


Defining Maritime 4.0: Reconciling principles, elements and characteristics to support maritime vessel digitalisation

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Abstract

As complex systems, maritime vessels generate and require the utilization of large amounts of data for maximum efficiency. Designing, developing, and deploying these systems in a digital world requires rethinking how people interact and utilize technology throughout all areas of the industry. With growing interests in Industry 4.0, there are broad opportunities for the incorporation and development of new digital solutions that will support the improvement and optimization of next generation systems. However, while different technologies have been deployed with various levels of success the current challenge is not generating data but being able to harmoniously integrate different data streams into the decision-making process. To support the development of next generation vessels, a comprehensive understanding of Maritime 4.0 is necessary. Current conceptions of 4.0 within the industry remain ambiguous and based on our research, have demonstrated a divergence in the levels of technological maturity and digital solutions in different industry sectors. This study leverages current state-of-the-art literature and a series of interviews to formulate a descriptive definition of Maritime 4.0 that incorporates technologies that can be integrated to support decision-making. Through a rigorous, empirically grounded, and contextually relevant approach, the contribution of this study is the establishment of an organized set of technologies and characteristics related to 4.0 and establishment of a practical definition.

1 | INTRODUCTION

The Maritime industry facilitates trade and commerce through the delivery of valuable raw material, components and finished products [1,2]. While global trade continues to increase, new and emerging technologies have emerged that are changing the way that companies and engineers design, develop, and utilise vessels. In response, European ship builders have focussed on the development of specialized vessels with high-complexity and high- technological content.

In an effort to facilitate and increase the competitiveness of this sector, research into next generation technologies (i.e., fully autonomous vessels) has shown a general need to increase the sectors overall use of digital technologies. Lessons learned from the manufacturing industry have

served as a critical resource for identifying areas of improvement that must be strengthened for the next generation of vessels to be feasible. This includes the incorporation of new technologies, materials and optimization processes into the engineering and design practices of the greater industry [3,4].

Through the integration of reporting and real-time tracking technologies in vessels, the amounts of data being collected over the past 5 years has grown exponentially [5,6]. However, despite this, increase in data collection remains a critical gap in integrating this data into an architecture that will support future needs. This challenge is central to next the phase of vessel development as it will determine how vessels connect and interact with one another, assuring that the quality of the data is useful and relevant in all aspects of the vessel (design,

construction, operation) [7]. Marking one of the largest overall challenges facing the industry due to a lack of clarity relating to 4.0 within the industry, along with a multiplicity of descriptions and terms.

As a first step in addressing this challenge, the relationships between all areas of vessels must be well defined and documented. This requires that usage information and design parameters or component attributes be considered from project conception to data collection, and design alterations, thus allowing for the integration of data into reliable parameters that in turn facilitate the successful inclusion of data streams.

In an attempt to address this, this study presents an initial basis that aims to support the formalization of Maritime 4.0 (M4.0). Based on technical literature, published cases and common figurative usage, this paper introduces a descriptive definition that consolidates principles that reflect the objectives of M4.0. Highlighting critical research areas and presenting current research that has been performed to support the digitalization in maritime development. Owing with respect to Industry 4.0 (I4.0), this article aims to present a descriptive definition that consolidates principles that reflect the objectives of M4.0 [8].

1.1 | Research approach

As digitalization grows in importance as a consideration in design, production and operation of vessels, there is a need to have a well-defined basis for M4.0. To date the incorporation of digital technologies has been largely user driven; however, opportunities for next generation development require integrating technological data streams.

As shown in Figure 1, the characteristics and principles introduced in this study were developed based on the responses from a focus group and series of interviews performed

with industry experts from March 2019 through October 2019, which supplemented current literature and industrial material. The responses were studied based on three areas: (a) context understanding, (b) identification of digitalization challenges and (c) defining the technologies, elements and characteristics of M4.0.

In the first instance, the focus group comprised 13 individuals from six different companies was conducted on ‘4.0’ in the maritime industry. It was found that there is a general lack of consensus regarding what the term means and how it relates to the industry. M4.0 at the time of the interviews was described as

- The management of interconnected systems.
- Digital technologies that support the management and operation of production.
- The configuration of large-scale physical and digital systems.
- Predictive and autonomous solutions that support all areas of a vessel's lifecycle.

These descriptions are similar to the separately defined I4.0. Which raised the research question—‘What is 4.0 in relation to the maritime industry?’

The literature included in this article is based upon the findings of academic publications related to Shipbuilding 4.0, Shipping 4.0, Maritime 4.0 and Shipyard 4.0. Business reports, technical publications and white papers due to the strong demand for digital solutions by customers.

The follow-up practitioner interviews with 23 individuals involved in the maritime industry served not only as a process for confirming the working definition, but also as an opportunity to discuss in greater detail the relationships between different 4.0 technologies in the industry and how they have been implemented as discussed in Section 3. Experts participating in the interviews stressed that no comprehensive definition existed for M4.0, this reinforced that further research was required in order to adequately address the topic. One key problem described was that many times, the digital technologies and solutions implemented were done at the behest of the customer, but that many times they were unsure (or do not know) how this technology will integrate and function with next generation systems. For that reason, an analysis of the industries digital technology maturity level was performed (Section 3.1).

2 | INDUSTRY 4.0 IN CONTEXT

The initial context and basis for I4.0 emerged out of research at MIT in 1999, where the concept for Internet of Things (IoT) was first presented [9]. Since then additional digital technologies have been developed and the German government in 2011 coined the term now representing the fourth industrial revolution. However, I4.0 has been operationalized through different national initiatives around the world, which include ‘Industry 4.0’ in Germany, ‘Industry 2025’ in Switzerland, ‘Smart Manufacturing’ in the USA, ‘Industria 4.0’

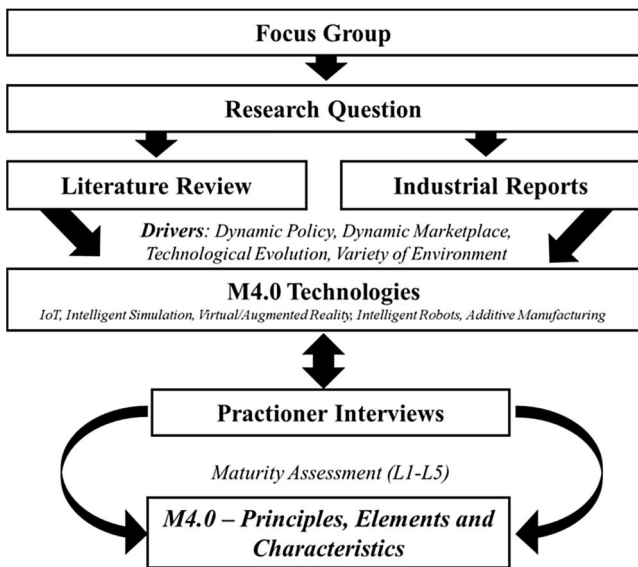


FIGURE 1 Research approach

in Italy, 'Norge 6.0' in Norway, 'Usine du Futur' in France and 'High Value Manufacturing' in the UK. This general variation in the semantics of the concept illustrate that despite possessing common technologies the term has not been consolidated.

Despite these variations in nomenclature, the general census is that I4.0 symbolizes a push to promote advancements in data management, device communication and digitalization through both vertical and horizontal integration. Provided through cyber-physical systems, internet and future-oriented technologies that enhance human-machine interaction paradigms to deliver value-added processes [10–12], which in effect merges historically separate worlds (digital and physical), to create a synergy between operational technologies and information technologies for improved predictability and optimization capabilities [13–15].

This study defines I4.0 according to the core elements and technologies as a collaborative digital end-to-end process (socio-technical) that facilitates vertical and horizontal integrated production. Based on this the following enabling technologies have been identified as being highly relevant [8]:

- **IoT** describes an interconnected global dynamic information network that links heterogeneous physical and virtual objects for the purpose of communication, configuration and actuation [16–18]. This includes consideration and inclusion for sensing, intelligence, communication interoperability, self-configurability and programmability throughout the management and collection of data [19].
- **Robotics and intelligent automation** encompasses rule-based tasks that a machine/robot can be programmed to carry out and perform. The ability to fulfill planned/unplanned operations according to an awareness and understanding of dynamic content, data and business events [20–22].
- **Cloud computing** (CC) is an internet-based computing technique or service that allows for the storage and processing of data or resources according to optimized and structured units connected by IP networks [23–25]. CC provides accessibility to data from outside of the facility through on-demand services that relay a series of multiple, independent logical entities through a series of abstractions and physical resources [26].
- **Additive manufacturing** (AM) is defined by the American Society of Testing and Materials as 'The process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies; Synonyms: 3D printing, additive fabrication, additive process, additive techniques, additive layer manufacturing, layer manufacturing, and freedom fabrication' [27]. Enabling the production of functional parts with complex internal structures and optimized physical properties, reduces transport distances and stock on hand for production of customized accurate and strengthened intricate objects [28–31].
- **Big data analytics** (BDA) refers to the operation and evaluation of data from different sources to support insight

discovery, improved decision making and process optimization according to its 4 Vs (volume, variety, velocity and veracity) [32]. These four dimensions to BDA facilitate real-time data acquisition, transmission, storage and large-scale data-processing mechanisms, which ensure the right information is available for the right purpose at the right time to the right person [22,23,33,34].

- **Intelligent simulation** incorporates AI and other data-driven approaches to deliver an integrated simulation system that consists of both symbolic reasoning systems (expert systems) and numerical computation packages [35,36]. Through this integration, real-time data can be included and analysed in virtual models, so that engineers, operators and managers can test and optimize systems before implementing a physical changeover. This reduces the down time of machines, the setup time, while increasing production quality [37,38].
- **Augmented reality** (AR) supports a variety of services that support human workers respond to rapidly changing production environments, such as selecting parts in a warehouse and sending repair instructions through a networked and connected system [37,39,40].

The technological elements that represent I4.0 provide for and support the mass customization of products, which in turn increases the use of automatic and flexible systems that are better able to facilitate communication between parts, systems and humans. I4.0 facilitates the improvement of products, creation of services and ability to adjust business models for improved communication in the value chain [8].

3 | MARITIME DIGITALIZATION TECHNOLOGIES

Digitalization and the dynamics of the maritime industry are driving a need to rethink how connected systems and IoT can be leveraged to facilitate the next stage in vessel development. As digital technologies continue being developed, M4.0 has become increasingly important to the European maritime industry and represents an opportunity to lead the world in the development of next-generation vessels. Given high dynamic pressures, there is a need for improved efficiency, in design, production and operation, which will allow for companies to design vessels that better meet customer and market requirements.

Concepts for 'digitalized' maritime systems are often referred to as smart or intelligent products depending on the functions delivered. As illustrated in Figure 2, the rise of digitalization can be seen in based on the number of publications as well as quantified by analysing the number of new enabling devices, networks, services and contents that form the backbone of a greater digital architecture.

Based on the literature and the primary market driver for digitalization relates to vessel operations and shipping. Recognizing that the intelligent navigation of vessels has greatly improved through digitalization efforts (i.e., real time tracking and positioning of vessels in transit) there is an

increasing demand by customers for vessels to be more advanced and efficient. These requirements include provisions for collision avoidance, information displays, monitors, alarms, satellite communication, integrated ship management and assisted port manoeuvring.

Today digitalization in shipping is largely linked to cost and capacity optimization, operations and navigation performance management [41,42]. Each of these criteria impacts value beyond the vessel, such as better engagement with customers and more informed decision making, efficient use of transport infrastructure and new operating models, with applications in the following areas [5,43–46]: Innovative transportation, remote operation, maintenance, real-time tracking, route planning, optimization, risk management, equipment monitoring, hull monitoring seafarer training and management (Table 1).

Research into the feasibility of different autonomous systems has been developed to support ports, shipping, vessel management and situational awareness. Where through the integration of different data the system can operate in a predictive and self-managed state to resolve situations in real-time based [44,45,62]. Through the combination of technologies, these vessels aim to improve the safety, resilience and profitability of the maritime industry. Marking a revolutionary shift from the traditional crew manned vessels. This automated system will rely heavily on the incorporation of many different forms of data and the careful integration of technologies. Despite the push for such vessels, there remain issues that must be addressed (in part through M4.0) before they are a viable solution.

3.1 | Vessel design and construction

Historically the ability to utilize past knowledge has allowed for the industry to advance incrementally and remain highly competitive. Yet shifts in customer needs and a growing demand for future proofing has created an environment that challenges engineers, shipbuilders and operators to develop

vessels with increasingly greater complexity. From design, shipbuilding and maintenance, to the optimization of cargo routes the maritime sector is rapidly evolving in response to economic, political, demographic and technological trends. Consequently, the utilization of digital technologies has been identified as an area of improvement that can facilitate the meeting of these challenges in a pre-emptive and responsible manner.

Despite recognizing the value and importance of digital technologies there remains a large gap in how these technologies integrate and will ultimately facilitate the next generation of vessel development. Recognising this, the table below briefly illustrates the levels of digital technology in the industry. The metrics presented are based on an evaluation of the maturity levels of the core 4.0 technologies, which are discussed in detail in the subsequent sections of this paper.

3.1.1 | Vessel design

Maritime vessels are complex engineering systems that are designed through an iterative and multifaceted process, influenced by a number of factors (both internal and external) [63]. Determination of the basic design type is a critical factor when determining the parameters and processes that will be undertaken from conception to delivery. Driven by stakeholder needs and subsequent requirements, designers are expected to develop cost-efficient solutions capable of performing specific tasks, while maintaining strict adherence to both international and national rules and regulations [64]. However, historically vessels are based on existing designs that integrate minor innovative breakthroughs, making the inclusion of digital solutions requested from a customer at best, difficult to integrate. Finding a balance between these restrictions is a challenge for the designer/engineer, system integrator and shipyard, due to the recognition that the vessel will operate for 20+ years, while much of the onboard technology will be outdated in much sooner.

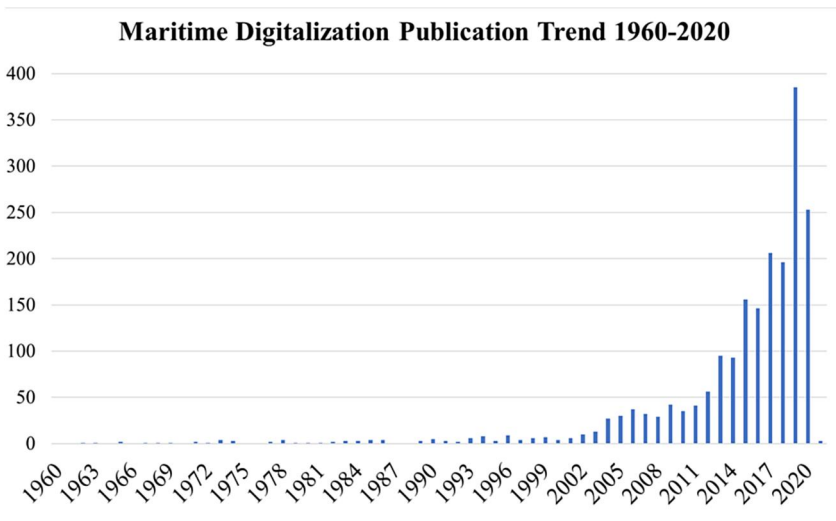


FIGURE 2 Timeline of publications pertaining to maritime digitalization

This approach to development and method of incorporating digital technologies into vessels complicates balancing technical capabilities, with stakeholder (builders, cargo owners, customers, ports operators, classification societies, environmental matters, comfort of the crew/passengers, etc.) expectations. Based on the literature and focus groups, each technology is presented to illustrate the current state and areas of research for future application.

- **IoT:** Based on review of the vessel design approach and subsequent processes, the incorporation of data into the design process from sensors and personal user information (PUI) is limited but represents a growing area of research [65,66]. While the utilization of such data is to this point limited there are several examples of vessels being produced that have utilized incremental improvement for the improvement of fuel efficiency, predictive maintenance and design improvement [66,67].

The incorporation of PUI data is viewed as a quantifiable means for mitigating subjective design decisions, and thereby an IoT solution that can drastically increase performance and vessel value for prospective stakeholders. Despite the acknowledged potential benefits of using PUI and sensor data in the design process, there are challenges that must be considered to insure that relevant, accurate and reliable data is articulated to those involved. Due to the relative newness of integrating data streams into vessel design, decision engineers are confronted with the task of identifying, analysing and incorporating these outcomes into their designs [68]. This challenge when considered in a larger context, connecting IoT, simulation and operation can provide designers with not only data to predict future behaviours but also structural and mechanical data that can be used to optimise the design.

- **Intelligent simulation:** The direct ability to import data from vessels under real-time operating conditions allows for the improvement of CAD and CAE solutions. By combining machine learning into the simulation process engineers have the ability to reduce cost and improve key quality areas of vessels based on data that can only be obtained in operational conditions. According to several researchers this intelligent simulation system goes beyond the traditional virtual prototyping techniques used in vessel design, by allowing for designs to be optimized according to operational and environmental conditions [69–71]. Through increased sensors and IoT devices, vessels can begin to test and optimize the design while significantly reducing the design time [71], which can impact how materials and other design considerations are evaluated.
- **Virtual reality:** Virtual reality refers to an immersive, interactive system that takes place through screens or other platforms [72]. The advancement of virtual reality technologies has reduced the cost for adoption and through the ability to demonstrate complicated scenarios in a virtual environment customer, operators and engineers are able to

interact with the design in a level of detail that provides unparalleled insight to the vessel's functions or layout. Ranging from marketing and design, there have been, since the mid-2000s, efforts in place to integrate this technology in design procedures to support awareness and conformity [73]. Despite utilization, virtual reality remains underutilized, and is expected to shorten the overall design–review–modification process [74].

3.1.2 | Vessel construction

Shipbuilding is an area of the maritime industry that most closely aligns to I4.0 with several shipyards creating plans for implementation, and with higher levels of maturity based on the analysis shown in Table 1. One of the leading initiators in the EU to be investing heavily in digital technology is Navantia in Spain which has begun incorporating robotics, IoT, and AM into their shipbuilding activities [75]. Globally, the competitiveness of the industry has made the shift to 4.0 more important than ever due to it changing the way that operators perform their daily tasks and how materials are stored, processed and ordered. As demonstrated by Navantia, this includes how shipyards handle the integration of machines into the human environment and augmented reality.

- **Intelligent robots:** Traditionally, shipbuilding has been closely related to the processing and conversion of sheet metal into panels, and hulls. Though with diminishing use of steel construction and the development of new materials many new opportunities have emerged for improvement [49,57,71]. Robotics and automated production are promising areas, offering to improve the quality and reliability of vessels.
- **AM:** The construction of maritime vessels is unquestionably an expensive and extensive process, involving many individuals, processes and materials. While the widespread use the AM is still yet to be seen there is an increasing reliance on parts that can be made through this new manufacturing technology. This growing trend is due to roughly 25 years of research that was observed to analyse the viability of the technology. Based on literature and the results of the maturity level assessment, AM appears to be well suited for the maritime industry and will likely be capable of providing large savings in shipbuilding and maintenance [76–78]. AM has for the past 10 years been described as a disruptive technology that promises to have profound implications for the entire supply chain and is viewed within the industry as a technology that will in 10 years become an everyday essential. Fuelled by the rapid development of new technologies and materials, the costs for development continue to decrease which presents an advantageous for shipyards that are working to advance their production capabilities. This will be seen through the ability of AM to replace traditional manufacturing technologies through the elimination of non-value-added stages of production (assembly).

TABLE 1 Digital technology and solution application areas

	Autonomy	IoT	Robotics	Big data	C. Comp.	BlkChn	VR	Intel. Sim.	DPS	Add. Man.
Transportation [45,47]	X									
Operation [44,48]	X	X		X	X				x	
Maintenance [7,48–50]	X		x	X		X	x	x		x
Tracking [44,45,48,51]		X		X	X	X			x	
Routing [51,52]		x		X	X				x	
Optimization [5]		x		X	X			x		
Risk management [4,48,53,54]		x		X	X			x		
Equipment monitoring [55–59]	X	x	x	X	X				x	
Hull analysis [7,45,57]		x		X	X					
Training [56,60]							x			
Management [61]							x			

This supports adoption, competitiveness and facilitates the development of parts that have intelligent properties, including integrated sensors.

- **Intelligent simulation:** The role of CAD/CAE has a long and established roll in vessel development, enhancing the various phases of the design process to assure shorter lead times. In today's environment, facing increasing complexity CAD/CAE and AR are becoming more important than ever. As they can support those involved in the construction process perform tasks such as assembly, context awareness, data visualization and human–machine interface integration. This marks a decided shift in simulation development, from analytical/optimization-oriented models, to integrate models that are recurrently from other decision tools and simulations [37].
- **Augmented reality:** The added value of AR within construction areas allows for individuals to interact with virtual information in a physical environment (expanded details). AR solutions help in the accomplishment of daily tasks by providing added details that improve employee's ability to interact with and diagnosis issues in a physical environment. This technology has also demonstrated the ability to integrate with quality control measures where workers can evaluate work, with evaluations and corrections provided in real time [79].

4 | MATURITY OF MARITIME DIGITALIZATION

Digitalization has spurred and encouraged automation and has urged the development of intelligent systems; however, the technology required is less mature in the maritime industry than other leading industrial sectors.

In an effort to better understand the level of technology maturity within the industry, an evaluation based on the CLIMB (Chaos-low-intermediate-mature-best practice)

TABLE 2 Maritime digitalization technology maturity

Technology	Adoption level		Features		Integration level	
	Des.	Con.	Des.	Con.	Des.	Con.
<i>IoT</i>	L2	L3	L1	L1	L1	L2
<i>Robotics/IA</i>	L1	L3	L1	L2	L1	L2
<i>Cloud Computing</i>	L1	L1	L1	L1	L2	L3
<i>Additive Man.</i>	L1	L2	L1	L3	L2	L4
<i>Big Data Analytic</i>	L1	L1	L2	L2	L1	L3
<i>Intel. Sys.</i>	L2	L2	L1	L2	L2	L4
<i>AR/VR</i>	L2	L3	L2	L4	L2	L3

maturity assessment framework was performed to generate a representative picture of the current situation and the current diffusion of technologies [80–82]. To aim this, the technologies listed in Table 2 derived from Section 3 were analysed to determine their level of maturity. For that 23 individuals were asked to evaluate the technology according to three units based on five levels of maturity:

- (1) the level in which the technology is currently employed/ utilized
- (2) whether the complete features and capabilities of the technology are being utilized
- (3) the level of integration between digital technologies.

For each technology, the questions were scored using a Likert 5-point scale (1, 3, 5, 7, 9), so the respondent could assign a value based on their experiences. The lowest levels scored with 1 correspond to the lowest levels of adoption/ implementation, while the highest level of maturity 9, corresponds to the greatest level. The score for each technology in design and construction was calculated by applying an additive scale validated by the CLIMB methodology (summing the

single scores of the questions describing the area) then normalized in per cent to establish a maturity value [82]. The following formula defines how the score for each generic area (A_i) was calculated:

$$a_i = \frac{\sum_{j=1}^{m_i} q_{ij}}{8 * m_i}$$

Equation (1): CLIMB Maturity Level Formula [82]

where

a_i score corresponding to i th area, expressed in per cent

$i = 1, \dots, 8$, is the indicator for the areas

q_{ij} score of the answer to the question j , i th area

$j=1, \dots, m_i$, indicator for the questions

m_i , number of questions of the i th area

$8 * m_i$, maximum score the area can assume.

The values (A_i) for each of the three units previously detailed were then expressed according to their level of maturity.

- L1: Little planning or operation (0%–20%)
- L2: Limited operation (21%–40%)
- L3: Intermediate operation (41%–60%)
- L4: Systemic operation, fully implemented (61%–80%)
- L5: High maturity and digital alignment (with integration and interoperability) (81–100%)

Des., design; Con., construction.

The level of maturity calculated for each technology in design and construction, presented in Table 2, shows that in several instances there is a difference between the maturity of technologies when comparing design and construction. When comparing the technologies' maturity levels within these two distinct environments, it was found that collectively the construction sector of the industry has adopted digital and advanced technology solutions to a higher level than their design counterparts. These results have facilitated a deeper understanding of the current technologies and provided a clearer picture as to how despite different needs, digital harmony could be possible.

5 | CHALLENGES FACING DIGITALIZATION

The growth and implementation of technologies (Section 4) presents both opportunities and challenges for the industry as vessels are generating increasing amounts of data and are obligated to operate in a competitive and crowded environment (operating space in ports and sea lanes). This will require that vessels utilize and integrate technologies that will be capable of addressing these challenges in both immediate and long-term scenarios. Even though there will always be aspects of the industry that want to do things, the 'old' way—the way we always have done things', there is going to be added pressure for more focussed solutions that can effectively

leverage resources and improve the development process through harmonization of data sources.

The cautious nature of maritime development is one of the most well-regarded aspects of the industry but also presents unique challenges [48]. Due to high costs and limited availability of evidence to prove the viability of many new technologies, there are a number of challenges to overcome in the coming years. This will require a systemic view of the problem and solutions to be developed before the true abilities of digital technologies can be experienced in the industry [7]. Until complete feed-back loops can be built where decisions, technologies and capabilities can be understood, there remains a possibility of short-term decisions can delay the long-term possible gains of digitalization.

Furthermore, if decisions are taken without a complete view of the problem, substituting digital tools for paper-based approaches can increase to the complexity of the problem without producing a long-term value-added solution. The ability of the industry to overcome integration, training, cost, environmental concerns, energy efficiency, safety, security and human-factor challenges, will require extended and continuous research through a more systemic and systematic manner than in the past.

5.1 | Integration

One of the greatest challenges that any complex system must manage is integration. In respect to the maritime industry, this includes the integration of components, systems, technologies and data. Many of the approaches for design and development within the industry rely on experience and proprietary strategies that are not designed to function and operate with other technologies or firms [44,58]. This general lack of openness presents challenges that impact the competitiveness for all areas of the industry and creates a heterogeneity problem when compiling the data generated.

This makes design and production complicated and dependent on robust considerations and decisions. Integration requirements will dramatically affect how vessels and their components are designed, manufactured and operated. Through the ability to remain connected and support real-time data collection, the needs for autonomous vessels are slowly becoming realized [62]. This requires knowledge and evidence, but it has been demonstrated that data types and sources must be considered early in the architecture development and will enable a better, more robust vessel.

5.2 | Training and education

With the rapid development and adoption of technologies there is always a risk that people will fail to fully integrate into their new environment and be able to perform their daily tasks. As data and analytical skills are becoming more demanded, it is increasingly important these skills be taught to employees and personnel currently employed in the industry [56]. This, has in

many industries, been addressed through skill building efforts, trainings and professional development. However, in the maritime industry there remains a challenge due to much of the work and maintenance of vessels being done manually in shipyards across Europe.

With the emergence of autonomous systems and a push for autonomous vessels, there will over the next 10 years an increasing challenge to keep pace with the evolving and sometimes competing technical standards and best practices [60,83]. With respect to crew and vessel operators with decreasing demand for highly experienced personnel on autonomous or semi-autonomous vessels, there will be fewer jobs and opportunities for promotion. This threat to employment is equally true in regard to ports that are pursuing similar technologies. This can present a challenge to efforts if regulations and training efforts are not managed in a manner that keeps the interests of both owners and employees well aligned. In addition, the challenge to train personnel to operate vessels in conflicting areas (ports with autonomous systems operating) [56]. It will be critical in the interim for coordination between manned and unmanned vessels to reduce the probability for accidents in common areas.

5.3 | Cost

To implement and adopt new technologies, there are inherent direct and indirect costs that must be considered. Despite many technologies becoming gradually more affordable over the past several years (IoT, CAD, CAE, VR, AR, AM), there remains limits to what companies can invest into [61]. With increasing reliance on digital technology companies that have been able to invest into these solutions have demonstrated greater resiliency and flexibility to meet changing industrial needs [84]. In the competitive market of today, this ability to reduce vessel development time can be vital to a company's profitability.

Digital technology can be an enabler for growth that supports the next generation of vessels; however, it must be understood as a means to realize possibilities, not an end [85]. When introducing AM technology, there exist barriers for acquiring these pieces of equipment [61]. Despite the potential advantages or capabilities of the technology, companies are rarely capable to solely focus on the monetary value of acquisition, but also the cost of materials, operating cost, maintenance and the training of personnel to manage the system are also introduce barriers for successful technology acquisition.

5.4 | Cyber security

With each new technology that is developed, there are numerous new security challenges that emerge, particularly when there is integration between technologies that were not developed to operate with one another. Consequently with new risks being introduced to systems there is the real possibility

for vulnerabilities to be attacked and compromised [86]. This can include the adjustment of navigation routes, movement of cargo, as well as targeting of safety systems. Based on recent vulnerability studies, areas of operation that can be targeted include [53,86–88]:

- **Security systems** represent any aspect of industry where access is restricted/controlled. This can include access to CCTV feeds, security gates, as well as access to customs or border control areas.
- **Communication systems** with IoT and connected technologies there is a constant upload and download link that, when left unsecure, can provide access to radios, mobile communication, emails, etc.
- **Business systems** include, but not limited to, software systems that manage the operation of business efforts. Through this vulnerability, HR and other business-oriented resources can be exploited.
- **Terminal systems** represent and control the scheduling and management for vessel maintenance.
- **Port systems** within the operation of ports and harbours their automated systems that interact with humans and vessels on a daily basis. This includes cranes that move containers, as well as control gates that can be exploited for smuggling.
- **Navigation systems** include, but not limited to, the manipulation of GPS data, vessel re-routing or any other function that causes the vessel to deviate from its intended course/destination. The ability to target critical areas of the vessel in this manner could lead to collisions or acts of piracy.
- **Operation systems:** The ability to target vessel operating systems through the manipulation of speed, engine, fuel dumps, cargo movement and ballast adjustment. Each of these aspects of the vessel can poise extreme risks to the personnel, the environment and the organization managing the vessel.

5.5 | Regulations

The laws and regulations are models that help organizations and companies to set their business goals. This allows them to create boundaries for projects, depending on the realm of business functions. The system developers and manufacturers must analyse the potential impacts of the system that are constructed (e.g. autonomous vessels [62]) and submit to the government authorities for review and approval to build the system according to the US and European Union Laws [55]. The development and approval of such regulations is a lengthy, time-consuming process. So, while digital technology continues to accelerate at an exponential pace with new opportunities, there generally remains a delay in gaining approval to deploy unprecedented systems.

The laws and regulations shall include the stakeholder security interests like Intellectual Property Rights, Information Assurance, Security Laws, Supply Chain Compliance and

Security Standards. Examples of standards include ISO/IEC 27002, Information Security Standard (2013); Chapter 13 of the Defense Acquisition Guide (DAU, 2010) and the Engineering for Systems Assurance Guide (NDIA, 2008). Apart from the regulatory point of view, it is necessary to understand the rules and regulations that govern systems from a business perspective to better understand how the boundaries are built for the system [62,63].

6 | DEFINING MARITIME 4.0

Recognizing the diverse understanding related to the meaning and understanding of M4.0, within the maritime industry this section addresses the issue by presenting a descriptive view of the concept. The aim of this is to support the integrated development of digital platforms that are capable of extending the lifecycle of vessels and support next generation vessel realization. This is done through the recognition of needs and requirements imposed on vessels (i.e. greater performance, lower ownership cost, increased safety and security and reliability), and acknowledgement of the challenges that must be overcome for autonomy and true digital connectiveness. Based on the results of the interviews conducted with industry practitioners and academics, it was determined that M4.0 refers to [8]

- The automated integration of real data into decision-making.
- The adoption and implementation of connected technologies for design, production and operation.
- Reduction of vessel environmental impact, related to production, operation, disposal (including emissions, underwater noise and material utilization).
- Affordable and sustainable operation.
- Reduction of risk, increasing safety and security.

The desire for 'M4.0' stems from the fact that we are embarking on the next phase of digitalization in the industry, both in reality and perception. This list of eight initial principles reflects the areas of digitalization that are emphasized by practitioners. Based on the size and scope of the principals, it is determined that in respect to next-generation vessels there is a complex and highly connected architecture at work. This section draws from the principals of system architecture development, to merge I4.0 with maritime to create a descriptive definition of M4.0 that can be used to advance and support vessel development.

6.1 | Descriptive view of 4.0

As digitalization grows in importance as a consideration in the development of maritime vessels, there is a need to have a more rigorous and comprehensive definition capable of integrating the needs of different sectors within the industry. From this 4.0 can be defined as the integrated integration of digital technologies, to support the performance of tasks across

sectors within the maritime industry to improve the function, operation and management of vessels during the design, development, construction, and service of vessels. The range of digital technologies, solutions and approaches applied to vessels throughout their lifecycle should be designed to integrate and share data through both active and passive means. The deployment of technologies should be capable of supporting task performances through all areas of operation to support the realization of requirements and functions for next-generation vessels both for the system itself and its environment.

The descriptive representation of M4.0 illustrated in Figure 3 (systems of systems) considers forces and outcomes for achieving digitalization by integrating technology into the entire system of systems architecture. This illustration of the definition presented above considers the target objective, as well as the independent connected systems required to support a comprehensive and integrated digital architecture.

Based on this definition of M4.0, it is apparent that there are similarities between I4.0 and M4.0, particularly in regard to technologies/solutions and integration. However, the differences reside in how each of the technologies interact and intersect with one another across multiple areas of the maritime sector. As I4.0 was initiated to promote and support the next generation of development in the industrial sector according to their needs, M4.0 represents the needs of the industry and for that views the opportunities provided through digitalization to go beyond production and construction efforts.

6.1.1 | Drivers for M4.0

Since the emergence of I4.0 there are several drivers that have affected the growth and interest of the concept. Drivers for M4.0 represent external socio variables that influence the development of the concept of 4.0 within the maritime industry. Based on the results of the focus group, interviews, literature and white papers related four major drivers were identified [53,86–88]:

- *Dynamic policy* represents regulations mandating some aspect of the system (initiative established by Governments). Affected by the market though customer needs, this includes national initiatives such as those being pursued though I4.0 in Section 2. On the basis of the current situation and the present regulatory limitations, there are both national and international laws that must be considered, this includes, but is not limited to, regulations pertaining to system testing. The overarching matters under discussion centre around the classification of vessel types, manning requirements, liability, the exercise of authority, security-oriented control, seamanship competence (IMO-COLREG) and the level of autonomy [45,51,62,89–91]. With regulations being split between national and international bodies, there is a need for harmonious integration of requirements and definitions. At the international level, the Interim Guidelines for Mass Trials (MSC.1/Circ.1604) is the only

Aspects of the industry encouraging/impacting digitalization

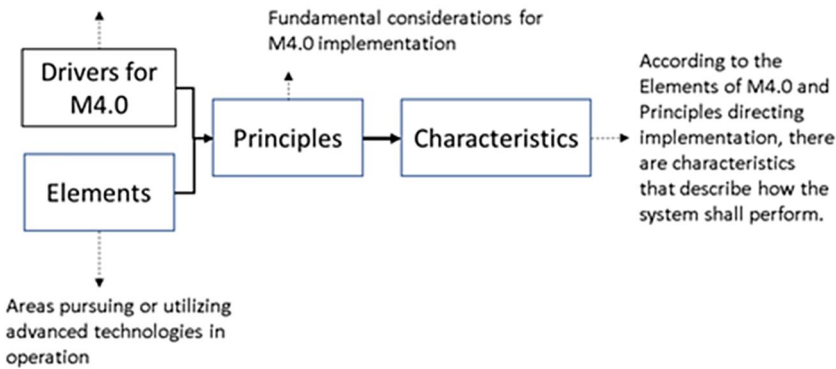


FIGURE 3 Descriptive representation of M4.0

regulation in place specifically developed to address the requirements and development of autonomous vessels [92].

- **Dynamic marketplace:** Market pressures require the development of vessels able to deliver value while maintaining a high level of responsiveness. Businesses must stay ahead of competition during design, construction and operation, while being maintained to satisfy market and customer needs. Similar to other industries competitiveness drives innovation [93]. When considering the market in next-generation vessel demand, there are several criteria to consider: (1) shipbuilding, (2) subsystems and (3) operational context. The shipbuilding industry is highly affected by shipping and service demands around the world. Since the 1940s, Europe has gone from having a market share of nearly 80% to 6% in terms of tonnage and 35% for marine equipment [94]. This shift has pushed European shipyards to focus on their core competencies which are in the area of complex vessel development. The second element for consideration aligns with the first and requires European providers to continually evolve and develop increasingly value-added solutions. Ultimately driven by demand, efficiency, safety and operating cost, vessels are required to compete in a rapidly changing environment [95].
- **Technological evolution:** The ability to meet specific market and customers' needs requires the ability to efficiently change the vessel to accommodate new, novel technologies. Technology influences all aspects of the system and is an enabler for new and advanced systems. Over the course of the past 20 years, extreme changes in the area of technology has occurred [44,47,96]. As demonstrated in diversity of the energy source used to power vessels (fossil fuel, electric, hybrid, hydrogen, solar), adaptations to the hull design, advancement in navigation, as well as autonomous and semi-autonomous system controls. Driven by a demand for increased efficiency and environmental sustainability, new materials and propulsion technologies are being developed to meet the needs of the market and the IMO (regulations for a lower carbon footprint) [97]. This has led to new technological solutions being developed that include advanced rudder and propeller systems (new materials, AM,

etc.), CO₂ emission scrubbers to clean the exhaust from vessels, waste heat recovery and exhaust gas circulation systems, as well as improved pump and water-cooling systems [61,98]. Automated ballast control and navigation technology continues to evolve providing operators/owners with GPS and other real-time tracking systems that help to reduce human error [99,100]. Each of these new advancements increases some aspect of efficiency while subsequently increasing complexity.

- **Variety of environment** indicates the number of embedded systems, integration of diverse technologies or number of operational contexts. The increasing complexity of maritime systems and the technology included within them has made integration increasingly complex due to their being a diverse range of technologies included. Acknowledging the emphasis of complex and specialized vessel development in Europe along with the shifting market needs, these integrate technologies are embedded into all aspects of the system and categorizes them as a system of systems.

6.1.2 | Elements of M4.0

In this context, M4.0 elements represent industry aspects (sectors) that operate together to address and respond to the primary drivers. M4.0 is built around four elements that respond and intersect to create an integrated architecture [8]:

- **Vessel design** reflects the incorporation of data from existing and previous vessels for improvement and optimization of the vessel.
- **Vessel construction:** The process of construction describes production process used to deliver the vessel to the customer, including consideration of the supply chain, manufacturing technologies, representing both time and money, incurred from design to delivery.
- **Operation:** Marine transportation systems, diving operations, ports, dredging and waste disposal. Operation and usage are the actual conditions and behaviours of the vessel, generating and producing data used for decision making

regarding navigation, fuel consumption and operating environment.

- **Service:** Manufacturers, engineering consultant firms in marine electronics and instrumentation, machinery, tele-communications, navigation systems, special-purpose software and decision support tools, research and exploration, and environmental monitoring.

The objective of M4.0 is for the delivery of a high-quality, optimized and reliable vessel that leverages the latest technologies for the maximisation of customer value.

6.1.3 | Principles guiding M4.0

In considering the close link to I4.0, the basic principles discussed in the literature considering interoperability, virtualization, decentralization, real-time capabilities, service orientation and modularity can be extended. By recognizing the elements and drivers of M4.0, shown in Figure 3, it is possible to identify areas of coupling that relate to the four following principles: (1) connected and automated operations, (2) innovation, (3) safety and security and (4) sustainability.

Connected and automated operation: Through a desire for optimised vessels this principle refers to the actual level of digitalization and integration of the vessel. Leveraging data so that it can deliver the greatest value requires not only the information generated by the systems, but also recognition of the industrial business being served. This data-driven approach considers that under the current conditions there are many sensors that can be used to provide and generate many types of data. The challenge therefore is not directly linked to this first stage, the challenge rather is in the ability to understand and develop new sensors and data streams that provide more value to the entire industry.

Innovation: The integration, adoption and inclusion of technology that allow for and support syncritic data. Through consideration of the innovative data solutions, information relating to the vessel can be used to evaluate varying options and iterations for decision-making activities. When considering the necessary processes for data to be integrated from vessels across different elements of M4.0.

- Real-time capability to collect integrated system data.
- Virtualization through AR and intelligent simulations that link real data with virtual models.
- Interoperability provided through cyber-physical systems that allow for humans and machines to communicate with each other.

Safety and security: Determination of the appropriateness of data sources in relation to design parameters and application is critical to maintaining and delivering a reliable and safe vessel through independent and encapsulated systems. The challenge for how to deliver this principle to the vessel requires consideration of how data is utilized and effectively integrated with other data sources. Insuring that the

information being generated and collected is of paramount importance in order for proper decision-making. Failure to meet this can result in a negative value for those involved if the 'context understanding' during data collections is unclear. Integrating and merging the data into viable and manageable virtual systems allows for 4.0 to deliver operational data protection that cannot be tampered or molested, enhancing the vessel as a system.

- **Robustness** is the ability of the vessel to maintain its level and set of specification parameters. Robustness is determined by the sensitivity of chosen system specification parameters to context changes.
- **Resilience** refers to the ability of vessel system to anticipate and prevent adverse events.
- **Redundancy** allows for more constant performance and functionality in the face of potential faults or failures. Redundancy and modularity can be powerful together because it allows a module to be taken away without the system losing a critical function of the vessel. For this, the number of interfaces and secondary functions should be minimized to support the management and articulation of complexity.
- **Survivability** refers to the vessels ability to avoid or withstand a hostile environment (internal/external).

Sustainability: Designers, shipowners and operators have in recent years requested the retrofitting of existing vessels and the development of new energy-efficient vessels with better performance and lower operating costs. Sustainability therefore represents a mechanism that describes value considerations and can be reflected through materials, noise generation or other quantifiable matrices relating to sustainability. The expectations and effects of this principal relates to the continued optimization need to meet the shipowner expectations to have rapidly modernized the fleet with the energy efficiency system solutions on the ship.

6.1.4 | Characteristics

Characteristics are distinguishable features of M4.0 proposed to create realistic operating profiles and to improve the maritime industry. In recognizing the potential value of digitalization and M4.0 regarding vessel systems and stakeholders, vessels must not only meet current needs but also be able to interact with one another so that they can accommodate the needs of tomorrow. A preliminary list of characteristics has been developed from the literature that was, these characteristics seek to illustrate M4.0 systems in a pragmatic manner.

- The vessel shall operate with or interact with some autonomous decision-making process, while generating data relevant to a common basic set of attributes.
- The vessel has stable core functionality but aims to be optimized through secondary functions.
- The vessel has a long lifecycle.

- The M4.0 architecture and vessel are subject to a dynamic marketplace with strong competition.

7 | CONCLUDING REMARKS

Managing large amount of data is increasingly seen as a competitive advantage for companies and is viewed as a principal way to deliver and provide for autonomous operations in all elements of the industry. The demand for increasingly complex vessels will continue to push engineers and shipbuilders to incorporate real time into intelligent simulations through the utilization of IoT and Big Data to support decision-making. It is inevitable that some form of autonomous vessels will emerge on the market, providing superior capabilities, and is thus critical that European Shipyards implement forward planning capable of meeting this inevitability.

Ultimately, M4.0 is an integrated system of systems concept that requires the utilization of innovative technologies for the development of sustainable, secure and connected vessels. By bringing together not only the technologies and elements of it is possible to harmoniously synchronize efforts for industry improvement. Therefore, vessel systems and their architectures must be capable of changing and planning for this by developing new connected technologies that transcend I4.0.

Although a wide range of benefits have been achieved through the inclusion of digital technologies, there remain issues yet to be identified and addressed. The definition of M4.0 discussed in this article provides a basis for conversation about the aspects, elements and characteristics that represent a new paradigm for maritime systems. The principles and characteristics introduced in this paper are not considered to be comprehensive, as more are certain to be identified as the research area matures. Additionally, case studies (physical and digital) will be required to ensure the completeness and applicability of the proposed M4.0 definition. Relationships, amongst the different sectors within the industry utilizing digital technologies will be required, to leverage capabilities, and principles, as to date this has only been identified at a very high level and will require further research.

7.1 | What lies ahead?

Even though I4.0 and M4.0 utilize 'similar technologies', the value potential will only be realized when the maturity level and competencies of the industry have increased. A key question to be answered is can the different technologies and data streams from the various sectors of the industry be integrated and if so, how much data is good or needed. Therefore, future research should focus on advancing our knowledge in two critical areas:

- (1) The identification and development of competencies to support the realization of digital technology adoption in the maritime industry. This could be guided by the following questions:
 - a. What competencies are required to support digitalization in the maritime industry?
 - b. What measurable benefits could these competencies offer?
- (2) The integration of data streams from different sectors in the maritime industry to support advanced decision-making in a business environment.

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