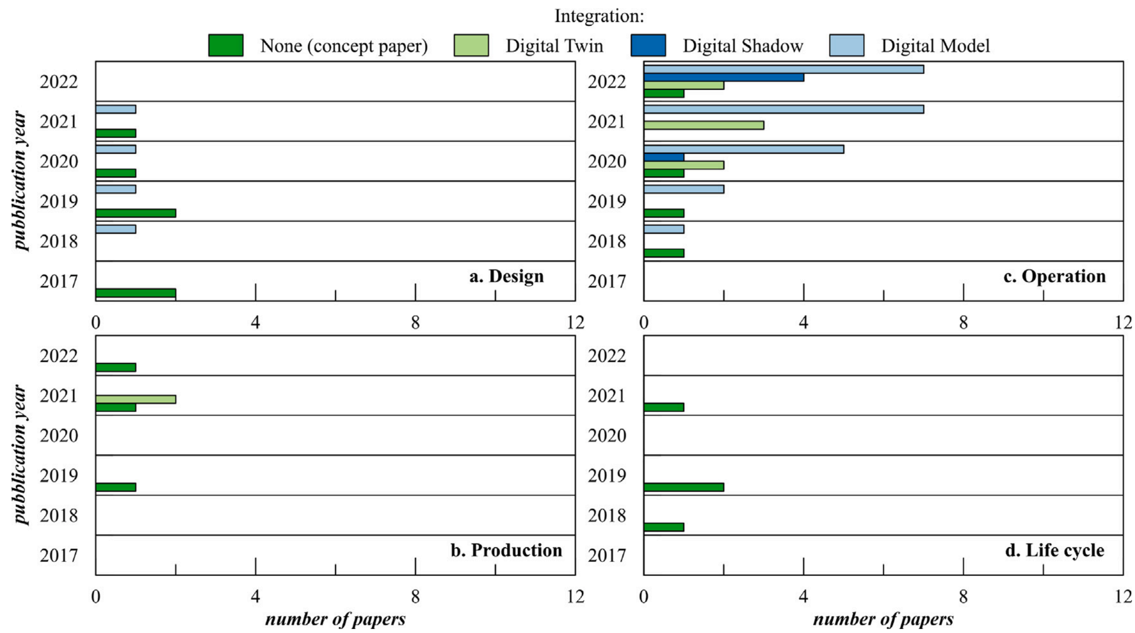

Fig. 11. Integration categorisation per year among different phases: (a.) design, (b.) production, (c.) operation and (d.) life cycle.

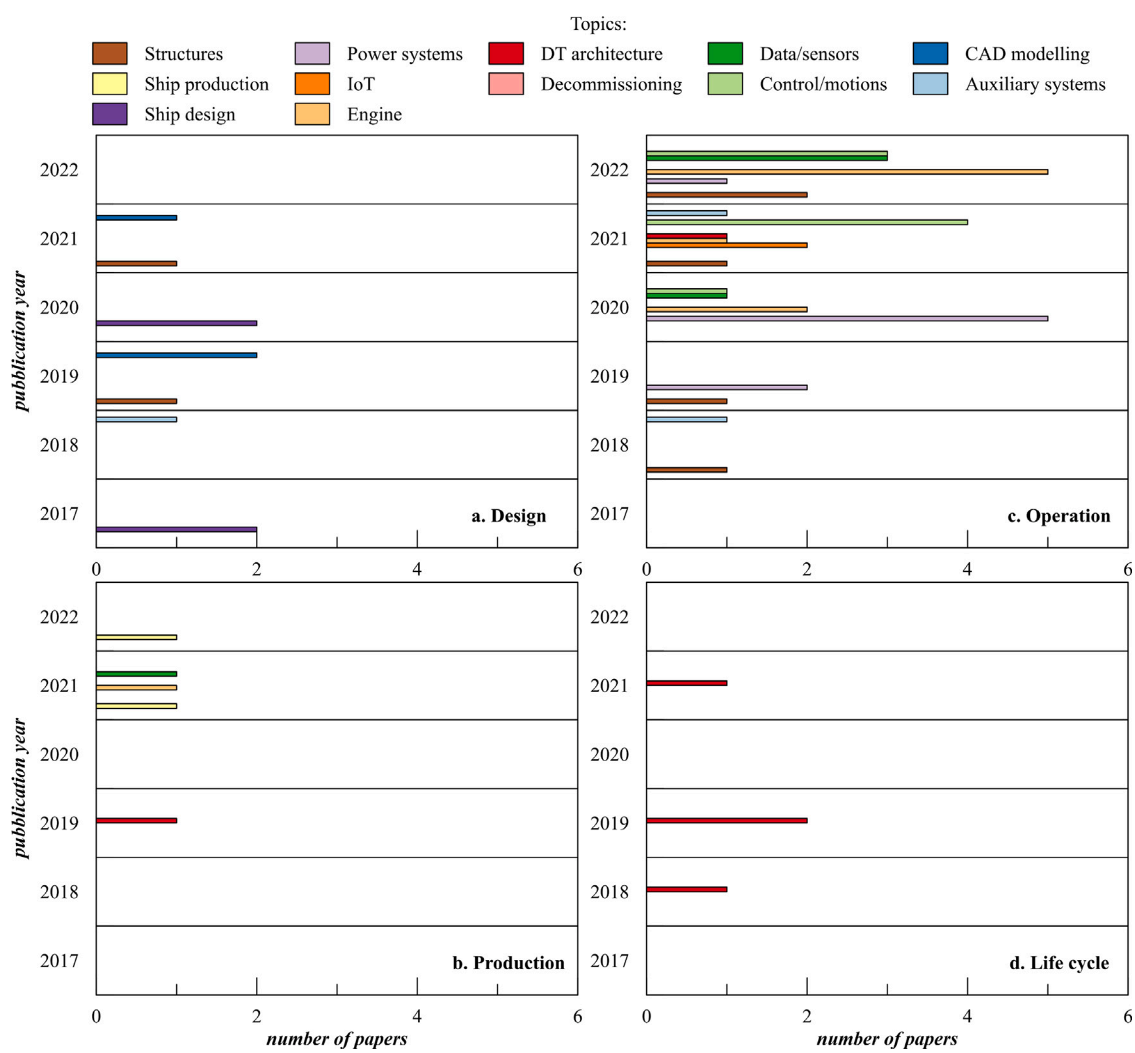

Fig. 12. Topics categorisation per year among different phases: (a.) design, (b.) production, (c.) operation and (d.) life cycle.

Table 3
Model categorisation of the subset of selected papers for the operational phase.

ID	Paper reference	Field	Model type	Description
#1	Wang et al. (2022b)	Data/sensors	Black-box	Employment of a BNN for temperature prediction in the engine room
#2	Wang et al. (2022a)	Power system	White-box	Physic-based simulation of the state of charge of batteries
#4	Coraddu et al. (2022)	Engine	Hybrid	Development of a hybrid model for engine performances combining ANN with physics-based analytical formulations
#7	Rogers and Ebrahimi (2022)	Data/sensors	White-box	Physic-based analytic models for pressure prediction inside engine cylinders
#8	Stoumpos et al. (2022)	Engine	White-box	Physic-based model for dual-fuel engine performances
#9	Van Der Horn et al. (2022)	Structures	White-box	Fatigue analyses based on FEM models and wave spectra combined with Monte Carlo simulations for forecasting
#10	Fang et al. (2022)	Structures	Black-box	Derivation of surrogate models for a crack from a database of FEM calculations
#11	Schirmann et al. (2022)	Control/motions	Hybrid	Comparison between Multiple Regressions and ANN for ship motions supplemented by physics-based predictions for heave, roll and pitch
#14	Nielsen et al. (2022)	Control/motions	Hybrid	Maneuvering simulations combining ANN with motion equations
#20	Kutzke et al. (2021)	DT architecture	White-box	Physic-based models for an underwater vehicle performances
#21	Coraddu et al. (2021)	Engine	White/Black-box	Comparison of physics and ANN-based models on a dual fuel engine
#22	Han et al. (2021a)	Structures	Black-box	Monitoring of stress data with ANN models
#23	Major et al. (2021)	Control/motions	White-box	Physics-based models for coupled ship-crane motion predictions
#24	Chu et al. (2021)	Control/motions	Hybrid	Combination of ANN and motion predictions for heave compensations
#26	Schirmann et al. (2021)	Control/motions	White-box	Physics-based models for heave and pitch motions
#29	Taskar and Andersen (2021)	Control/motions	White-box	Physics-based models for added resistance in waves
#30	Liu et al. (2021a)	IoT	Black-box	Generic black-box models for data communication
#31	Ko et al. (2021)	IoT	Black-box	Generic black-box models for data communication
#32	Cheng et al. (2020)	Engine	Black-box	Quality control of data based on ANN models
#33	Bondarenko and Fukuda (2020)	Power system	White-box	Physics-based models for onboard power estimation
#35	Zhang et al. (2020)	Data/sensors	–	Generic models for data communication (not specified)
#38	Perabo et al. (2020)	Power system	White-box	Employment of the OSP platform of physics-based models
#39	Nikula et al. (2020)	Power system	Black-box	Prediction of thruster characteristics with surrogate models
#41	Pedersen et al. (2020)	Power system	White-box	Employment of the OSP platform of physics-based models
#43	Coraddu et al. (2019)	Power system	Black-box	ANN models to predict speed loss due to fouling
#44	Johansen and Nejad (2019)	Power system	White-box	Physics-based model of a drivetrain in 5 Degrees of Freedom
#55	Bekker (2018)	Auxiliary systems	White-box	Physics-based model for onboard auxiliary systems

simple regressions, multi-regression techniques, artificial neural networks (ANN), Bayesian neural networks (BNN) or random forests. The adoption of such methods is strictly related to the availability of a significant amount of comprehensive high-quality data of the attribute that should be predicted by the model. The Black-box models can be cyclically updated when new or larger sets of data became available to users.

– *Hybrid* models: the hybrid approach (sometimes referred to as *grey-box* models) combine benefits from both white and black-box approaches. The approach consists of using the physical laws derived from white-box models with statistics of the black-box ones, aiming at reducing the error of the predicted attributes, while keeping a reasonably low computational time. The accuracy of the hybrid model depends on the ratio between the physical information needed by the white-box part and the statistical information needed by the black-box part. In case the amount of physical information is higher than the statistical data, it then becomes important to properly define a consistent bulk of physical data to obtain good results. On the other hand, if the model has few physical assumptions then the statistical part drives the accuracy of the process.

This categorisation of models can only be applied to papers dealing with the creation of DT-oriented models. Therefore, the categorisation between white, black and hybrid models can be performed only on papers that pertain to the operational phase and in which content is at least a *paradigm*, according to the provided classification. *Concept* or *technology* papers do not define a model in detail and, consequently, should be discarded for this categorisation.

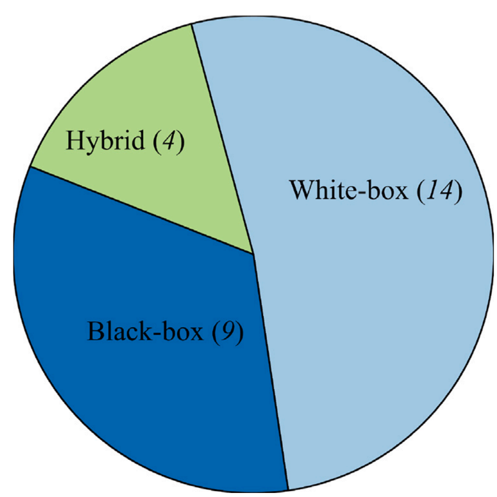

Fig. 13. Division of operational papers according to the digital model categorisation.

Table 3 provides the papers eligible for the model categorisation, resulting in a final number of 27 contributions. The table recalls the field of applications already provided in Table 2 and adds the categorisations of the model together with a short description of the method employed to reproduce the analysed issue. Fig. 13 shows the subdivision of the operational papers between the three possible model representations of white-box, black-box and hybrid.

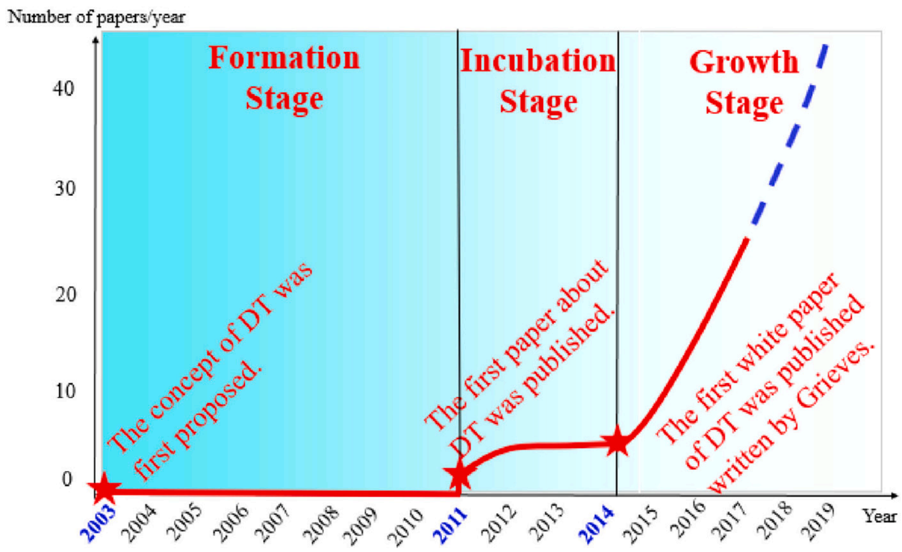

Fig. 14. Status of global DT research (Tao et al., 2019).

Further categorisations for operational papers are still possible, focusing, for example, on the software or packages eventually used by authors to develop the models. Here, it has been decided to avoid such a granularity for the operational phase only, to avoid an excessive unbalance with the other phases of ship's life-cycle. Furthermore, an eventual supplementary categorisation on software will not add significant content to the main goals of the review, as, besides the already highlighted lack of dedicated model libraries for ships specific applications, the adoption of different software is not identifying a gap between the maritime sector and other industries. On the other hand, the classification of model types can be useful as a starting point for the identification of possible modelling solution specifically for ships.

The general distinctions provided in this Section are the starting point of a more detailed analysis of the status of DT employment through the ship's life cycle. Based on the content of the selected 58 papers, the answers to the initial main RQs of this study are possible.

4. Detailed analysis of DT status through ship's life-cycle

After analysing all the data in Section 3, it is possible to answer the initial RQs defined in Section 2.1. This Section provides a point-by-point analysis of RQs to figure out what possible improvements and challenges could be identified for future research in the maritime field.

4.1. RQ-1: What is the status of DT applications in the shipping industry?

The answer to this question is related to the growth of scientific publications across the years selected for the research. According to what has been observed by Tao et al. (2019) in the general industrial field, 3 stages can be identified for the DT status of research: *formation*, *incubation* and *growth* (see Fig. 14). In the *formation* stage, very few papers are published as the technological foundations are not mature enough to support effective applications. In the *incubation* stage, first conceptual papers and application examples are published as technological background increases up to entering the *growth* stage where publications raise exponentially increasing the number of examples and applications of DTs.

For the maritime sector, the results of the publication filtering have not changed the general trend observed with the initial rough search provided in Section 1. Starting in 2017–2018, with conceptual papers on a general application in ship design (Ferguson, 2017; Stachowski and Kjeilen, 2017), structures (Tygesen et al., 2018) and a ship-oriented DT (Van Os, 2018), the only examples of models were oriented to auxiliary systems for design (Dimopoulos et al., 2018) or operations (Bekker, 2018).

Afterwards, in 2019, the dissemination was still based on conceptual activities, including the only work centred on decommissioning, in particular on the recycling of materials (Kamath et al., 2019). During this year relevant dissemination in journals starts on the specific field of power systems using data-driven modelling to study the power increase due to fouling (Coraddu et al., 2019).

The trend in the publication numbers increases in the consecutive years, underlying that, adopting the same parameters observed by Tao et al. (2019), the DT topic has now reached the *growth* stage for the maritime field with about 2–3 years of delay compared to other industrial fields, such as manufacturing (see Fig. 2). Therefore, even though the numbers remain lower compared to other industry sectors, it can be stated that the advance of DT technology in the maritime industry has reached a stage of maturity that will increase the number of publications in the next years. This advancement should be oriented through a homogeneous application among all the phases of the ship life cycle, encouraging the effective application of onboard DT technologies. The number of studies performed in the last years does not cover all the relevant phases of the ship's life, privileging the operational aspects. The same concerns are also relevant regarding the integration level, as it is explained in the following Sections.

4.2. RQ-2: What are the phases of the ship life-cycle involved in DT applications?

The application of DT technologies through the ship's life cycle is probably the most crucial aspect to be analysed in this review. The concept of DT has been proposed and developed with the intent to consider the whole life cycle of an industrial product. However, the analysis of the filtered papers in Section 3 already identified that the marine sector is far from offering valuable investigations in all the phases of ship life. Therefore, it is worth highlighting the areas lacking research and identifying the reasons through a thorough analysis of the specific stages of the ship's life cycle.

4.2.1. Design phase

According to the provided classification, 10 papers pertain to the design phase. The lack of papers at a content level associated with an application is immediately apparent, with only one framework work. Besides two paradigms and two technology studies, most of the papers are concept works. Analysing the topics, the framework paper (Sapkota et al., 2021) is not associated with the design of the whole ship, but with the design of a single subsystem/object of the global product, in this case, structural components. Structural design deals also with the technology paper (Mondoro and Grisso, 2019). The other two topics in this life cycle phase are associated with CAD modelling and ship design. The papers dealing with CAD modelling (Munoz and Ramirez, 2019; Munoz and Fernandez, 2019; Fernandez, 2021) postulate the adoption of a virtual 3D CAD environment for the advanced and detailed design phase of the ship, which is not properly in line with the DT concept, having no direct communication with a hypothetical physical environment, until the beginning of the production phase. Thus, this topic is a bit borderline between design and production but according to the authors, and traditional ship design praxis, the 3D virtual model is prepared (or started to prepare) before production.

The remaining papers deal with ship design. The most recent one (Nikolopoulos and Boulougouris, 2020), classified as paradigm, presents an example of holistic design optimisation (Papanikolaou, 2019) for a merchant vessel, foreseeing the possibility of using design points derived from onboard measurements on existing ships. Such an example in ship design is more concrete than the remaining conceptual papers (Stachowski and Kjeilen, 2017; Ferguson, 2017; Arrichiello and Gualeni, 2020) but still far away from the establishment of a DT-based methodology to be applied for the design of ships.

All the papers related to ship design are collocated in years between 2017 and 2020, which the authors have related to the *incubation* stage of DT technology for the maritime sector. As the ship is one of the most complex objects to design (Andrews and Dicks, 1997), it involves the resolution of multiple concurrent problems associated with different subsystems all being a potential instance in a DT environment (see Fig. 5). Such a complexity in the modelling of different instances may be the cause of delay in the establishment of a proper methodology for DT-based ship design. As it will be observed in the next analyses, maritime industry research is more focused now on building DT models, hence the design phase is still considered to be in the *formation* and *incubation* stages.

4.2.2. Production phase

The final subset of relevant papers contains 5 papers for the production phase. Two concept papers (Vidal-Balea et al., 2022; Wu et al., 2021a) are related to the production of the whole ship, thus to the digitisation of the shipyard. The paper from (England, 2019) is related to the integration of 3D virtual environment in the production process, while the other two papers present applications of digital twins in the production of marine engines (Hu et al., 2021) and in the specific working of the data exchange system (Jagusch et al., 2021).

All papers dealing with the production part are aligned with the shop-floor DT concept given by Tao and Zhang (2017), which is the basis for all the digital processes in industrial productions. As all the examples are a direct translation of a consolidated process in other industries, it is reasonable that not that much effort is provided by research for this phase, as shipyards can directly use technologies derived from other industrial sectors. Production is, therefore, the phase where potentially less effort is needed from the maritime perspective, as it is the sector closest to already existing 4.0 industries.

4.2.3. Operation phase

The main bulk of papers in the final subset concerns the operation phase of the ship. Here, 38 papers are present, spreading across 8 of the 12 topics, excluding only ship design, CAD modelling, ship production and decommissioning.

Among the different topics, the most populated areas are engine, power system and control/motions with 8 papers each followed by structures with 5. Structural papers mainly deal with the prediction of future loads on the structure to prescribe predictive maintenance on the system, using environmental data measurements and forecasting techniques. This is absolutely in line with applications found in other industries (Liu et al., 2021b).

However, the majority of the remaining papers in the operation phase categorisation truly consist of the development of models that could be applied to cover a DT instance in a DT environment. Thus, they are far away from directly representing the application of DT technologies for the operation phase (see following Section 4.4.2). Some of the authors erroneously call a driven data-based model or a system engineering model hybridised with machine learning corrections, the DT of the ship or system. Except for papers dealing with sensors, IoT communications, or small applications on models, almost all papers suffer from the above consideration.

Stating the above, the paper from Perabo et al. (2020) denotes a consciousness of the adoption of system engineering models to assess DT issues, as they are proposing one of the few open libraries for ship-oriented models (other examples are Gaspar (2018) and Fossen (2011) for ship motions) to be used as starting point for DT applications. Concerning the adoption of physics-based or data-driven models, there is a nice balance between development in the field, mainly due to the background of the researchers involved in the model development. It should be stressed that the application and availability of models suitable for DT applications are not limited to the specific examples reported in this review. As mentioned, only papers that clearly state the suitability of the model for a Digital Twin application are considered, due to the research assumptions of the systematic review process. Almost all models developed in the context of model-based engineering can be directly used or easily adapted to a DT concept. However, a specific literature research should be performed in that direction to figure out all possible models developed for the ship industry, but this goes outside the scope of the present review.

4.2.4. Retire phase

The retire phase is, currently, the least considered stage of a ship's life-cycle. Only one paper has been identified within this category (Kamath et al., 2019); a concept paper concerning the problem of recycling materials onboard during decommissioning. Also this work, as the first concept on ship design, appears in the early formation of the DT concept in the maritime industry. However, being the retire phase the last stage of ship life, it is hard to study digital technologies on ships that have not been designed, built or operated with digital aids. It is then foreseeable that the retire phase will be the last to have a growth of publications for the maritime sector, as it is a problem too far in the future to be faced at the moment, where the focus, as already mentioned, is still on model developments.

A possible boost for this life cycle phase may be to associate retire with the refitting of an existing unit. Of course, refitting is literally a re-design of the ship, thus a topic in affinity with the design phase. However, design and retrofitting require different analyses and processes, thus retrofitting could be a good candidate to boost retire phase for the ship's DTs.

4.2.5. Life cycle

Considering the provided classification in phases, there is a group of four papers laying in the category of life-cycle. As previously mentioned, this subgroup considers works that deal with more than one single phase or that describe the concept of DT across the product phases. All four papers (Giering and Dyck, 2021; Ibrion et al., 2019; Nikolopoulos and Boulougouris, 2020; Van Os, 2018) are conceptual description of a DT architecture suitable for the whole ship life cycle. Such papers are borderline with reviews like the ones presented in Section 1.1 but are not indexed as reviews in scientific databases.

4.3. RQ-3: What is the twinning level used in relevant applications?

The answer to this question is directly linked to the previous one, concerning the observations given for the operational phase. The analysis of the paper data set provided in the previous section indicates that the larger part of the research that falls under the DT technology pertains to model development. As such, the level of integration between the virtual and physical environment is not automatic during the development and testing of the models. Data are stored somewhere from available onboard recordings and then used offline to perform simulations (Digital Model), sometimes simulating real-time data exchange (similar to a Digital Shadow). This is clearly stated only by Nikula et al. (2020), but not underlined in the other publications on digital models or mentioned in the previous reviews of DT in the ship's sector.

The only papers dealing with effective communication of data between the environments are the ones associated with sensors (Wang et al., 2022b; Rogers and Ebrahimi, 2022; Huang et al., 2022; Jagusch et al., 2021; Zhang et al., 2020) or IoT communications (Liu et al., 2021a; Ko et al., 2021). All these papers are not proper examples of technologies specific for ships but are referring to communication systems already available and usable in the industry. The sole work purely oriented to ships, not dealing with only model developments is provided by the experimental example of DT for a model test (Fonseca et al., 2022), where a DT approach is proposed as an extension of the wireless control system used in the model basin.

The lack of examples of high integration levels on ships is due also in this case to the absence of effective applications in the hypothetical physical environment, thus almost all models are developed and disseminated in literature as off-line applications, thus Digital Models.

4.4. RQ-4: Is the approach adopted in line with other industry sectors?

The answer to the previous three questions highlights that the maritime industry research on DT is now developing models that could be used for a wider application of digital technologies in the near future. The main weaknesses appear to be related to the application of DT in the design and retire phase and the availability of models for the operational phase capable to cover all the systems onboard and the ship as a living object. The following sections analyse these points in comparison with general industrial applications.

4.4.1. Design phase

The application of digital twin in general industrial application for the design phase is mainly centred on the following aspects (Liu et al., 2021b):

– *Iterative optimisation*: the path towards a good design implies a continuous improvement of the product specifications through the different design phases. Such target in the industry is aided by DT technologies capable of providing an iterative optimisation between static configurations and dynamic executions (Liu et al., 2019c), improvement of the material selection (Xiang et al., 2019), reporting the evolution of the dynamic parameters (Zhang et al., 2019). Such capabilities may speed up the identification of the optimisation direction compared to traditional simulation-based design.
– *Data integrity*: a problem identified in manufacturing was the lack of storing design information throughout product updates between different stakeholders (Terzi et al., 2010; Grieves and Vickers, 2017). The DT-based design actually allows designers to preserve this memory, without disclosing proprietary information (Lutters, 2018).
– *Virtual evaluation and verification*: the DT technology allows for changing the traditional verification and validation of the product requirements, giving the opportunity to spot unexpected cases (the Unexpected Undesirable) that a traditional process may ignore (Grieves and Vickers, 2017). Furthermore, the adoption of high-fidelity models in multi-physics environments allows for the testing of multiple operation uses of the product, supporting the virtual prototyping in different scenarios.

All the above-mentioned points are currently missing for the maritime sector concerning the design phase, resulting in an apparent massive gap with manufacturing. However, it should be considered the context of DT application for design in manufacturing. It should be emphasised that digital technologies are currently being used in the industry for the redesign of existing products, and evaluation of performances for new objects. According to principal reviews on DT (Jones et al., 2020; Liu et al., 2021b), no literature is available for products designed from scratch. Thus, it can be stated that the manufacturing industry is also lacking a complete methodology for the concept design of a completely new object. A direct application in the marine industry of DT-based design as actually applied in Industry 4.0 may be more suitable for a retrofit of a ship, rather than the design of a new vessel.

4.4.2. Operation phase

The simulation is one of the most important parts of a Digital Twin, as is the core of the mutual interconnection between the real and virtual environment in real time. This part is mainly composed of data exchange and multi-physics simulations with different levels of fidelity according to the life cycle phase of the product (Hehnenberg and Bradley, 2016). The availability and development of such methods allow the application of DT technology to perform the following instances in the product operation phase (Jones et al., 2020; Liu et al., 2021b):

– *Predictive maintenance*: in the industrial application, predictive maintenance is the most applied field (van Dinter et al., 2022), essentially for reducing the design margins taken by designers in the initial stage.
– *Fault detection*: this is the topic most related to sensors and data communications and is actually fully working for pre-known anomalies detection.
– *Monitoring of system states*: the high fidelity model composing a DT may reproduce the actual state of a physical object in the virtual environment with less data than in a conventional system state analysis (Lu and Brilakis, 2019), allowing easy comparison between measured and simulated data.
– *Performance prediction*: the DT technology allows to optimise and predict the product performances (Okita et al., 2019). Nowadays the prediction part is fully operative, and research is ongoing for the effective optimisation (Liu et al., 2021b).
– *Virtual tests*: the DT is used to test off-design conditions and see the effects that such conditions may have on the physical object (Eckhart and Ekelhart, 2018).

The application of the above processes is already in an advanced stage in the concept of a 4.0 industry. Given the above, the application on ships is limited mainly to structures for predictive maintenance, but the performance prediction for power systems is close behind and will grow constantly in the near future due to the focus of the shipping industry on this area. In this sense, some libraries are starting to appear specifically for ship applications, as the already mentioned OSP and Vessel.js platforms for ship-motions modelling. However, there is a lack of main libraries available for specific onboard systems for marine applications. Use is eventually made of available libraries of the manufacturing industry as the GT-ISE (Technologies, 2016) for engines or object-oriented libraries at disposal in simulation tools/platforms like Simulink (2020), Simscape (MATLAB, 2022) or Modelica (Wetter, 2009).

4.4.3. Retire phase

Also in the manufacture industry, the retire phase is scarcely considered, with the main focus on the recycling of electronic equipment (Wang and Wang, 2019). However, some exploratory examples are present concerning the remanufacturing of objects (Liu et al., 2019a). Such an application remains, nowadays, the sole possibility to employ DT technologies for the retire phase.

Such considerations give confidence for what has been introduced before for the retire phase of ships, meaning associating this phase with the retrofitting of an existing unit. In fact, using data available on an existing vessel may allow to employ a DT-based process to evaluate the impact on performances of a converted unit, e.g. installing a new propulsion system.

5. Future research directions

Besides disseminating a correct definition and distinction between the Digital Twin environment and Digital Model development, multiple research paths have been identified for the digitisation in the life cycle of ships, consisting of:

- Construction of multi-physics model libraries, either modular or specific per ship type.
- Application of Digital Twins in the operation phase onboard ships as an aid for operators, including full-scale testing and validation exercises.
- Design methodologies based on Digital Twins.

The first point is likely to be pursued first, as DT research in the maritime sector has been principally active in the last years in the development of models for future DT applications. Especially concerning the power generation on board (power systems and engine) the status of the research is continuously progressing, forced by the upcoming green transition for ships. Besides, the prediction of control or motions is also considerably developed, as such topics are strictly related to the real-time evaluation of fuel consumption and, consequently, to the optimisation of the actual route of the sailing ship.

With a set of model libraries available, it will be possible to develop and improve DT-based systems for the operation phase of the ship. These will not only be limited to the monitoring of small subsystems (Rogers and Ebrahimi, 2022; Huang et al., 2022), but also to broader problems specific for ships linked to safety or collision avoidance, or the optimisation of the current route. The latter is likely the most attractive and useful topic for operators of cargo ships, where consumption and emission reduction are key performance indicators of vessel performance. For complex ships like offshore vessels, optimisation of the vessel's operability would be another key aspect, while for passenger ships safety issues remain of utmost relevance. The challenge is here, as already mentioned, identifying and developing the models suitable to achieve the tasks.

Concerning ship design-related issues, the research directions should be divided clearly distinguishing between two possibilities: (1) the design of a new unit, and (2) the retrofit of an existing unit. The comparison with the manufacturing industry highlights that a direct translation of DT-based design to the maritime field may be suitable for retrofitting purposes. In such a case, the iterative optimisation and the virtual evaluation and verification of new solutions are well-researched and developed but still subject to the availability of suitable multi-physics models for parameter evaluation.

The main challenge in the maritime industry appears to be the determination of a design methodology for new ships based on DT technologies. As highlighted in Section 4, also in the manufacturing industry there is a weakness in procedures aiming at new designs, and a ship, except for series constructions of shipping vessels, is always a unique object. Therefore, any future study on the application of DT in the design of new ships may be a novelty for the manufacturing industry. However, the challenges are extremely high, as the process requires the availability of a wide set of multi-physics models having sufficient reliability to be used at different design speeds without propagating too many uncertainties throughout the design process. Thus, the establishment of a robust design process is subordinated to the availability of robust simulation models.

The achievement of the above milestones may lead to many benefits for a ship. One of the biggest incentives of DT adoption by shipping operators is support for implementing any measures in compliance with regulation requirements, whilst optimising the revenue of the ship. Vast benefits are expected from accurate data management in measuring the effects of a refitting, monitoring different aspects of ship performance, calculating the level of degradation of hull and machinery, and the performance of new systems and technologies fitted onboard.

The benefits of ship digitalisation enabling increased automation, decision support, remote monitoring, and overall boosts to safety and performance are evident. Overall, digital twining is a matter of business value in managing complexity when dealing with the interdependence between technical, operations, chartering, safety, regulations perspectives that affect all performance metrics for ship operators. Quantification of such benefits remains a conjecture, due to the lack of real applications. Suitable IoT infrastructure (sensors, databases, and platforms) is required to collect and integrate the data models and data that constitute the digital twin. Hence, it is important to weigh the digital twinning benefits against costs. DT application is likely to be dependent on establishing trusted and convincing DT platforms based on cross-domain modelling standards and innovative architectures, ensuring that ship operators and other industry stakeholders can set up their own ship-specific digital twins, leveraging their own business models and building their own confidential knowledge, all at a reasonable cost.

The systematic literature review and analysis provided in this paper covers the indexed works on Scopus and WoS databases between 2013 and August 2022. It should be also noted that the relevant open-access articles on Digital Twins in the shipping industry published and indexed between September and November 2022 do not alter the conclusions of the presented systematic review. The main works confirm the focus on the operation phase, covering the field of engines (Liu et al., 2022), structures (Liu and Ren, 2022; Parunov et al., 2022) and control/motions (Lee et al., 2022; Raza et al., 2022; Dubey et al., 2022). In addition, only one paper addresses the IoT (Lv et al., 2022), and another is related to the ship's operational profile optimisation (Eom et al., 2022), specifically on the berthing process. The models employed in these recent papers follow the same categorisation identified in the systematic review, following physics-based or data-driven approaches. Other recently indexed articles also cover conference proceedings that, at the moment, are not available in the open literature. Therefore, a systematic review as proposed is premature for such papers and further inclusion of more recent works could be performed in future systematic reviews, following the same approach.

6. Conclusions

The study presented a systematic review of the status of Digital Twin employment through the ship life cycle. The bibliographic analysis, covering the most relevant scientific databases (i.e. Scopus and WoS) led to the identification of 215 publications mentioning DT in the title and abstract. The study proposes a systematic methodology to perform a review, being capable of identifying only relevant papers on the topic, and grouping papers in categories relevant to answer the main research questions. The systematic review identified 58 papers related to various aspects of the ship life cycle allowing for an analysis of the status of the research in the field.

The status of DT research for the ship industry is 2–3 years delayed compared with other industry sectors, especially manufacturing. The research is currently centred on developing models specific to ship systems, necessary for the growth of applications in the near future.

Nevertheless, there is still the problem of nomenclature to be fixed, requiring researchers to call independent models Digital Models instead of Digital Twins.

Between the life cycle phases, the retire and design phases suffer the largest delay in the availability of suitable models, with the retire phase to be re-thought as a retrofitting stage. Given the above, the main challenges identified for the sector relate to the design or retrofitting of ships. Current research is producing suitable models to be applied for DT applications; however, a complete methodology for the design of a new object is still currently missing also in manufacturing. Therefore, a DT-based procedure is truly a challenging aspect of future research that may also have an impact on other industries.

Such matters have been identified in the recently started project The Digital Twin for Green Shipping (DT4GS), which aims, in part, to create a novel DT-based procedure for the design of green ships. Thus, the project has the potential to fill the gaps identified in this review (DT4GS, 2022).

Such an impact could be measured in the future by applying the systematic method proposed in this study. Following it in future reviews will provide a clear and comparable status of the future developments and progresses in the DT applications throughout the life cycle of ships.

CRediT authorship contribution statement

F. Mauro: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **A.A. Kana:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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