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Navigating shipbuilding 4.0: analysis and classification of technologies for the digital transformation of the sector"

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ABSTRACT
Shipbuilding, a pivotal industry supporting shipping, fishing, wind energy, and defence, confronts global competitive pressures amidst contemporary challenges. Despite its significance, the sector faces ongoing challenges in achieving digital maturity. This study is part of a research that aims to expedite the shipbuilding digital transformation, particularly by identifying current applications of key enabling technologies (KETs) in the shipbuilding activity through a comprehensive literature review. The KETs are first identified, then they are categorized based on two criteria: the main focus of the technology and the specific *function* in the shipbuilding process. While the analysis reveals an extensive quantity of applications (88), they are rather scattered and do not present a strong trend, predominantly relying on traditional approaches and backing mass production-like processes. It is also shown that the applications of KETS in the shipbuilding industry is still very immature, with only 15% of applications in the deployment phase, while the vast majority remain in the conceptual or development phases. Moreover, this study highlights the interconnected nature of these KETs, that point to the need to support shipyards in setting key priorities and strategies for their implementation. The study concludes by proposing avenues for future research to address these challenges and boost the shipbuilding industry towards its digital transformation.

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Shipbuilding; digital transformation; technology road-mapping; KET; competitiveness; automation; technology management

1. Introduction

The ship construction industry has been a key component of every major civilization throughout history, and it still plays a major role in the global economy today. This industry is highly strategic for any region, and society would benefit even more if efficiency and competition were continually increased.

Shipbuilding is the cornerstone that connects in the upstream side to suppliers and subcontractors providing many jobs in different disciplines, and in the downstream it supports multiple other key sectors and industries (OECD 2020; Kamola-Cieślik and Czapiewski 2021), as it is graphically represented in Figure 1. For example, the construction of commercial ships enables maritime shipping, which accounts for 80% of global trade by volume (World Trade Organization – United Nations 2022). Shipyards also build vessels and marine structures for important sectors such as offshore oil and gas, green energy production and fishing. Additionally, the shipbuilding industry supports the entire port sector to operate efficiently by providing tugs and dredges, allowing many other export and import activities to succeed. Lastly, it allows a country to build and repair its naval vessels, and thus strengthen its defense capability.

However, shipbuilding has faced challenges throughout its history, related to global financial crisis, political situations and trade trends (Colton et al. 2002; Kamola-Cieślik and Czapiewski 2021). Nowadays, some of those challenges remain active and others have evolved. In Section 2, the challenges that the shipbuilding industry is facing will be discussed. Then in Section 3 the concept of digitalization of the industry 'Shipbuilding 4.0' is presented, as one of the strategies to deal with the current challenges. Later the methodology to perform a literature review is presented in Section 4, and the results are shown in Section 5. Finally, the discussion and limitations are given in Section 6, and the conclusions of this work in Section 7.

The purpose of this work is to provide an updated overview of the shipbuilding industry, examining its challenges and the key technologies aimed at elevating its digital capabilities to overcome these challenges.

2. Challenges in shipbuilding

Shipbuilding is confronted by four specific challenges at the moment, two long-standing and two recently developed. The two long-standing challenges are the high fluctuation in the demand and the unstable

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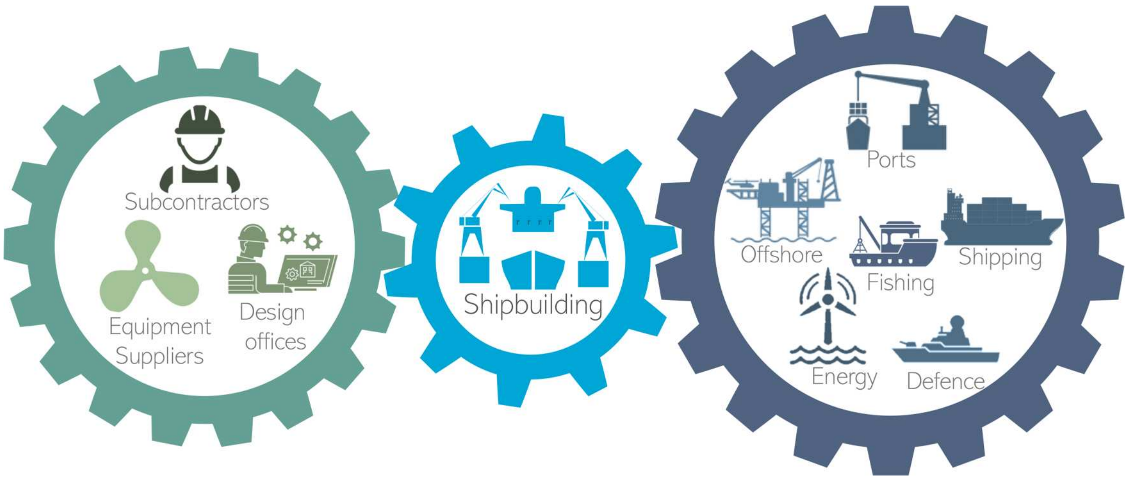

Figure 1. Shipbuilding relationship with other industries.

political environment. The two recent issues are the labour shortage and the uncertainty about the energy transition. Those must be addressed for existing shipyards to maintain their production capacity and competitiveness. Before discussing how to address them, a more detailed presentation will be provided below.

2.1. High fluctuation in the demand

One of the most significant challenges of shipbuilding has been the instability of the demand for newly built ships. In 2008, the number of orders reached a record high, but it subsequently fell by more than half by 2013 (Muhammad Fareza 2020; Clarksons 2023). The year-on-year change in global shipbuilding output exhibited a fluctuation of +/−60% in the '80s. Subsequently, the variation has persisted within the range of +/−20%, signifying substantial variability that significantly impacts the continuity of shipbuilders. This volatile environment led to the closure of around 50% of the number of active shipyards in the last two decades (Kamola-Cieślik and Czapiewski 2021; Clarksons 2023).

Additionally, the global shipbuilding market has shifted significantly in recent years. We must consider that shipbuilding is an industry that can move its production location easier than others, because the transportation cost of its final products is marginal, considering that the ships can move all around the world by themselves when finished. In the 1990s, the market was relatively evenly distributed between the main producers: South Korea, Japan, Europe, China, and the United States. However, China has now captured more than 50% of the global market share as shown in Figure 2. This has forced the other producers to focus on specialized niches, such as very complex ships like naval vessels, cruise ships, chemical ships, and offshore structures (OECD 2020; Kamola-Cieślik and Czapiewski 2021; Maritime Data 2023). This situation can be explained by the natural shift of labour-intensive industries to lower-wage countries, but also to get lower prices for steel and other materials, and the backing of governments. Those factors however can quickly change again and force the industry to move to another scenario.

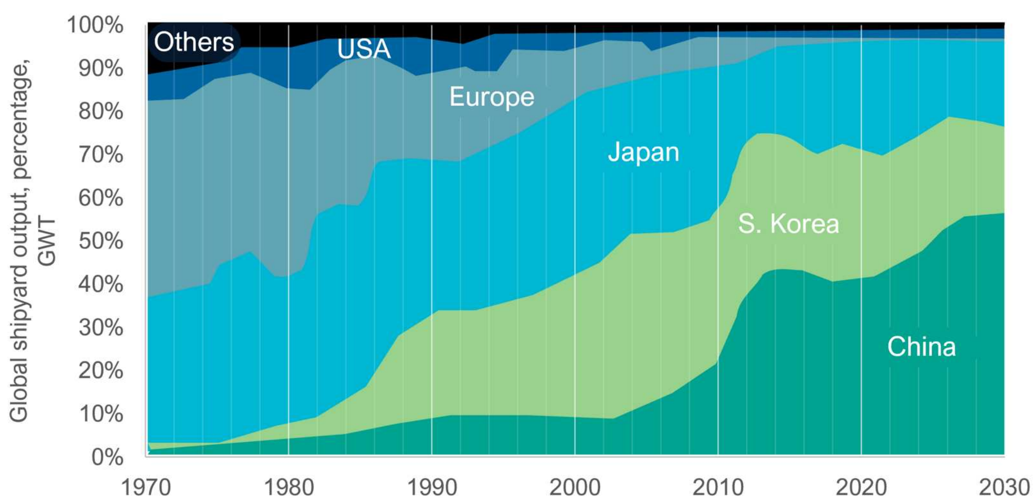

Figure 2. Shipbuilding new orders market share. Based on Maritime Data (2023).

The high variability in demand hinders the ability of shipbuilders to maintain a skilled labour workforce and formulate strategic investment plans. When demand is high, shipbuilders need to hire more workers and invest in new technology. However, when demand is low, they need to lay off workers and reduce their investment. This makes it difficult to maintain a stable labour force and keep up with the latest technological developments.

2.2. Unstable political environment

The shipbuilding industry is highly sensitive to global economic and political conditions. In recent years, the industry has faced an increasing number of challenges in this regard, including unequal government support, unstable political situation, lack of financial support, and lack of clear policies about the energy transition.

Governments around the world play a significant role in the shipbuilding industry, providing subsidies and other forms of support to their domestic shipyards. This can lead to unfair competition, as shipyards in countries with more generous government support may be able to offer lower prices for their ships. For example, according to Blanchette et al. (2020) the Chinese government provides significant financial support to its shipyards, which has helped them to become a dominant player in the global shipbuilding industry. This has put pressure on shipyards in other countries and regions, such as South Korea, Japan, and Europe.

The shipbuilding industry is also affected by the political situation in the countries where shipyards are located. Political instability can lead to disruption of production and increased costs. For example, the ongoing political crisis in Russia has disrupted the supply chain of key materials and components for shipbuilding in Europe, as well as the supply of ships already contracted (Meijer 2023).

2.3. Labor shortage

Shipbuilding is a labour-intensive industry that requires workers of many different disciplines, with high skills and flexibility to adapt to different conditions and scenarios. To maintain a sustainable and competitive shipbuilding industry, we need to ensure a considerable level of workers, have good attractiveness, and warrant a safe working environment for them. The challenges regarding the labour situation are the shrinking of working population, lack of attractiveness, and unsafe conditions.

In many countries, the demographic distribution is diminishing. The demographic pyramid charts of the main players in shipbuilding are presented in Figure 3. Each graph is divided into demographic populations of 5 years range, with the newborns at the bottom and the oldest at the top. For the sake of simplicity, the working population is assumed to be people between 20 and 65 years old. Using the same data, a projection of the working population 20 years in the future is presented in gray colors. This is done by assuming that the current population aged 0 to 45 will still be alive in 20 years, and that they will all be between the ages of 20 and 65 at that time. As it can be observed, the working population of the future will be smaller than the current one. If those economies want to maintain at least the same level of output, they must increase their productivity per labour hour to be able to produce the same amount with less labour force. It could be done by focussing on automation and process optimization.

Looking closer at the working population of the shipbuilding industry, this problem is even more pronounced. In addition to the fact of having a smaller

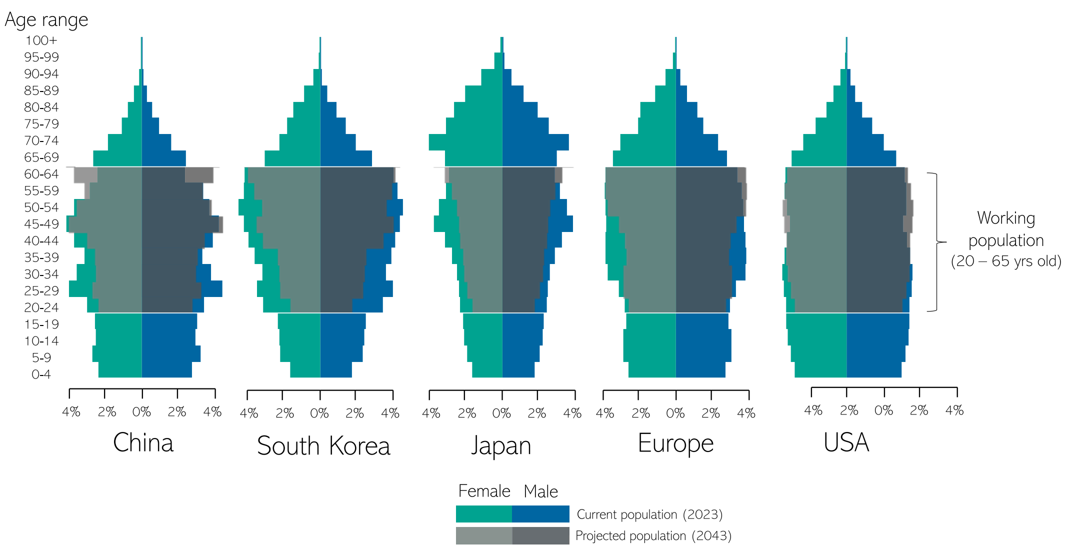

Figure 3. Demographic distribution by region. Based on Population Pyramid (2021).

working population in general in those regions, shipbuilding must compete with other industries to attract those new workers, but unfortunately, it is seen as an old-fashioned industry, and not many young people are willing to work in it. As Arias et al. (2020) concluded, the main reasons why this is happening are the lack of public-specific training, the image of physical work and a dirty environment, and the difficulty of offering a long-term contract, due to the before mentioned variability in work and labour-force.

2.4. Uncertainty about the energy transition

The shipbuilding industry faces a pressing challenge: the need to develop and implement innovative technologies to reduce carbon emissions. This imperative is being driven by both international regulations and the shipping industry's own commitment to environmental sustainability. However, the transition to cleaner propulsion systems is uncertain, making it difficult for shipowners to make informed decisions about investments in new vessels. This lack of clarity is increasing the already volatile market conditions.

Despite the growing demand for cleaner fuels, such as liquefied natural gas (LNG), ammonia, hydrogen, and methanol, there is a lack of consensus on the most viable long-term solutions. This uncertainty is hindering the development of new technologies and making it challenging for shipowners to plan for the future. The absence of clear government policies governing this transition further complicates the situation. Without definitive guidelines, shipowners are hesitant to invest in new ships, fearing that regulatory changes could render their investments obsolete prematurely.

The transition to cleaner shipping is inevitable, and the shipbuilding industry must play a leading role in shaping this transformation. By embracing innovation, collaboration, and regulatory clarity, the industry can pave the way for a sustainable and economically viable future for maritime transportation.

In conclusion, the shipbuilding industry is facing several significant challenges that need to be addressed to maintain its competitiveness and sustainability. These challenges include the volatility of the order book, an unstable political environment, a labour shortage, and uncertainty about the energy transition. In response, the shipbuilding sector must be innovative and implement new strategies to remain competitive. The digital revolution promises to deliver an increase in productivity and is already applied successfully in other sectors and industries. This increased productivity can effectively address the initial three challenges, while enhanced control and insight offer a potential solution to the fourth. The digital transition serves as a key enabler for these improvements, and a more detailed exploration will follow in the subsequent section.

3. Shipbuilding 4.0

Industry 4.0 (I4.0) is a term that emerged in 2011 to describe the fourth industrial revolution, which is characterized by the adoption of new technologies such as Artificial Intelligence (AI), Additive Manufacturing (AM), and extended reality (XR) among others. Many of these technologies have already been developed and implemented in other manufacturing and services sectors, reducing the labour level, dealing with uncertainty, and producing unique products among others (Ran and Singh 2016; Alcácer and Cruz-Machado 2019; Salunkhe and Berglund 2022). The Industrial Revolution 4.0 seems to offer shipbuilding a way to deal with the identified challenges. However, the level of automation in shipbuilding is still relatively low (Iwańkowicz and Rutkowski 2023; Centobelli et al. 2023; Papanikolaou et al. 2024), and further effort is needed to accelerate the digital transformation of the sector.

The concept of Shipbuilding 4.0 or Shipyard 4.0 has been analyzed by some researchers, with most of the work focussing on small-scale or single companies (Torres 2018; Sánchez Sotano et al. 2020; Reznikova et al. 2021; Agis and Brett 2024). Those studies highlight the enthusiasm surrounding the transformation of the sector and the corresponding benefits, such as more digital business opportunities, further optimization of the ship life cycle, and improved productivity, quality, and safety during construction. However, they also mention a series of factors that need to be addressed before I4.0 can be fully implemented in the industry, including technological, organizational, and information-related issues, discussed below.

Technological factors are such as the complexity of the process, volume of batches, data acquisition hardware and software, and the connectivity in the working place. Also, complementary considerations must be addressed, such as the interoperability between different systems. In shipbuilding, this is a big barrier to digitalization since the ships are unique products, with low standardization of components, and there are no data exchange standards to effectively integrate tools and systems from different vendors.

Organizational factors are related to the changes required for the digital transformation, such as the need to change the company culture and get acknowledgment from top management, adapting mindset from all the organizational levels, and the need to invest in new technology and training.

Information factors represent the difficulty in acquiring and analyzing effective data to make informed decisions. They include the technology awareness limitation, the overwhelming number of high-tech solutions, and the high uncertainty on the upfront costs, risks and benefits of each technology.

However, there is not an updated compilation of the current technologies applied in the shipbuilding industry to the best knowledge of the authors, which would be very valuable for shipbuilders and academics to have a more precise understanding of the trends, topics and more addressed processes.

The purpose of this research is to analyze the existing literature on the digitalization of the shipbuilding industry, to make an overview of the existing technologies, and to propose research directions to accelerate the digital transformation of the sector. With this result we expect to provide shipbuilders with better information to make more informed decisions in their digital transformation plan, addressing mainly the information factors that hinder the digital transformation process.

The following research questions were defined to better understand the current digital technologies used in shipbuilding and the approaches of managers to deal with the investment and implementation process:

RQ1: What are the I4.0 relevant KETs for shipbuilding?
RQ2: What are the focuses of current applications of I4.0 technologies in the shipbuilding process?

The following sections develop further the method, results and discussion. In Section 4 the methodology of this literature review is exposed. In Section 5 the results are presented regarding the bibliometrics analysis and the application of key enabling technologies (KET). Finally, in Section 7 the conclusions are presented.

4. Literature review methodology

A Systematic Literature Review (SLR) is a comprehensive and structured approach to reviewing existing literature on a specific topic or research question. It involves systematically searching, selecting, appraising, and synthesizing relevant studies to provide a comprehensive overview of the current state of knowledge in a particular field. This Systematic Literature Review (SLR) was conducted following the method proposed by Kitchenham et al. (2009). Considering this, initially, the document exploration was performed in the platform database Scopus, using the search string below, which includes terms and synonyms for the three main pillars of this research. Those are (1) the shipbuilding industry, (2) the digital transformation and the (3) competitiveness. Those concepts were intended to get the publications regarding the digital technologies or concepts that are pushing shipbuilders into the digitalization process with the purpose of improving their competitiveness, by being innovative or optimizing the production processes.

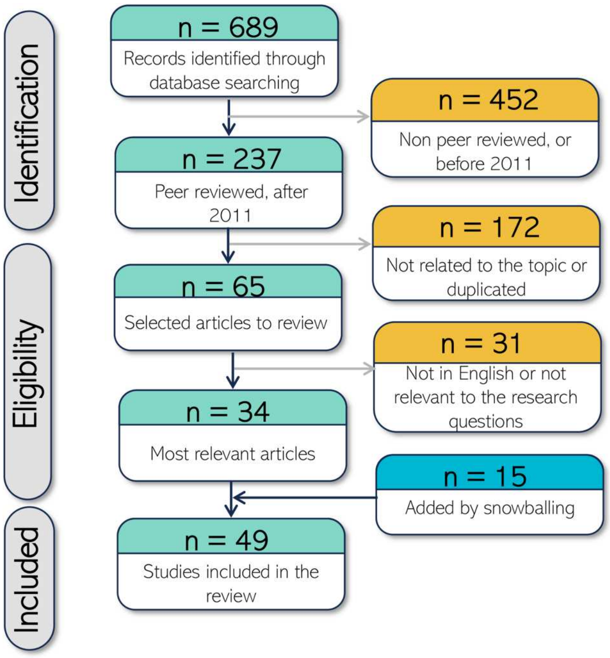

Figure 4. Schematic for methodology adopted in this research.

SEARCH STRING: TITLE-ABS-KEY ((shipyard OR shipbuilding OR yard OR shipbuilder) AND (digital OR digitalization OR automation OR 4.0 OR transformation) AND (optimization OR improvement OR innovation OR productivity OR competitiveness))

Next, the selection of documents was performed as depicted in Figure 4. Using the presented search string, resulted in 689 results. Then documents without a peer-reviewed system were removed in order to ensure scientific relevance. Due to the fact that this work focuses on Industry 4.0 applications, a term which appeared in 2011, only documents after this year were considered. A subtotal of 237 papers remained for further analysis.

Then a selection process based on titles and abstracts was performed, to exclude those that were not related to the objectives of the research. Only articles related to shipbuilding were selected. Many other related topics are out of the scope of this work, like most of documents focussed on ship design, ship operation, or ship repair. Only papers of those topics directly relevant to the shipbuilding process were considered for the review. For instance, the documents about design and engineering that were included, were those that had some focus on Design for Production (DFP) or that are intended to make the shipbuilding process faster, easier or safer. The same criterion was used for papers regarding ship operation, which only included those about technologies that can be used in the shipbuilding process as well, like technologies to inspect welding or hull structures in difficult access areas. This selection process resulted in 65 documents left.

Those documents were fully read to verify their relevance and pertinence to the focus of the research. A total of 31 papers were excluded since they were about particular features of some technologies, and did not provide relevant information to answer the research questions. Additionally, 5 documents were rejected for not being written in the English language. Finally, 15 additional articles were included by snowballing during the full read of documents, as they were the main references for other documents of each technology. A final 49 articles are cited in this review.

The selected articles were through fully read and the application of each technology in the shipbuilding process was identified. For each application the specific function and (if applicable) sub-function was identified, as well as its maturity level according to the Technology Readiness Level (TRL).

4.1. Shipbuilding functions definition

One consideration to make is the classification regarding the shipbuilding functions. This is needed because there are no international standards of taxonomy for the shipbuilding functions. For instance, some authors refer to outfitting processes like the installation of auxiliary steel elements like stairs, handrails, and hangers, and others refer to outfitting as the installation of pipes, cables, and equipment. The classification of functions and sub-functions used in this research is shown in Table 1.

Here, the functions are defined in a primarily chronological order, even though many activities occur concurrently. Each function is assigned a letter code for easy reference throughout this document. Only the ‘ship production’ function includes corresponding sub-functions, as this is the main focus of the study. The sub-functions are coded by appending a number to the function letter.

It’s worth noting that the term function might be misleading when applied to areas like HR or logistics, which are continuous functions in the shipyard. However, the majority of other concepts align more naturally with the term. Even in the cases of HR and logistics, certain processes are tied to each shipbuilding project, with defined starting and ending points, making it reasonable to consider them as functions as well.

It is worth mentioning that the main focus of this research is the ship production function itself. This is the function where the actual construction of the ship occurs, from getting the engineering information, to the performance of sea trials and successful delivery to the shipowner. However, some external functions are also included because of the strong relationship with the ship production function, such as ship design and ship operation. For ship design, KET applications with the main focus of improving the ship production function were considered, like the design for production DFP approach. For ship operation technologies, we considered ship maintenance and monitoring KETs that can also be used during ship production to track progress or quality.

5. Literature review results

In this section, the selected literature is analyzed and presented. First, a bibliometric analysis of the reviewed articles is performed in order to verify the

Table 1. Shipbuilding functions and sub-functions definition.

Functions / Sub-functions	Definition
A. Design	Focused on documents about conceptual and basic design, or functional and detailed engineering related directly to the shipbuilding process, like considering DFP features.
B. HR	Issues directly related to the personnel and not attached specifically to a singular process, like health and security and training.
C. Logistics	Including the supply chain management and the warehouse operations within the shipyard.
D. Planning	The process of general planning of each project, and transversally of the shipyard. Including general planning like allocation of blocks in the yard or block sequence (building strategy) but also detailed scheduling for mid and short term.
E. Shipyard operation	Related to operations not directly involved in the production of new ships but to the functioning of the shipyard like maintenance of equipment, cranes, vehicles and energy consumption management.
F. Ship production	
F.1 Hull construction	Process of building the metal hull, including sheet cutting, panels, subassemblies, block/section construction and erecting, welding procedures and dimensional control are considered here.
F.2 Outfitting	Outfitting including the fabrication and installation of pipes, pumps, valves, cable trays and the cabling process.
F.3 Equipment and system installation	It refers to the installation and integration of main equipment such as engines, gensets, cooling units, hydraulic pumps, electrical cabints, and navigation and communication systems.
F.4 Painting	All the processes related to painting like cleaning (water pressure), blasting, painting and fairing. Both external and internal painting process.
F.5 Acommodation	Internal processes like isolation, internal walls installation, ceiling, furniture and decoration.
F.6 Transporting equipment	This refers to all the planning, maintenance and operation of transporting equipment such as forklifts, cranes, self-propelled transporter and trucks.
F.7 Project management	Administrative processes closed related to the ship construction project, such as knowledge and document management, relationship with the customer and requirements management.
F.8 Quality assurance	The process dedicated to the quality control of the ship by specialized personnel like NDT. However, in many cases the quality control is made in the same process, thus not all the quality control processes are classified here.
F.9 General production work	Used for those documents referring to the whole shipbuilding process in general.
G. Ship operation	Related to the operation (monitoring) and maintenance of the ships by the crew members and the ship repair yard, that can help the shipbuilding process itself.

most cited elements, the trends through time and the rough relationships between KETs. Next, a classification of KETs for shipbuilding is proposed considering the main focus, clustering them in 5 groups: Product, Process management, People, Equipment or IT systems. Finally, an extensive list and analysis of the current applications of technologies is depicted considering the shipbuilding functions. The goal of compiling insights into emerging technologies and research initiatives in shipbuilding is to provide shipbuilders with a valuable resource to support their digital transformation journey.

5.1. Bibliometric analysis

To gain a first impression of the topics and focus of the selected documents, a bibliometric analysis was performed. All documents were labelled with the following elements: main and secondary KETs, shipbuilding function and sub-function, the TRL and the publication year. The definitions for the shipbuilding functions and KET's classification are presented in Sections 4.1 and 5.2 respectively.

This data was processed in the VOS Viewer software (van Eck and Waltman 2010) to develop a bibliometric network of the specific technologies and functions studied, to better understand the trends in academia regarding shipbuilding 4.0. The result of this network is presented in Figure 5.

From the graph, it can be concluded that research topics have varied slightly over the years. Older documents (average publication year) are related to robotics and autonomous vehicles and robots (AVR), such as the development of welding robots and curved plate automation attempts. Later research focussed on simulation and system integration approaches, with discrete event simulation (DES) approaches being used despite a lack of proper and accurate data. This led to the need for more centralized and integrated data sources. In recent years, the trend has been the evolution of this approach to become the digital twin, and big data analytics. Those technologies have the biggest potential to improve the productivity and competitiveness of shipyards by being more efficient and helping to deal with uncertain scenarios and situations during ship construction.

Optimization approaches have also been a strong focus of research. It includes various methods, from traditional ones as rule-based algorithms, to novel ones like AI including neural networks (NN) or genetic algorithms (GA). It could be explained by the challenge of shipbuilders having very different disciplines working in the same space and performing

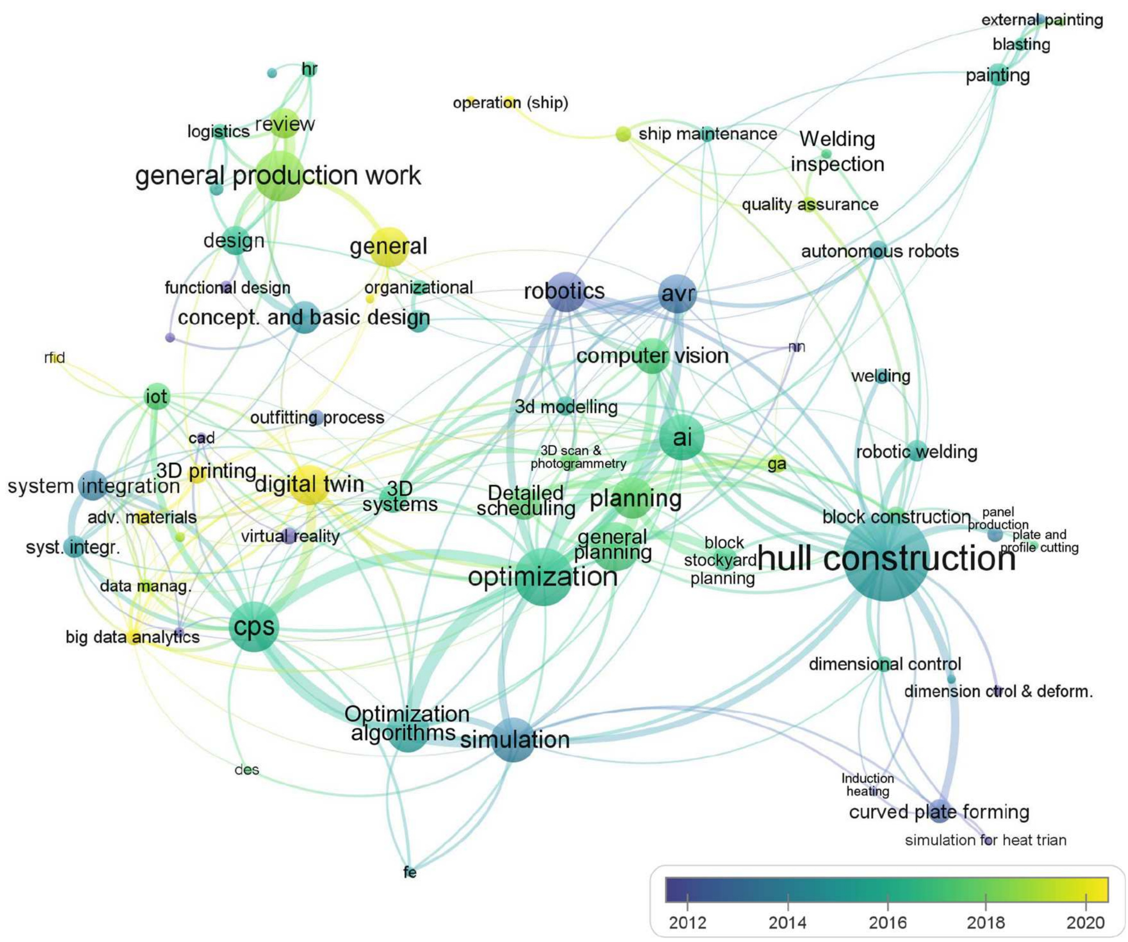

Figure 5. Bibliometric network of literature search.

unique tasks. This situation leads to a large coordination effort in order to reduce construction time, rework level, non-productive time, and variability of resources.

Hull construction is the shipbuilding function investigated the most. This is because it is the most similar to a mass-production factory, with similar interim products. However, the automation of the process developed only to a basic level, since the products are similar but not identical. This makes traditional programming processes for robots time-consuming.

Outfitting function, on the other hand, are far more heterogeneous and diverse, so they have remained less automated or digitalized. They deal with the additional fact that they are performed inside the vessel instead of a workshop, making it more difficult to have proper communication systems because of the steel environment.

The digitalization process in shipbuilding has very different approaches regarding time, technologies, and processes. Also, many technologies seem to have stronger connections with other ones, suggesting a support or prerequisite between them. These relationships must be explored in a deeper way to understand the complete panorama of digital transformation of the sector, in order to support shipbuilders in the pathway to the digital era.

5.2. Key enabling technologies – KET

Key Enabling Technologies (KETs) are technologies that help different industries or sectors become more digitalized, especially in line with Industry 4.0 trends. In a critical review of selected papers, we observed that the terms and classification of KETs varied widely among the documents. This is because there is no standard definition for each technology, as they are innovations that are constantly evolving and adopting different names depending on the country, time, and context in which they are applied.

However, in order to have a better understanding of the current KETs, it is good to have a classification that can help to analyze the entire scenario in a better way. This work proposes a novel classification of the KETs, considering traditional and accepted frameworks, with some updates to the current industry scenarios.

The initial framework for analyzing a production company, as proposed by Hayes and Wheelwright (Hayes and Wheelwright 1979), is based on two key dimensions: product and process. The first dimension, product, includes technologies designed to enhance various aspects of the vessel, incorporating advancements like novel materials, topology optimization, and 3D printing. This will be our first group for KET's as well. The second dimension, process, looks into the details of how things are made, breaking it down into two further parts: managing the process and the production effort.

The field of process management will be our second group, including a spectrum of technologies that is leveraged to optimize various operational functions. This includes the implementation of lean management principles, artificial intelligence, and other optimization algorithms. Meanwhile, the production process, as declared by Cobb and Duglas (1928), is essentially a function of labour and resources.

The labour component leads to the creation of our third category: People. It focuses on technologies aimed at enhancing the performance and capabilities of the workforce. This involves the incorporation of technologies like extended reality (XR), exoskeletons, and other human augmentation tools. On the other hand, the Resources category predominantly involves capital investments. In the contemporary digitalized landscape of production enterprises, these investments are split into traditional equipment and information technology (IT) systems, thereby constituting the last two groups.

In the Equipment category, technologies are geared towards improving integration, including advancements such as robotics, collaborative robots (cobots), drones, and digital twin technologies. Simultaneously, the IT Systems category involves horizontal and vertical integration of systems, big data analytics, and the utilization of cloud and edge computing, among other technologies. This comprehensive framework offers a perspective on the multifaceted technological landscape within production enterprises in the current digital era. The final classification of the KET's and the corresponding groups is presented in Figure 6.

The classification process was complex, as many KETs seemed to belong to more than one group. This is because, depending on the specific application of the technology, it could be used to help one or more groups. Additionally, in almost every case, each technology requires integration with another technology from a different group to be efficient. For example, AI algorithms are intended to optimize or solve problems using data obtained from sensors (IoT) or corporate information (Big Data) and presented in the Digital Twin (DT) environment. Therefore, the classification considers the most common applications, but should not be considered rigorous or inflexible.

5.3. Applications of KET in shipbuilding

One of the main goals of this study is to present an updated overview of the applications of I4.0 KET in the shipbuilding industry as described in Section 3. An extensive compilation of the applications of KET was performed, based on the selected documents to

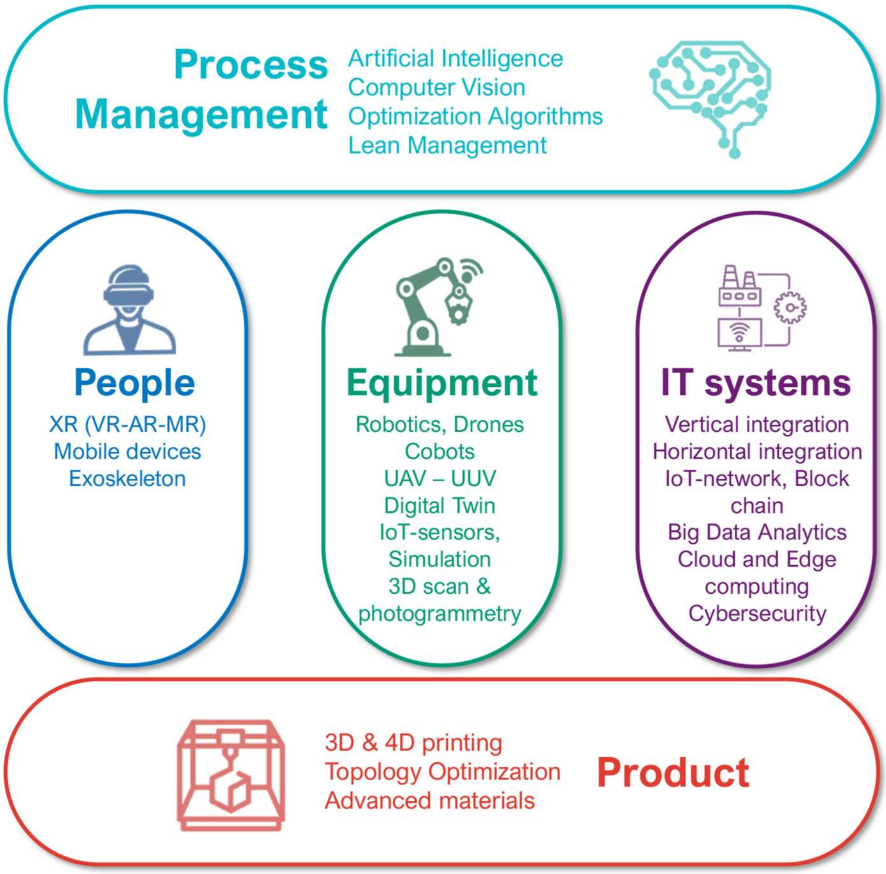

Figure 6. Classification of KET for shipbuilding 4.0.

review. A quantitative compilation is shown in Table 2, and will be described and analyzed in this section.

5.3.1. A. Design

Naturally, the KETs more related to Design For Production (DFP) are the ones in the product group of technologies. This includes the use of 3D model in early functions instead of 2D drawings (Perez-Martinez and Perez Fernandez 2023), visualization of assembly sequences both with 3D printed prototypes (Schulze and Dallasega 2023) or digital simulations (Pang et al. 2021; Hoffman et al. 2023), in order to have early insights from customers, suppliers and production workers. This visualization can be further extended by using a VR environment (Fernández-Caramés and Fraga-Lamas 2023; Schulze and Dallasega 2023) and having a more detailed exploration of the systems on board from a production perspective.

5.3.2. B. Human Resources – HR

Improving training and health & safety are the main goals of the technologies developed for this function. Although many KETs in specific production processes are intended to increase productivity, quality, and safety, this section collects the applications whose main purpose is safety. The development of XR applications for training is one of the KET with more commercial advancement. Mainly there are applications in training welding, painting, and crane operations (Sanchez-Gonzalez et al. 2019; Muñoz and Perez-Fernandez 2021; Fernández-Caramés and Fraga-Lamas 2023). Also, the use of skeletons is getting progressively popular, mainly for warehouse workers, but some projects are checking the applicability in grinding and welding operations in overhead positions in shipyards (Fernandez and Péter Cosma 2021).

Technologies about IT infrastructure and equipment are also getting attention regarding the safety and health of workers. Namely the use of drones to inspect dangerous areas such as confined spaces or tall structures (Fernandez and Péter Cosma 2021). The use of power electricity lines for transmitting data is another trend that intends to improve the connectivity inside of the vessels during construction and, therefore have better communication with workers in case of emergency (Huh et al. 2018).

5.3.3. C. Logistics

Studies found in logistics are mainly regarding supply chain analysis. Those are about technologies that may change the make-buy decision for many interim products by using 3D printing (Ziółkowski and Dyl 2020; Centobelli et al. 2023), or how to interconnect data of the value chain (Stanić et al. 2018; Schulze and Dallasega 2023; Scipioni et al. 2023). These developments could bring major benefits by reducing

Table 2. Number of applications by KET, category and shipbuilding functions.

Categories and KET's	A. Design	B. Human Resources	C. Logistics	D. Planning	E. Shipyard operation	F. Ship production	G. Ship operation	Total
	Shipbuilding functions							
Equipment		3	2	2	3	18	3	31
3D Scan & photogrammetry						2		2
AGV			1			1		2
Robotics						6	1	7
Simulation		1		1				2
UAV Drones		1					1	2
UUV							1	1
Digital Twin – Shipyard		1	1	1	3	7		13
IoT- sensors						2		2
IT systems		1	4			8		13
Block chain			1					1
Cloud and edge computing			1			2		3
Horizontal integration			2					2
System integration						2		2
IoT- network		1				4		5
People	1	3	1		1	8		14
Augmented reality			1		1	6		8
Virtual reality	1					1		2
XR		2				1		3
Exoskeleton		1						1
Process Management	2			2		9		13
3D modelling	1							1
AI	1			2		5		8
Computer vision						1		1
Lean						3		3
Product	4		1			7	5	17
3d printing	1		1			7	3	12
Digital Twin – Ship	3						1	4
Advanced materials							1	1
Total	7	7	8	4	4	50	8	88

delivery time and inventory levels, but it requires a missing common standard to integrate them effectively.

5.3.4. D. Planning

The main technologies applied in this function are intended to improve the planning procedure by using simulation, digital twins, and AI optimization algorithms. The planning function has been a strong focus of improvement for many decades, but a lack of data was the biggest challenge for technologies such as discrete event simulation (DES) and other simulation techniques (Lee et al. 2020). Digital twin technologies are being developed to gather more data in a simplified manner, in order to simulate different scenarios during the construction function (Lee et al. 2014; Hoffman et al. 2023). AI optimization techniques are also being developed to close the gap of missing information and produce more reliable and faster results in the simulations (Woo et al. 2021; Iwańkowicz and Rutkowski 2023).

5.3.5. E. Shipyard operation

The main focus of applications for shipyard operations is the predictive maintenance of the equipment and machinery, in order to get a higher energy efficiency. This can be achieved via sensing the shipyard and processing this data in a digital twin platform (Hoffman et al. 2023; Zhong et al. 2023). It also presents the objective of optimizing movements of materials and equipment to improve energy efficiency (Pang et al. 2021). Additionally, the use of AR tools to support the maintenance activities in the shipyard is also part of the current research (Fernández-Caramés and Fraga-Lamas 2023). Fortunately, equipment management is the most similar aspect to a mass production manufacturing company, so many commercial tools are available. However, the main challenge to take into account is the connectivity in the shipyard considering the irregular and open space environment, and the wave-isolating steel structure inside the ship.

5.3.6. F. Ship production

It can be observed from Table 2 that most of the applications are related to the ship production process. This is due to the selecting and filtering process that intentionally focuses on the ship construction phase of the life cycle of a ship. Therefore, this function was further divided into the production sub-functions defined in Section 4.1, and the corresponding classification is shown in Table 3. A description for each sub-function is presented below.

F.1 Hull construction

Hull construction is the sub-function with the biggest development in digital technologies. The main application is focussed on the equipment, mainly in the

Table 3. Number of applications by KET, category and sub-function in the ship production function.

KET's grouped by categories	Sub-functions of the function 'F. Ship production' F.1 Hull construction	F.2 Outfitting	F.3 Equip.and syst. Integration	F.4 Painting	F.5 Accommodations	F.6 Transporting equipment	F.7 Project management	F.8 Quality assurance	F.9 General production work	Total
Equipment	9	2		3		1		2	1	18
3D Scan & photogrammetry	2									2
AGV	1									1
Robotics	2	1	3							6
Digital Twin – Shipyard	4	1						1	1	7
IoT- sensors						1		1		2
IT systems		2				1	3	1	1	8
Cloud and edge computing							1	1		2
System integration							2			2
IoT- network		2				1			1	4
People	1	3	2						2	8
Augmented reality	1	2	1						2	6
Virtual reality		1								1
XR			1							1
Process Management	6	1					1		1	9
AI	4						1			5
Computer vision	1									1
Lean	1	1							1	3
Product	3	1	2		1					7
3d printing	3	1	2		1					7
Total	19	9	4	3	1	2	4	3	5	50

robotic welding process, which has been improved by the use of robotic vision and AI algorithms (Sanchez-Gonzalez et al. 2019; Sánchez-Sotano et al. 2020; Lei et al. 2020; Diaz-Cano et al. 2022; Zheng et al. 2022). However, there are still challenges regarding the positioning and monitoring of parameters to ensure good welding, and how to deal with access to constrained spaces. Another discussed topic is the management of distortions of the structure. It includes the monitoring and comparision of the actual structure with its CAD file, via photogrammetry or laser scanning (Paoli and Razionale 2012), and the tracking of all local deformations to verify the global dimension control (Hoffman et al. 2023; Iwańkowicz and Rutkowski 2023). This topic is strongly related to the development of curved surfaces using heat lines, which is a common practice by Asian shipbuilders. Still, there are no commercial off-the-shelf (COTS) solutions for automatic bending or straightening, either cold or hot, so it is very dependent on the expertize and knowledge of operators.

Digital twin is another common approach, mainly because hull construction is the most similar sub-function to traditional manufacturing mass production processes. The focuses of researchers are to continuously monitor the progress of work, update the dimension control of the hull, and simulate different locations of blocks within the shipyard (Wang et al. 2022; Noordin and Salleh 2022; Guan et al. 2022; Hadžić et al. 2023).

The 3D printing technology is also having an increasing impact, like the fabrication of small boat hulls by additive manufacturing (Ziółkowski and Dyl 2020), or the printing of non-structural elements with intricate shapes for steel hulls such as hooks, doors, and hatches (Ziółkowski and Dyl 2020; Schulze and Dallasega 2023).

Finally, the AI technology is improving many other processes related to hull construction. Among them, it can be highlighted the use of AI to make an automated classification of parts (Iwańkowicz and Taraska 2018), a detailed planning of assembly sequence (Wang et al. 2023), the prediction of welding defects (Curiel et al. 2023), and the interpretation of radiography as a non-destructive test (NDT) (Oh et al. 2020).

F.2 Outfitting process

The use of XR technologies is the main approach for the outfitting sub-function. It is intended to deal with the high complexity of the outfitting process, where workers of many disciplines perform their jobs at the same time in a very constrained space: pipers, electricians, and HVAC installers. VR devices can help to realize clashing problems or better installation sequences before the actual construction, and to provide the customer with a better visualization of the vessel (Centobelli et al. 2023). On the other hand, AR technologies can contribute by monitoring the compartments on-work, to verify that the already installed elements are in the right positions and check that the missing elements will fit perfectly (Fernández-Caramés and Fraga-Lamas 2023).

Other technologies have also development in the outfitting sub-function, like digital twins and IoT. Initial tasks in the workshops like pipe fabrication and welding are researched to implement robotic welding of pipes (Sánchez-Sotano et al. 2020), and digital twin to monitor this prefabrication function (Kunkera et al. 2022). The monitoring of pipes after prefabrication is more complex and difficult. On board the ship this difficulty is due to the steel structure inhibiting the use of sensors, and in open spaces in the yard due to the limited range of WiFi networks. However, some researchers are trying to overcome this with new RFID tags, WiFi6, power line communications (PLC) and 5G networks (Fraga-Lamas et al. 2016; Sanchez-Gonzalez et al. 2019; Fraga-Lamas et al. 2021).

Another trend in shipbuilding is the application of advanced outfitting, that is the installation of outfitting as soon as possible in a modular way. This is related to the lean principles, and therefore some researchers are trying to implement it to reduce energy consumption and increase the quality of the ship such as dimension control achieving a no-tolerance block lifting approach (Noordin and Salleh 2022).

F.3 Equipment and system integration

The installation of main and auxiliary equipment such as engines, hydraulic pumps, and generators, requires a lot of technical information and guidelines. That is why the focus of this sub-function relies on the enhancement of workers by providing better information to perform the installation and integration tasks. The use of AR is the most promising technology, allowing them to have access to detailed blueprints, 3D visualization of parts and assembly steps, and direct assistance from more experienced workers and technical engineers (Fernandez and Péter Cosma 2021; Fernández-Caramés and Fraga-Lamas 2023).

Another topic for research is the propulsion system, especially the propeller. This element has one of the most complex shapes on the ship, and it is worth optimizing it for every vessel, thus the traditional manufacturing process could be improved by 3D printing, specifically the Wire Arc Additive Manufacturing (WAAM) technique (Ziółkowski and Dyl 2020). This also will reduce significantly the delivery times from specialized manufacturers of those elements.

F.4 Painting

Although painting is a key part of shipbuilding, both external and internal in the ship to maintain a good quality and lifecycle of the vessel, its digitalization process is not currently deeply investigated. The main focus of research is in the automation of the blasting and painting sub-function, by robot crawlers or automated crane equipment (AMBPR 2017; Sanchez-Gonzalez et al. 2019). However, crawlers are limited to flat surfaces and in the other hand robotic man-lifts, and automated crane equipment are not widely commercially available. The lack of research in this field could be explained by the high complexity of precisely identifying the hull shapes to be used by an automated robot. This could be improved by the recent advances in computer vision and 3d scanning techniques aided with artificial intelligence to process the cloud of points faster and easier.

F.5 Accomodations

Almost no researchers have focussed on the digitalization or automation of the accommodation sub-function. This could be because the main focus of this sub-function is to provide a high-quality perception to the passengers and crew members rather than improving their productivity. However, the potential of 3D technologies and topology optimization has started to be researched, trying to reduce the weight of non-structural walls, and to improve their behaviour for sound and thermal isolation (Nieto et al. 2018). Another good potential exists in the use of AR technologies to verify the accommodations before and during construction with the customers, suppliers, and workers.

F.6 Transporting equipment

There are very few studies about transporting equipment digitalization. The found literature tries to establish infrastructure networks and sensing devices that properly work in open areas to monitor the location and function of big equipment such as cranes, forklifts, man-lifts, and self-propelled transporters (Schulze and Dallasega 2023). Moreover, that information is used to make the analysis of the vehicle fleet with KPI such as the average distance, daily utilization and average cargo weight (Park et al. 2022).

F.7 Project management

Project management is the administrative part of the ship production function. Thus the aim of existing KETs is to enhance the data integration among stakeholders, both internally and externally of the shipyard. This includes designers, suppliers, and production from the shipyard perspective, and customer and classification societies from an external perspective (Schulze and Dallasega 2023). However, this process is hindered by the lack of common standards for exchanging information in the maritime field (Ran and Singh 2016). Another research focus is the integration of the Knowledge Management (KM) system with risk and configuration management RM, CM, for a better administration of complex projects and processes of the shipyard (Cerezo-Narváez et al. 2021). Finally there is an study on the automatic generation of drafts documents based on the requirements, by using AI tools and use of NLP tools to search documents (Cerezo-Narváez et al. 2018).

F.8 Quality assurance

Quality applications are normally included as a purpose of the other technologies. That is why this quality section includes fewer applications itself. However, there are some applications specifically intended to check the quality of the product, such as the monitoring of welding parameters to identify possible failures in quality (Emblemsvåg 2020), the quality data management plan, and its sharing process with the customer (Sanchez-Gonzalez et al. 2019; Emblemsvåg 2020).

F.9 General production work

This category includes applications that do not pertain to any specific ship production sub-function, but are applicable in most of them. It serves as a summary of technologies applicable to shipbuilding. Those include the use of XR technologies to visualize the ship before and during construction, adding layers as the new components to come, or assembly instructions and drawings (Fernández-Caramés and Fraga-Lamas 2023; Schulze and Dallasega 2023). Also, the use of 5G and WiFi6 to improve connectivity in the workshops (Fernandez and Péter Cosma 2021), and tracking data from working teams are collected by sensors and mobile devices to update the actual progress of construction and simulate different scenarios to adapt to unexpected deviations. Finally, it is stated that digital transformation requires a previous and simultaneous organization of production by lean principles in order to mitigate the losses of engineering-to-order ETO companies (Schulze and Dallasega 2023).

5.3.7. G. Ship operation

The technologies analyzed in this function are those with dual purposes for ship operation and shipbuilding. Those are mainly intended to be executed for inspection tasks such as aerial drones (Ortiz et al. 2014), underwater autonomous vessels (Hover et al. 2012; Sanchez-Gonzalez et al. 2019) or crawling robots (Milella et al. 2017; Sanchez-Gonzalez et al. 2019). Additionally, the use of 3d printers on boards can provide a new way of maintenance and repairing approach, where shipyards can play a significant role by providing remote support for this operation (Ziółkowski and Dyl 2020). Finally, other approaches are regarding the selection of materials for ship construction and operation, searching for the lightest and the most suitable for recycling (Noordin and Salleh 2022; Scipioni et al. 2023).

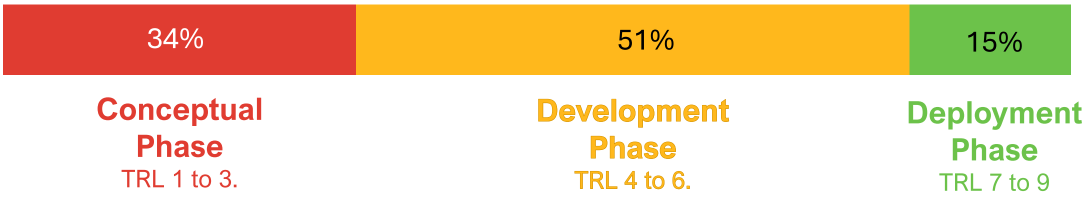

Figure 7. Maturity of digital technologies for Shipbuilding.

5.4. Maturity of technologies

The literature review of 88 digital technologies in shipbuilding revealed significant differences in the maturity levels of these technologies. Each technology was classified based on its maturity using the Technology Readiness Level (TRL) framework. As shown in Figure 7, 34% of these technologies are at the conceptual or research phase (TRL 1 to 3), 51% are in the development phase (TRL 4 to 6), and only 15% have reached the commercial or deployment phase (TRL 7 to 9). This classification was based on available information from diverse sources and additional research by the authors, though some technologies proved challenging to classify precisely. Despite these challenges, this categorization provides a clear picture of the relative readiness of digital technologies in shipbuilding.

A key insight from this analysis is the scarcity of technologies in the commercial phase specifically tailored for shipbuilding, with most still in early functions of development. This limited maturity could be attributed to several factors inherent to shipbuilding. Unlike industries such as automotive or electronics manufacturing, shipbuilding relies on low-volume, engineer-to-order (ETO) projects with unique and non-repetitive processes. These projects involve concurrent engineering and extensive human coordination rather than automation, making data collection and transmission challenging. Additionally, shipbuilding's relatively small market size compared to high-volume manufacturing sectors often attracts less attention from technology providers. Furthermore, large, established shipyards, often referred to as 'mega shipyards,' develop proprietary digital tools and technologies that remain inaccessible to the broader industry. This combination of factors limits the widespread development and application of mature digital technologies, slowing the overall digital transformation of the industry.

5.5. Technologies interrelationship

The analysis of the literature shows that there is a considerable number of research on every KET, but it is mostly focussed on individual technologies. However, virtually all technologies are connected to other ones as prerequisites to enable them, or to enhance their functionalities. For example, in order to effectively integrate digital twin technologies, shipyards must initially invest in connectivity and data acquisition, with the Internet of Things (IoT) serving as a fundamental requirement (Curiel et al. 2023). Additionally, it is advisable to prioritize the implementation of a Model-Based Systems Engineering (MBSE) approach in the ship production process before proceeding with the adoption of digital twin technology (Pang et al. 2021). Those will be examples of a relationship of prerequisite between technologies. Another instance involves the utilization of 3D printing, which can be enhanced through topology optimization processes (Ziółkowski and Dyl 2020). However, it is important to note that while this relationship enhances the technology, it does not constitute a strict prerequisite, as components could be printed with the same shape obtained through traditional manufacturing processes. Furthermore, an additional example of technology enhancement involves the integration of computer vision AI with augmented reality (AR) (Fernández-Caramés and Fraga-Lamas 2023). This facilitates computer image processing to detect faults and improve the capabilities of operators wearing AR devices.

Yet, some authors have developed strategies to facilitate the definition of digitalization paths and the identification of interrelationships between technologies. Hoffman et al. (2023) has highlighted the importance of directing investments towards solutions that benefit the enterprise level instead of solutions that are aimed at impacting a single function or process. Other researchers have expressed the need to consider the interrelationship of administrative and human resources requirements, as not all of the challenges of digital transformation are technical (Sánchez Sotano et al. 2020). Sánchez-Sotano et al. (2020) has developed a Social Network Analysis (SNA) that represents the relationship between technologies, showing that AI, Big Data, IoT, and Cloud Computing are the core ones. However, this network falls short in supporting the determination of investment paths or a roadmap, as the relationships are not yet clearly defined or easily identifiable. In addition, Sanchez-Gonzalez et al. (2019) has made a detailed list of digital technologies for the maritime industry, including ports, shipping, ship design, and shipbuilding, but did not present any relationship between them. Lastly, other studies state that there is a lack of in-depth research on the implementation of digital technologies in shipyards (Kunkera et al. 2022), and the participation of universities is essential in this process (Muñoz and Perez-Fernandez 2021).

The shipbuilding industry needs more organized efforts to speed up its digital transformation and create suitable tools for shipbuilders. This can be achieved by giving shipbuilders better information when developing digital transformation strategies, taking into account technological, economic, and organizational factors in a comprehensive manner.

The above points out both the absence of and the necessity for a more integrated approach in discussing Industry 4.0 (I4.0) in shipbuilding. Building strong connections between initiatives, focussing on specific goals, and understanding their combined impacts are crucial for the shipbuilding industry to fully embrace I4.0 endeavors.

6. Discussion, limitations and further research

In the face of contemporary challenges confronting shipbuilding, there exists a growing determination to elevate the digital maturity of the sector to overcome these obstacles. This study aims to contribute to this progression by helping shipyards to comprehend the challenges of the sector, conducting a comprehensive review of existing technologies, and emphasizing the need to formulate structured digital strategies tailored for implementation by shipbuilders.

A deeper exploration of the industry and its prevailing challenges serves to assist managers and policymakers in directing their efforts effectively throughout the digital transformation. This paper systematically identifies key digital technologies for shipbuilding, emphasizing their specific applications within the shipbuilding production function. It serves as a consolidated informational resource for shipbuilders, facilitating the identification of trends and benefits inherent in each function and ship production sub-function. The research proposes the mapping of technologies and their interrelationships to foster a more holistic understanding of current and desired scenarios, thereby obtaining better outcomes compared to the analysis of individual technologies.

Certain limitations are inherent in this research, primarily attributed to the nature of available information. The study relies on published information, potentially excluding proprietary shipyard-developed roadmaps that may not be publicly accessible or usable by others. Furthermore, numerous technologies originating from major shipyards may not be commercially available to the wider industry. Lastly, the research confines itself to academic sources, acknowledging that additional information is available on the internet and from suppliers. However, such non-academic sources may be less reliable, given the potential for suppliers to manipulate information regarding benefits or risks to suit their interests.

Despite these acknowledged limitations, the anticipated impact of this research lies in its potential contribution to advancing digital transformation within the shipbuilding industry. This study aims to enhance the comprehension of digital transformation requirements for shipyards and academia, offering insights into relevant technologies and their interconnections. The objective is to facilitate the formulation of more informed digital strategy plans.

An area warranting further investigation is the development of comprehensive roadmaps to guide shipyards through their digital transformation endeavors. A roadmap, in this context, functions as a strategic plan delineating the sequential steps a shipyard must undertake to realize its digital transformation objectives and the mapping of technologies according to their benefits and maturity levels. It is crucial to identify the pivotal technologies requiring investment and clarify the intricate relationships among these technologies.

7. Conclusions

In conclusion, shipbuilding stands as a key industry, essential for the growth and progress of nations and regions globally. Despite its historical significance, the shipbuilding sector faces multiple challenges in the present and future landscapes such as high fluctuation in the order book, unstable political environment, labour shortage and uncertain scenarios about the energy transition. However, emerging technologies offer viable solutions to bridge these gaps and bring shipbuilding in line with advancements already adopted in other manufacturing and service industries. The concept of Shipbuilding 4.0 has gained considerable attention in both industry and academia, signalling a collective interest in elevating digitalization within the sector.

Recognizing the potential impact of KETs and gaining a deeper understanding of them can enhance the efficiency of their integration into the shipbuilding functions. Specifically, the focus of research in shipbuilding digitalization has evolved over time, with a primary emphasis on optimization approaches and a predominant investigation into the hull construction sub-function. Despite advancements, onboard sub-functions remain relatively less automated and digitalized because its very high complexity. The current use of Key Enabling Technologies (KET) is broad and varied, but they are typically studied in isolation as separate technologies. This makes it challenging for shipbuilders when it comes to prioritizing their investments.

Moreover, the intricate interconnections among technologies underscore the need for a comprehensive understanding of their relationships and precedence to derive maximum benefit. Notably, the application of KETs in shipbuilding remains immature, with only 15% of applications reaching the deployment phase, while the vast majority are still in conceptual or development stages. Moving forward, the shipbuilding industry must adopt a broader perspective on digital technology development and implement improved evaluation methodologies to create an efficient digitalization roadmap.

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