Industry 4.0 in support of shipbuilding manufacturing – Current state of the art, technological enablers, challenges, and opportunities

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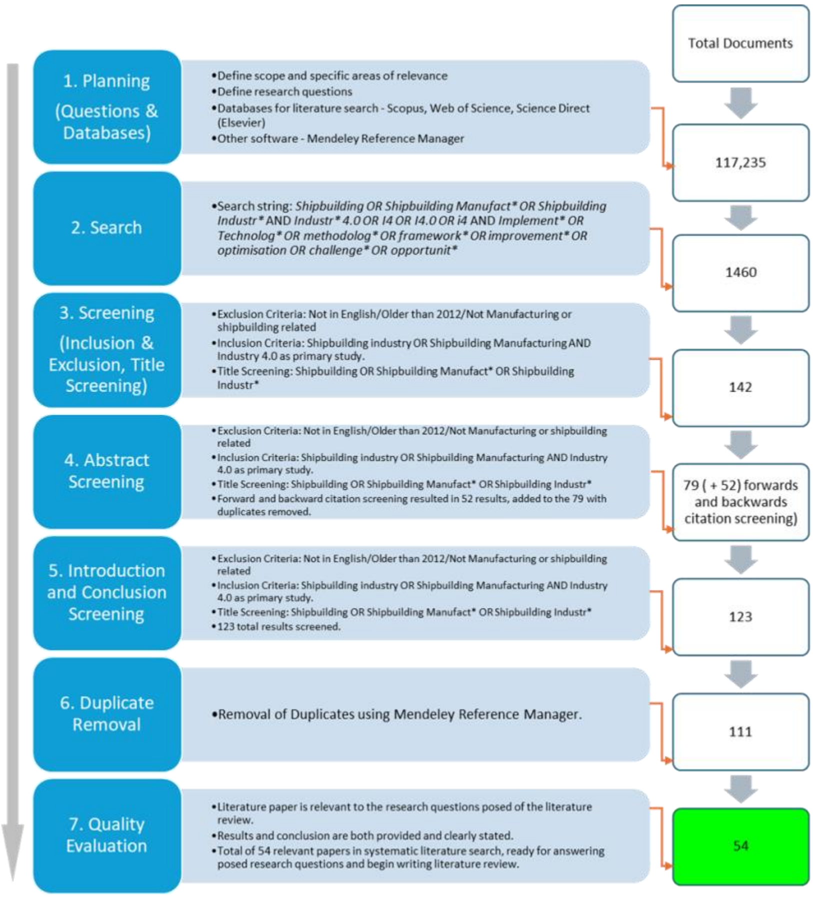

Highlights:

- Conducts the first systematic literature review focusing on Industry 4.0 implementation in shipbuilding manufacturing.
- Identifies key enablers such as digital twins, IoT, automation and data analytics.
- Highlights challenges including workforce readiness, cost, interoperability, and regulatory compliance.
- Proposes a structured research framework to guide future empirical studies in shipbuilding digitalisation.
- Offers theoretical and managerial insights to support transformation strategies in maritime sectors.

Title: Industry 4.0 in support of shipbuilding manufacturing – Current state of the art, technological enablers, challenges, and opportunities

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One Sentence Summary:

This study systematically reviews Industry 4.0 technologies in shipbuilding, identifying key enablers, challenges, and research gaps to support digital transformation in the maritime manufacturing sector.

Keywords:

Industry 4.0; Shipbuilding; Digital Transformation; IoT; Digital Twin; Systematic Literature Review; Maritime Manufacturing

Abstract:

This study conducts a systematic literature review to explore the implementation of Industry 4.0 principles in the shipbuilding industry. It identifies current levels of digitalisation and automation, the technologies and methodologies employed, and the opportunities for optimisation through Industry 4.0. The review reveals significant gaps in comprehensive studies addressing the unique complexities of shipbuilding and highlights the need for tailored approaches to integrate advanced technologies. By synthesising existing research, this study provides a foundation for future empirical research and practical applications in digital transformation within the shipbuilding industry.

Purpose:

The purpose of this study is to investigate the potential of Industry 4.0 technologies to enhance the shipbuilding industry, identify the specific challenges in adopting these technologies, and propose a tailored framework for effective implementation.

Design/methodology/approach:

This research employs a systematic literature review methodology, rigorously analysing scholarly articles, journals, conference papers, dissertations, theses, and other relevant materials. The review identifies key technological components such as the Internet of Things (IoT), robotics, digital twins, and cloud computing, and their applications in shipbuilding processes. The study systematically categorises and evaluates the existing research to provide a comprehensive understanding of the state of digital transformation in the shipbuilding industry.

Findings:

The review finds that while Industry 4.0 technologies offer substantial potential for enhancing efficiency, productivity, and maintenance practices in shipbuilding, the industry's unique complexities require tailored implementation strategies. The study highlights significant gaps in current research, particularly the lack of comprehensive studies addressing the multifaceted nature of shipbuilding projects, which involve bespoke designs, multidisciplinary coordination, and stringent regulatory requirements.

Research limitations/implications:

The primary limitation of this study is its reliance on existing literature, which may not fully capture the latest technological advancements or emerging trends in the shipbuilding industry. Future research should focus on empirical studies and real-world applications to validate and refine the insights gained from the literature review. Additionally, evolving regulatory landscapes and technological innovations should be continuously monitored to keep the research relevant.

Originality/Value:

This study contributes to the academic discourse by synthesising existing research on Industry 4.0 in the shipbuilding industry and identifying critical gaps and opportunities for future research. It provides valuable insights for industry stakeholders, guiding them in navigating the complexities of digital transformation and highlighting the need for tailored approaches to leverage Industry 4.0 technologies effectively.

1. Introduction

1.1 Shipbuilding Industry

In the vast expanse of maritime industries, shipbuilding stands as a cornerstone, driving economic growth, facilitating global trade, and shaping naval superiority for countries across the globe. Over centuries, shipbuilding has evolved from rudimentary craft to intricate engineering marvels, propelled by advancements in materials, manufacturing processes, and technology. At the heart of this evolution lies the complicated relationship between tradition and innovation, where centuries-old techniques intersect with cutting-edge methodologies to produce vessels of high sophistication and complexity, whether that be for military, commercial or private use. Shipbuilding is an intricate process, with a multitude of disciplines with specialisms in project management, engineering, supply chain and procurement amongst others, working across various geographical locations over a significant period of time, usually years. Each vessel constructed can cost in excess of hundreds of millions to manufacture (Ang et al., 2016), adapting to continuously changing economic, political, and environmental landscapes over its long manufacturing product lifecycle, whilst simultaneously complying with numerous quality and environmental regulatory requirements.

Shipbuilding, with its roots tracing back thousands of years, has seen a dynamic evolution in design and construction techniques over the centuries (Walker, 2010). This study focuses on modern shipbuilding practices since the turn of the millennium, placing special emphasis on advancements following 2012 with the introduction of the 'I4.0' movement. The naval shipbuilding industry is typically characterised by complex manufacturing processes, involving high-mix low-volume manufacturing (Cil et al., 2021). To answer the question of what is the current state of Naval Shipbuilding today, and more specifically: 'What is the current level of digitalisation and automation in Shipbuilding Manufacturing Processes?'; 'What are the existing technologies and methodologies employed in shipbuilding operations?'; and 'Where are the opportunities for optimisation and improvement through the integration of I4.0 technologies?' the following sections will place particular emphasis on Naval shipbuilding within the United Kingdom (UK) and its current manufacturing lifecycle and challenges associated.

Defence expenditure in the UK has witnessed a consistent decline throughout the 20th Century, with His Majesty's (HM) Treasury releasing showing that "in 2021, the UK's defence spending as a share of Gross Domestic Product was estimated to have been 2.3 percent. Since 1980, the UK's defence spending was at its highest in 1984 when 5.5 percent of the UK's GDP was spent on the military. After 1984, defence spending declined gradually, and then at a much faster pace after the end of the Cold War in 1991, with the United Kingdom only just reaching the two percent benchmark set by NATO by 2018" (GOV.UK & Statista Inc, 2022). In 1980, defence expenditure was at 4.3% of GDP. The early 1980s saw an upward trend, reaching a peak of 5.5% in 1982, corresponding with increased spending during the Falklands War. Following this peak, there was a gradual decline throughout the 1980s, with a notable drop to 4.3% in 1989. The downward trend continued into the 1990s, with a significant reduction in defence spending after the end of the Cold War, decreasing from 4.1% in 1990 to 2.5% in 1999. During the 2000s, the percentage remained relatively stable, hovering around 2.5%. The 2010s witnessed a further gradual decline in defence expenditure, reaching a low of 2.0% of GDP in 2016. However, from 2017 onwards, there was a slight increase, culminating at 2.3% in 2021.

This has contributed to the reduction in vessel output, with the “Total Number of Naval Vessels Delivered from UK Yards by Decade, 1890 to 2010” decreasing as discussed by Stott (2023). They write that in the 1890s and 1900s, there were high outputs of around 350-370 vessels. This trend continued until a notable drop in the 1920s to about 150 vessels. Deliveries surged again in the 1930s and remained high through the 1940s and 1950s, peaking at approximately 350 vessels per decade. The 1960s saw a decline to around 200 vessels, which continued in the 1970s (150 vessels) and plummeted in the 1980s (below 100 vessels). This downward trend persisted through the 1990s and 2000s, with deliveries falling to about 50 and 30 vessels, respectively, reflecting reduced defence spending and changing priorities.

However, naval shipbuilding in the UK reached a critical juncture in its extensive history with the introduction of the “National Shipbuilding Strategy” (NSS) by the UK Ministry of Defence (MOD) in 2017, as noted by (Stott, 2023) This strategic initiative underscores the imperative for the UK to uphold and reinforce its capacity to construct sophisticated warships. Central to the NSS is the objective evaluation of pathways to effectively realise this goal. Notably, the UK Naval Shipbuilding sector is predominantly represented by a single major entity, BAE Systems Maritime, a subsidiary of BAE Systems involving sectors of Naval Ship and Maritime Services.

In 2015, BAE Systems secured one of the largest Naval Shipbuilding contracts to date, valued at £860 million (Oxford Economics, 2015). The contract was for the production of the Type 26 Global Combat Ship (GCS), designed to replace the longstanding Type 22 and Type 23 frigates that have served over the past two decades (The Global Combat Ship Programmes (Type 26 Frigate, Hunter Class Frigate, Canadian Surface), 2021) The T26 GCS has been selected not only by the UK but also by Australia and Canada, forming a tri-country alliance aimed at bolstering naval superiority and shipbuilding capabilities over the next 25 years (The Global Combat Ship Programmes (Type 26 Frigate, Hunter Class Frigate, Canadian Surface), 2021).

A projection for 2021 estimated that the "direct and indirect quantifiable value-added of the national shipbuilding industry for the Royal Navy would contribute at least £1.5 billion annually to the UK economy, creating up to 25,000 jobs" (Stott, 2023) In 2013, the GDP contribution towards the UK economy of BAE Systems alone was worth over £7.9 billion, with over 122,000 full-time jobs supported (Oxford Economics, 2015). This figure has since been updated, with a 2023 report from Oxford Economics revealing that in 2022, the UK GDP contribution by BAE Systems was up to a staggering £11.1 billion, sustaining 132,000 full-time jobs (Oxford Economics, 2023).

1.2 Industry 4.0

The idea presented by the German government in 2011 at the Hanover Fair known as "Industrie 4.0", i.e., Industry 4.0 (I4.0), focuses on the fourth industrial revolution, to revolutionise how products are built and manufactured (Ang et al., 2016). This new phase in the evolution of industry marks a critical juncture in the advancement of manufacturing, characterised by the incorporation of advanced digital technologies into industrial processes. Driven by interconnected cyber-physical systems, data analytics, artificial intelligence (AI), additive manufacturing, digital twin, IoT and more, this model shift holds transformative potential for a multitude of industries, in particular shipbuilding manufacturing industries.

The shipbuilding industry, characterised by its complexity and bespoke nature, stands to benefit significantly from I4.0 technologies. The integration of the Industrial Internet of Things (IIoT) allows for the seamless connection of devices and systems, facilitating real-time data collection and analysis. This connectivity supports predictive maintenance, optimises resource allocation, and enhances decision-making processes (Ang et al., 2016). Digital twins, which create virtual replicas of physical assets, enable detailed simulations and testing, thereby reducing the risk and cost associated with prototype development and maintenance. Studies on IoT in shipbuilding industries are however limited as discussed by Cil et al. (2021).

One of the fundamental features of I4.0 is the implementation of smart manufacturing, which relies heavily on data-driven decision-making processes. Big data analytics, or business informatics (Ang et al., 2016) plays a crucial role in this context, enabling manufacturers to process and analyse vast amounts of data generated from various sources such as sensors, machines, and production systems (Lee et al., 2015). By extracting valuable insights from this data, companies can optimise their operations, predict maintenance needs, and improve overall efficiency.

Another significant component of I4.0 is cloud computing, which provides infrastructure for storing and processing large datasets. Cloud platforms offer scalable and flexible solutions for managing data and running complex analytics. They also facilitate real-time collaboration and information sharing across different locations, thereby enhancing supply chain integration and coordination (Ang et al., 2016; Geissbauer et al., 2016). Integral to I4.0 advancements are also Artificial intelligence (AI) and machine learning algorithms, which enable continuous learning in systems through the use of data in order to improve their performance over time. These technologies support predictive maintenance, quality control, and adaptive production processes. For instance, Soori et al. (2024) write how "AI can identify patterns and anomalies in production data", allowing for early detection of potential issues and reducing downtime.

Advanced robotics and automation are also key drivers of I4.0, transforming traditional manufacturing processes. Robots equipped with sensors and AI capabilities can perform complex tasks with high precision and adaptability. Collaborative robots, or cobots, work alongside human operators, enhancing productivity and safety in the workplace (Zacharaki et al., 2022). The integration of these technologies not only improves operating efficiency but also facilitates the development of new business models and services. For example, manufacturers can offer predictive maintenance services, remote monitoring, and performance optimisation based on data insights. This shift towards a more service-oriented approach can create additional value for customers and open up new revenue streams.

1.3 Aim of the Study

This paper aims to critically investigate the strategic integration of Industry 4.0 (I4.0) technologies within shipbuilding manufacturing processes to enhance efficiency, quality, and global competitiveness. The primary research question is: *How can shipbuilding manufacturers effectively adopt and implement Industry 4.0 technologies to optimise production processes and sustain competitiveness in an increasingly digitalised environment?*

1.3.1 Methodology

The research adopts a structured literature review methodology, systematically analysing academic studies, industrial reports, and case studies relevant to I4.0 applications in manufacturing, with a specific focus on the shipbuilding sector. Key enabling technologies—including the Internet of Things (IoT), robotics, digital twins, and cloud computing—are critically evaluated in terms of their integration challenges, operational benefits, and strategic implications. The study further considers broader factors such as workforce reskilling, regulatory compliance, and supply chain digitalisation to present a comprehensive analysis.

1.3.2 Key Contributions

This study makes three significant contributions. First, it offers a structured framework for understanding the technological, organisational, and strategic dimensions of I4.0 adoption in shipbuilding, addressing a notable gap in current scholarship. Second, it identifies and categorises the key digital technologies most relevant to the sector, proposing pathways for their integration into existing shipbuilding workflows. Third, it discusses the socio-technical implications of digital transformation, including workforce development and regulatory adaptation, thereby extending the discourse beyond purely technological considerations.

By providing a holistic, strategic perspective on I4.0 adoption, this paper supports both academic research and industry practice, offering stakeholders practical insights into managing digital transformation within the complexities of shipbuilding operations.

1.3.3 Structure of the Paper

The remainder of the paper is structured as follows: Section 2 reviews the theoretical foundations of Industry 4.0 and its evolution in manufacturing industries. Section 3 examines the current state of shipbuilding manufacturing and its unique challenges. Section 4 analyses key I4.0 technologies and their potential applications within shipbuilding processes. Section 5 explores broader organisational and regulatory implications associated with digital transformation. Section 6 synthesises the findings into a strategic integration framework. Finally, Section 7 concludes the paper, highlighting key findings and suggesting directions for future research.

2. Systematic Literature Review

In this section of the review, the methodology of literature is outlined. A structured approach is employed to filter the relevant scholarly articles and information, ensuring the selection of those most appropriate to the subject matter. This refined method of extraction is inspired by similar methodologies outlined in "Augmented Reality in Support of Intelligent Manufacturing – a Systematic Literature Review" (Egger and Masood, 2019), "Producing a Systematic Review" (Denyer and Tranfield, 2009), "Guidance on Conducting a Systematic Literature Review" (Xiao and Watson, 2019), and "How-to Conduct a Systematic Literature review: a Quick Guide for Computer Science Research" (Carrera-Rivera et al., 2022). This involves a 9-step process to extract the most relevant information. Figure 1 highlights the steps and outcomes of each individual step or phase.

A successful systematic literature review (SLR) comprises three fundamental stages: Planning, Conducting, and Reporting (Xiao and Watson, 2019). These stages encompass various sub-steps, commencing with the planning phase of the review. The primary objective of a literature review is to explore scholarly articles and key texts, driven by the identified need or purpose of the review. This involves formulating specific Review questions, developing a structured framework for evaluating existing literature, and identifying gaps in knowledge (Xiao and Watson, 2019). It entails a methodical approach that involves locating relevant studies, selecting, and appraising contributions, analysing, and synthesising data, and presenting the findings to draw clear conclusions about "what is known and what remains unknown" (Denyer and Tranfield, 2009).

Egger and Masood (2019) propose a comprehensive seven-step methodology for conducting an SLR, which includes Planning, Search, Title & Abstract Screening, Introduction & Conclusion Screening, Evaluation, Extraction, and Writing. Carrera-Rivera et al. (2022) suggest a checklist for systematic literature review (SLR) implementation, dividing the review process into Planning and Conducting stages, each with multiple sub-steps. The following review will comprise of an amalgamation of the aforementioned structures, namely a 7-step process comprising: Planning (Questions & Databases), Search, Screening (Inclusion & Exclusion and Title Screening), Abstract Screening, Introduction and Conclusion Screening, Duplicate Removal, and Quality Evaluation.

Figure 1: Research methodology for systematic literature search with results obtained through each step visualised.

2.1 Systematic Literature Review Methodology

2.1.1 Planning (Questions & Databases)

The systematic literature review began with defining specific areas of focus, selecting databases, and formulating precise review questions (RQ). Exclusion criteria were based on these questions, structured to explore existing research and divided into sub-questions for clarity.

RQ1: Current State Analysis

- **What is the current state of shipbuilding and its manufacturing processes, including the production lifecycle, and identify optimisation opportunities through Industry 4.0 technologies?**

The aim was to comprehensively assess the current state of shipbuilding and their manufacturing processes, investigate the manufacturing/production lifecycle of shipbuilding, and identify opportunities for optimisation and improvement through the integration of I4.0 technologies, while addressing the current challenges in the shipbuilding industry.

RQ2: Technological Enablers

- **What are the core Industry 4.0 technologies, their application in shipbuilding, and their impact on efficiency, quality, and innovation?**

Following RQ1, the objective of this review question was to identify the core technologies associated with I4.0, such as, and not limited to, the Internet of Things (IoT), artificial intelligence (AI), cobotics, digital twins, additive manufacturing, and cyber-physical systems (CPS) to name a few examples. This was to better understand how each of these technologies can be applied within the context of shipbuilding manufacturing processes, filling the gaps potentially identified in Q1.

RQ3: Challenges and Opportunities

- **What are the primary challenges and barriers to Industry 4.0 adoption in shipbuilding and to identify opportunities and gaps for enhancing efficiency, quality, flexibility, and innovation through these technologies**

After addressing RQ1 and RQ2, the expectation was to acquire a comprehensive understanding of the shipbuilding manufacturing process alongside I4.0 principles and technologies. Subsequently, an examination of the potential challenges and opportunities associated with integrating I4.0 within the shipbuilding manufacturing environment was anticipated. Thus, the primary aim of this inquiry was to pinpoint the obstacles and hurdles in implementing I4.0 in shipbuilding manufacturing, encompassing factors such as cost, workforce readiness, data security, and interoperability. Moreover, the objective was to investigate the potential gaps in implementation of I4.0.

There are a number of sources that can be used to find literature, such as: (1) Electronic databases; (2) Forward Searching; and (3) Backward Searching (Xiao and Watson, 2019). The following databases were identified for use in conducting the literature review:

- Scopus
- Science Direct
- Web Of Science
- ProQuest

Google Scholar was used solely for an initial cursory literature review and finding grey literature such as conference proceedings and theses. It will not be referenced further unless relevant. Initial searches yielded 16,500 results from databases like Scopus and Web of Science. These databases were chosen for their extensive coverage of scholarly literature across various disciplines, offering peer-reviewed articles, conference proceedings, and other academic resources. Their advanced search capabilities and citation analysis tools enable efficient identification of relevant studies, citation patterns, and literature impact. Scopus, Web of Science, Science Direct, and ProQuest are thus highly valued for SLR's, providing a comprehensive exploration of relevant literature. Mendeley Reference Manager was used for data analysis and extraction.

2.1.2 Search (Strings)

To initiate the systematic literature review (SLR), the first step involved creating targeted search strings for the databases. These strings were developed based on the review questions and insights from initial evaluation of literature on Shipbuilding Manufacturing and Industry 4.0 (I4.0) implementation. The initial search strings were:

For RQ1: Current State Analysis

1. "(digitalisation OR digitisation) AND (current state) AND (shipbuilding OR shipbuilding manufacturing)"
2. "(technologies OR methodologies) AND (shipbuilding OR shipbuilding operations) AND (lifecycle OR production)"
3. "(opportunities OR potential) AND optimisation AND improvement AND (integration OR implementation) AND (I4.0 OR I4.0) AND (shipbuilding OR shipbuilding manufacturing)"

For RQ2: Technological Enablers

1. "(core technologies OR key technologies) AND (I4.0 OR I4.0) AND (shipbuilding OR shipbuilding manufactur*)"
2. "(efficiency OR quality OR innovation) AND (contribution OR impact) AND (core technologies OR key technologies) AND (I4.0 OR I4.0) AND (shipbuilding OR shipbuilding processes)"

For RQ3: Challenges and Opportunities

1. "(challenges OR barriers) AND (adoption OR implementation) AND (I4 OR Industry 4.0) AND (shipbuilding OR shipbuilding manufacturing)"

2. "(opportunities OR potential) AND (gap* OR method* OR flexibility OR innovation) AND (Industry 4.0 OR I4.0) AND (shipbuilding OR shipbuilding manufacturing)"

From this, the search strings were further refined to:

Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr*

AND

Industr* 4.0 OR I4 OR I4.0 OR i4

AND

Implement* OR Technolog* OR methodolog* OR framework* OR improvement* OR optimisation OR challenge* OR opportunit*

This refinement ensured inclusion of both core topics—Shipbuilding and I4.0—and addressed sub-topics related to challenges, gaps, and improvements in methodologies or frameworks..

2.1.3 Screening (Inclusions & Exclusions, Title Screening)

Not in English

- Non-English papers were excluded to ensure accuracy, as the author is proficient only in English. While "Industry 4.0" originated at the Hanover Fair in 2011 as 'Industrie 4.0' (Drath & Horch, 2014) in Germany, English literature is sufficiently comprehensive.

Older than 2012

- Literature before 2012 was excluded, as the I4.0 initiative began in 2011, and earlier studies may not be relevant due to technological advancements since then.

Not related to manufacturing or shipbuilding

- Only papers relevant to the shipbuilding manufacturing industry were included, excluding those related to shipping, ports, and logistics.

Inclusion criteria focused on primary studies related to I4.0 and its implementation in shipbuilding or manufacturing. Search strings were adjusted for each database; for instance, Science Direct does not support Boolean operators. Detailed search filters for each database are provided in Table 1 below.

.

Table 1: Initial Databases and Search String Refinement

Database	With Search Strings	With Filters	Further Refinement	Details of Further Refinement
ProQuest	115,549	468	74	With filters after removal of Dissertations & Theses: 74 results. Source type: Conference papers and proceedings, Scholarly journals. Document type: Conference Paper, Literature Review, Report, Research Topic, Review. Language: English. Title screening: Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr*
Scopus	1814	456	1	Source type: Conference papers and proceedings, Scholarly journals. Document type: Conference Paper, Literature Review, Report, Research Topic, Review. Year: 2012-2024 Language: English. Further refinement: Search within article title (Shipbuilding, AND manufacturing, OR shipbuilding AND industry) AND (industry 4.0)
Web of Science	100	33	26	With filters using title screening: Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr* Document type: Article or Review Article or Data Set. Language: English. Keyword: Shipbuilding, Shipbuilding Industry, Manufacture, Manufacturing, Industry 4.0
Science Direct	1586	959	42	Filtered with review articles, research articles, conference abstracts, from 2012 to 2024: 959 results. Further filtered with title screening: Shipbuilding OR Shipbuilding Manufacturing OR Shipbuilding Industry: 42 results.

This search, conducted on 27th March 2024, yielded a total of 142 results from three databases, including conference papers, literature reviews, reports, articles, and similar studies. Title screening (Shipbuilding Manufact* OR Shipbuilding Industr*) was used to narrow down the results. The next step is to conduct abstract screening, and review the introduction, conclusion, and forward/backward citations.

2.1.4 Abstract Screening

Further refinement of the papers was carried out by screening each abstract, applying the same inclusion and exclusion criteria as before. This time, the search included specific filters to ensure the primary focus was on Industry 4.0 implementation or research related to the shipbuilding industry:

(Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr*) AND (***Industr* 4.0 OR I4 OR I4.0 OR i4)***

This process yielded 79 unique results, as shown in Table 2.

2.1.5 Introduction and Conclusion Screening

In this phase, the same criteria were applied, examining each paper's introduction and conclusions for deeper insights. Using Mendeley Reference Manager, duplicates, book reviews, and articles within books were excluded. Relevant literature not meeting all quality criteria was included, acknowledging systematic search limitations Egger & Masood (2020). Forward and backward citation screening added 52 results not found initially, totalling 123 unique papers after duplicate removal.

2.1.6 Quality Evaluation (Review Full Text)

At this stage of the process, the literature papers were examined based on their quality, with the criteria for this modelled off the inclusion and exclusion criteria used in previous steps. The main quality criteria used were:

- Literature paper is relevant to the review questions posed of the literature review.
- Results and conclusion are both provided and clearly stated.

Table 2 highlights the results of the quality evaluation, giving 54 unique papers.

As a result of this filtration, 79 relevant papers were identified, with 52 sourced from forward and backward citation screening. After removing duplicates from an initial count of 123 papers, 54 unique papers remained. These papers were used for the literature review.

Table 2: The results of the SLR with 54 unique literature papers found.

<table>
<tr><th>Database</th><th>Search Strings</th><th colspan="2">Abstract</th><th>Forward/Backward Citation Screening</th><th>Remove Duplicates</th><th>Introduction and Conclusion</th><th>Quality</th><th>Search Strings Used</th></tr>
<tr><td>ProQuest</td><td>74</td><td>29</td><td rowspan="4">79</td><td rowspan="4">79 + (52) = 131</td><td rowspan="4">123</td><td rowspan="4">111</td><td rowspan="4">54</td><td rowspan="4">Depending on database use, different alterations or variations to the search strings were performed. For example, for Web of Science: (((TI=(Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr*)) AND ALL=(Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr* AND Industr* 4.0 OR I4.0 OR I4 OR i4 AND Implement* OR Technolog* OR methodolog* OR lifecycle OR production OR framework* OR improvement* OR optimisation OR challenge* OR opportunit*)) AND AB=(Shipbuilding OR Shipbuilding Manufact* OR Shipbuilding Industr*)) AND AB=(Industr* 4.0 OR I4 OR I4.0 OR i4)</td></tr>
<tr><td>Web of Science</td><td>26</td><td>25</td></tr>
<tr><td>Scopus</td><td>1</td><td>0</td></tr>
<tr><td>Science Direct (Elsevier)</td><td>42</td><td>25</td></tr>
</table>

2.2 Shipbuilding

2.2.1 Ship Manufacturing Lifecycle

The shipbuilding manufacturing life cycle includes several key stages, each representing a crucial milestone in creating a technologically advanced vessel. This complex process requires multiple disciplines and specialisations to design, construct, and deliver what is effectively a floating city. Despite variations in company, ship type (commercial or naval), or location, the production of ships typically follows a similar trajectory with ***Figure 2*** and ***Figure 3*** (Spoehr et al., 2021) highlighting a typical lifecycle for shipbuilding.

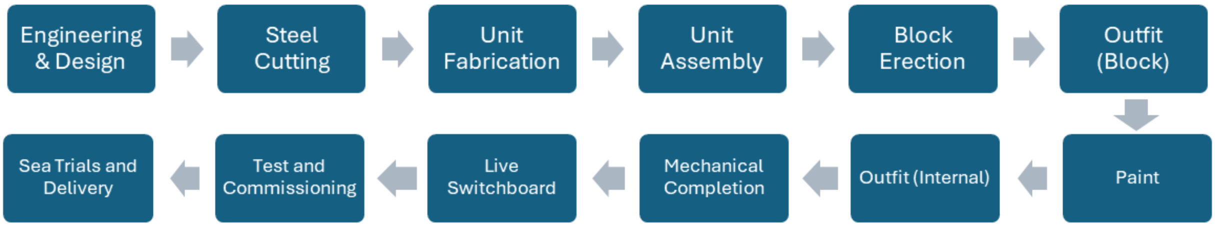

Figure 2: Shipbuilding Lifecycle

Figure 2 illustrates a simplified shipbuilding lifecycle. The process begins with engineering design and strategic planning to secure contract approval. Once a tender is successful, production starts with a ceremonial steel-cutting event. During this phase, steel plates and bars are fabricated, welded into panels, and assembled into blocks for the ship's forward and aft sections. These blocks are fitted with decks, bulkheads, and enhanced during the outfitting phase.

After steel outfitting and hot work, compartments are painted using powder coating or spray guns. Essential systems, including HVAC, pressure systems, and electrical cabling, are installed, along with living and working amenities. Once the switchboards are energised, the ship undergoes rigorous testing by quality assurance teams and commissioning specialists. The final stage involves sea trials for real-world testing. After addressing any remaining issues, the ship is delivered to the customer following successful completion of trials and final inspections. ***Figure 3*** provides a detailed explanation of these stages.

The shipbuilding lifecycle is complex, involving multiple departments and hundreds of personnel. The figure highlights key stages and functions, from initial conceptual design to final delivery. It begins with an analysis of operational needs, leading to preliminary design concepts. As the design progresses, detailed planning and design focus on the ship's systems and structural components (Kunkera et al., 2024). During construction, materials are procured and assembled into sections, which are then integrated to form the complete ship. Outfitting includes the installation of systems, equipment, and interiors. Rigorous testing, including sea trials, ensures performance and compliance with standards. Finally, the ship undergoes acceptance trials with authorities, is commissioned into service, and formally delivered to the customer. Multiple functions of an organisation are involved in the production lifecycle of a ship, namely the following in **Table 3** (Bruce, 2021).

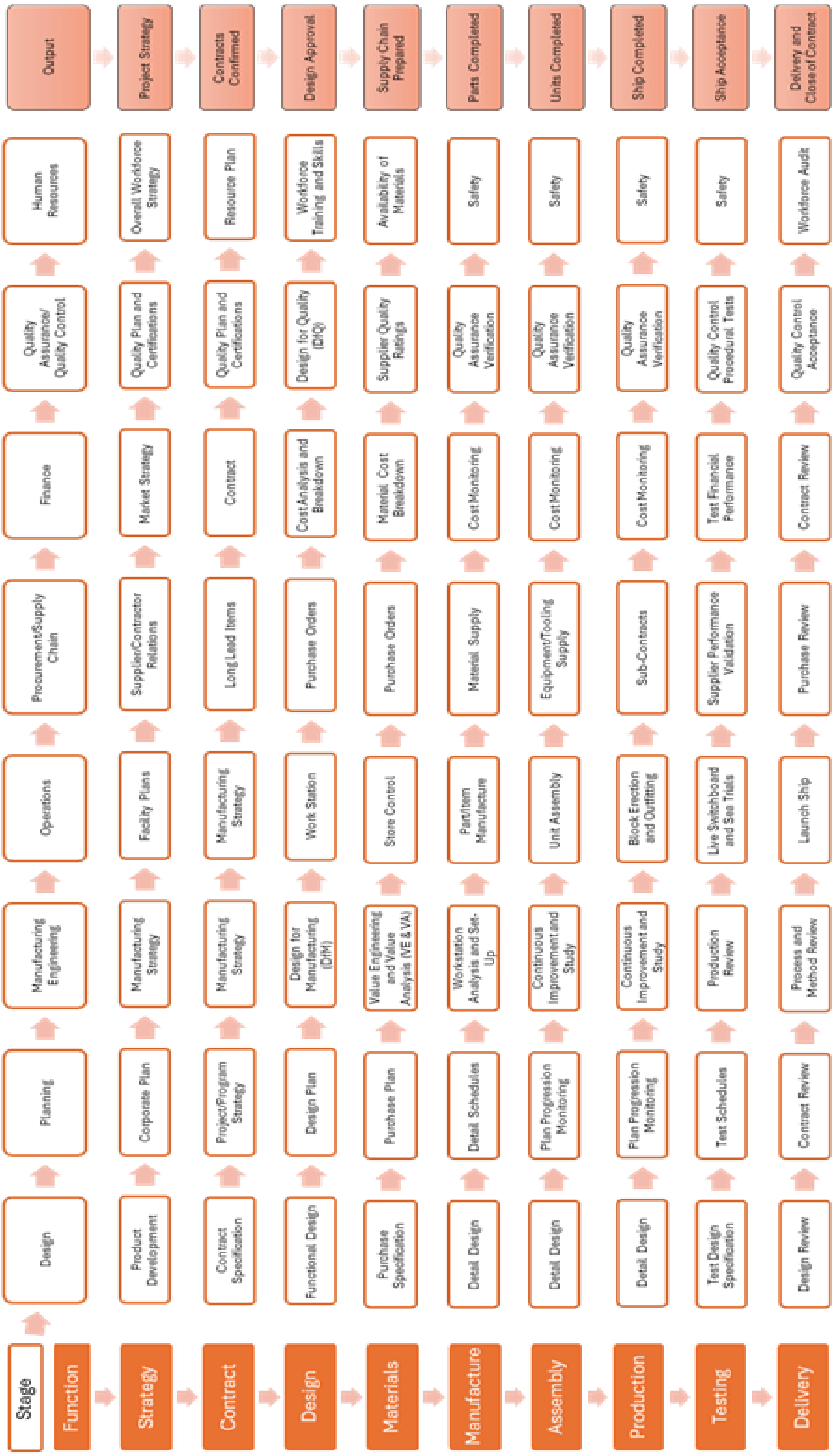

Figure 3: Shipbuilding Typical Functions and Breakdown Structure

Table 3: Examples of Functions involved in Shipbuilding, table created from information found within (Bruce, 2021; Spoehr et al., 2021).

Function	Role
Planning/Project Management	Plan all stages of the production from initial design of drawings, to planning when work orders are carried out and the final delivery of the vessel.
Design/Design Engineering	Designing the ship in initial product development, design for operation and production, and responsible for performance on sea trials during trials and commissioning.
Production Operations	Performing the actual construction of the vessel components including piece parts, panels, units and blocks to final outfitting and painting.
Manufacturing Engineering	Develop production methods and continuously improving form a lean manufacturing standpoint to ensure design and actual production remain in sync in the most efficient means possible.
Quality (Control and/or Assurance)	Overall Quality Management to ensure the shipbuilding meets all internal and external guidelines, policies, and regulations as efficiently as possible.
Safety, Health and Environmental (SHE)	Ensure all operations are performed safely and within internal and external guidelines, policies and regulations under both local and regional health and safety.
Supply Chain and Procurement	Responsible for purchasing and materials management, from specification to assembly and installation of procured items.
Human Resources	Ensure supply of skilled workforce and overall organisational management in terms of diversity, ethics, and inclusion to keep workforce performing cohesively.

2.2.2 Naval Shipbuilding Current Challenges

This section focuses on UK naval shipbuilding, which faces significant challenges in constructing bespoke vessels with unique design, production, and process needs compared to commercial shipbuilding. The decline in UK naval shipbuilding before the 2000s led to outsourcing to shipyards in Asia, notably Korea and Japan. While these shipyards excel in production volume, they do not necessarily produce higher-quality vessels (Kim et al., 2002, 2005). At the government level, Japan is focused on maintaining its current technological edge and competitiveness while modernising its shipbuilding industry to align with future advancements (Kim et al., 2002).

In established shipyards, effective change management is crucial for achieving transformation, whether minor or substantial. Shipbuilding expertise traditionally comes from heavy engineering and manufacturing practices passed down through generations (Spoehr et al., 2021), however, the sector is gradually transitioning to a more digital landscape. This shift is supported by the integration and collaboration between new research and development and the value chain. Spoehr et al. (2021) write that Naval shipbuilding is “characterised by extensive levels of organisational, functional, and production interdependence within and across firms in the value chain, making it one of the most intricate and complex value chains in industrial activity".

In countries with relatively newer shipbuilding industries, such as post-World War II Japan, adopting new technologies and processes was relatively straightforward. In contrast, the UK faced a prolonged struggle of 40 years to shift its workforce from riveting to welding, a transition that Japan quickly embraced, leading to more efficient ship production. Additionally, as ship sizes in the UK grew, existing infrastructure and shipyards became inadequate. Meanwhile, Japan invested in custom facilities designed for larger vessels, avoiding such limitations (Spoehr et al., 2021; Stott, 2023).

2.3 Industry 4.0 (I4.0)

2.3.1 Industry 4.0 Overview & Definitions

In today's ever-changing economy, conventional manufacturing sectors face challenges such as mass customisation, intensifying market competition, and advancing global integration (Zheng et al., 2021). There is an annual surge in demand for superior and innovative products, driving the necessity for expedited production processes, enhanced manufacturing efficiency, elevated product quality, and accelerated delivery schedules to meet these demands (Zheng et al., 2021). I4.0 represents a strategic effort to reach this goal by encouraging companies to adopt cutting-edge industrial digital technologies (IDT). This initiative focuses on blending physical and digital environments, leveraging new techniques to modify and enhance the adaptability of mass production systems (Torres, 2018; Zheng et al., 2021).

I4.0 principles are increasingly being adopted by numerous organisations, with an ultimate goal of establishing intelligent ecosystems where all components can actively share, gather, and analyse information in real-time (Hoyer et al., 2020). Crucially, this initiative extends beyond singular geographical sites or locations, or even specific manufacturing zones, but rather aims to comprehensively encompass various functions and the entire organisational supply chain (Hoyer et al., 2020). This inclusive approach enhances organisational resilience in production and facilitates better responses to external factors like fluctuating customer demand (Buer et al., 2018; Hoyer et al., 2020; Schneider, 2018). A significant advantage of implementing I4.0 is the capacity to produce customised items at a cost equivalent to mass-produced goods (Z. Li et al., 2017).

I4.0 encompasses a wide-ranging concept whose interpretation varies depending on geographical location and industry context, often lacking a universally accepted definition (Bierer et al., 2016). Generally, when discussing I4.0, it usually revolves around the usage of digital technologies within manufacturing processes (Waschull, 2022). This involves bridging the gap between both the physical and virtual realms to improve productivity, integrate horizontal and vertical supply chains more effectively, and foster increased digitalisation through a comprehensive approach. This approach includes integrating physical assets with digital ecosystems to optimise value networks (Price Waterhouse Coopers, 2016; Spoehr et al., 2021). A number of definitions exist for I4.0, and Table 4 gives insight into a number of these.

Table 4: Definitions of I4.0

Definitions of I4.0	Commonalities/Differences	Source
"I4.0 focuses on the end-to-end digitisation of all physical assets and integration into digital ecosystems with value chain partners."	Emphasises digital ecosystems and integration across the value chain. Lacks explicit mention of cyber-physical systems or automation.	(Price Waterhouse Coopers, 2016)
"…seeks to accelerate the growth of advanced manufacturing through the successful uptake and diffusion of digital and advanced manufacturing technologies and processes. It is underpinned by the transformative power of digital systems including the internet of things (IoT), internet of services (IoS), high performance computing (HPC), supply chain tower (SCT), augmented reality and virtual reality (AR/VR), artificial intelligence (AI), machine learning (ML) and collaboration platforms (CP) (Ash, 2018). At a conceptual level, I4.0 transforms production systems and products into inter-connected, intelligent systems and products by embedding digital functionalities into production processes and products."	Broader than other definitions; highlights a variety of digital technologies but does not explicitly mention customisation or cyber-physical systems.	(Spoehr et al., 2021)
"The application of digital tools and technologies to the value chains of businesses who make things … or are otherwise operationally asset intensive (e.g., power grids and wind farms). These technologies enable the physical and digital worlds to be merged and can bring significant enhancements to performance and productivity."	Focuses on asset-intensive industries rather than just manufacturing. Similar to PWC's definition in its emphases on digital-physical integration.	UK Made Smarter (Department for Business, 2017)
"It takes the automation of manufacturing processes to a new level by introducing customized and flexible mass production technologies."	Specifically highlights automation and flexible mass production, which are not as explicitly mentioned in other definitions.	(Fernández, 2020)
"The essence of I4.0 is the introduction of Cyber-Physical Systems into industrial applications. The Cyber-Physical System is formed by sensors, objects and actuators that can continuously communicate through the	More technical in nature, focusing on the role of cyber-physical systems and IoT, which are absent in some other definitions.	(Torres, 2018)

Definitions of I4.0	Commonalities/Differences	Source
Internet of Things, creating, thereby, a Network of machines and products extending all the way through the value chain. This network enables the collection and analysis of massive amounts of data, often in real time.”		
“Technologies such as cyber- physical systems, big data, and autonomous systems act as enablers for the core concept and vision of I4.0: the creation of a smart environment that is based on enabling all entities within that environment to collectively share, collect, and process their information in real-time.”	Emphasises real-time data processing and smart environments, aligning with cyber-physical integration and IoT.	(Hoyer et al., 2020)
“I4.0 (I4.0), a concept engineering ‘fourth industrial revolution’ that was recently introduced by the German government aims to revolutionise how products are built and manufactured. It encompasses concepts from cyber-physical system, internet of things, big data, e.g. I4.0 supports design and manufacturing trends in moving towards higher creativity, lower cost, and better responses to customer needs while at the same time coming up with on-demand production of optimal and intelligent solutions”.	Broad definition, emphasising a number of I4.0 concepts such as cyber-physical systems, IoT and the benefits of I4.0 in design and manufacturing for producers and customers.	(Ang et al., 2016)

The UK Government set out a report in 2017 titled the “Made Smarter Review”, an independent review of industrial digitalisation led by the CEO of Simens UK, Professor Juergen Maier (Department for Business, 2017). The report details how the adoption of IDT can potentially transform and revitalise manufacturing on a national scale. It reports that the benefits of accelerated innovation and the adoption of industrial digital technologies (IDT) could exceed £450 billion from 2017 to 2027, with the manufacturing sector anticipated to grow at an annual rate of between 1.5% to 3% (Department for Business, 2017).

2.3.2 Industry 4.0 Technological Enablers

To answer review Q2: (1) ‘What are the core technologies associated with I4.0, and how can they be applied in shipbuilding manufacturing?’ And (2) ‘How does each technology contribute to improving efficiency, quality, and innovation in shipbuilding processes?’, an investigation was carried out. Several crucial technological enablers exist to propel IDT within manufacturing organisations, elaborated upon in greater detail below. Within Industry 4.0, the foundational technological enablers are embodied by Cyber-Physical Systems (CPS), facilitating modular and customisable production systems (Zheng et al., 2021) through the merging of physical and virtual systems. I4.0 technologies pivotal to this transformation include but are not limited to: The Internet of Things (Iot), Digital Twin, Value Chain, Robotics/Cobotics and Additive Manufacturing (Masood & Sonntag, 2020; Trappey et al., 2017; Worrall & Spoehr, 2021; Zheng et al., 2021). The adoption of I4.0 hinges on the implementation of digital technologies such as these to support various aspects of business processes and ensure overall synergy within the organisation.

The Internet of Things (IoT) can be described as the overall web or system of physical assets, software or network connectivity that are embedded to facilitate these assets, for example sensors, to communicate through collection and exchanging of information in real-time (Ang et al., 2016). As CPS engage with IoT, they establish links between infrastructure, tangible assets such as machinery, human participants or employees, machinery, and processes spanning organisational confines (Zheng et al., 2021). This facilitates the integration of physical and digital environments, using sensors, actuators, and computational power to transmit data in real-time, thereby supporting decentralised decision-making processes (Trappey et al., 2017; Zheng et al., 2021). This can also be known as a Smart Factory system, where CPS communicate via the IoT to assist both human labour and machinery to perform and execute their tasks effectively and efficiently (Ang et al., 2016).

Digital Twin, a key technological enabler, can best be described by a three-part model presented by Prof. Michael Grieves in 2002: "(1) Real Space; (2) Virtual Space; (3) Data Flow Space" (Iwańkowicz & Rutkowski, 2023). Iwańkowicz & Rutkowski (2023) write that digital twin can be defined as: "an integrated, multi-physics, multi-scale, probabilistic simulation of a post-construction state or as a system that uses the best available physical models, sensor updates, history, etc., to reflect the life of its corresponding real-world twin. DT continuously predicts the state of its sibling to increase both the lifespan and probability of its successful operation." A Smart Factory may also consist of several other technological enablers, such as collaborative robots (cobots) and additive manufacturing (Ang et al., 2016; Worrall & Spoehr, 2021), and these will be discussed later on within the literature review. Table 5 provides a summary of key I4.0 technological enablers, not inclusive of all, nor are all mentioned topics that will be further referenced in this report.

Table 5: Summary of Exemplar I4.0 Technological Enablers (not exclusive nor will all be discussed within this article).

Technology	Description	Source
Cyber-Physical Systems (CPS)	Cyber-Physical Systems (CPS) are integrated systems that merge computational and physical components, enabling interaction with the physical world through networked communication.	(Ang et al., 2016; Fernández, 2020; Iwańkowicz & Rutkowski, 2023; Jagusch et al., 2021; Kunkera et al., 2022; Zheng et al., 2021)
Internet of Things (IoT)	The Internet of Things (IoT) refers to a network of interconnected devices and objects that can communicate and exchange data with each other over the internet.	(Fernández, 2020; Iwańkowicz & Rutkowski, 2023; Jagusch et al.,

Technology	Description	Source
		2021; Kunkera et al., 2022)
Digital Twin	A Digital Twin is a virtual representation of a physical object, system, or process that enables real-time monitoring, analysis, and simulation to improve performance and efficiency.	(Fernández, 2020; Iwańkowicz & Rutkowski, 2023; Jagusch et al., 2021; Kunkera et al., 2022)
Additive Manufacturing	Additive Manufacturing, also known as 3D printing, is a manufacturing process that builds objects layer by layer using digital 3D models.	(Fernández, 2020; Taşdemir & Nohut, 2021; Worrall & Spoehr, 2021; Zheng et al., 2021; Ziółkowski & Dyl, 2020)
Collaborative Robots (Cobots)	Collaborative Robots, often referred to as cobots, are robotic systems designed to work alongside humans in shared workspaces. They are equipped with advanced sensors and safety features that allow them to interact safely with human workers, enhancing productivity and flexibility in manufacturing processes.	(Egger & Masood, 2020; Fernández, 2020; Masood et al., 2018; Masood & Egger, 2020; Zheng et al., 2021)
Artificial Intelligence (AI)	Artificial Intelligence (AI) in the context of Industry 4.0 refers to the use of advanced algorithms and machine learning techniques to enable machines and systems to perform tasks that traditionally require human intelligence. This includes capabilities such as predictive maintenance, quality control, autonomous decision-making, and adaptive manufacturing processes.	(Egger & Masood, 2020; Fernández, 2020; Masood et al., 2018; Masood & Egger, 2020; Zheng et al., 2021)
Augmented Reality and Virtual Reality	Augmented Reality (AR) and Virtual Reality (VR) in the context of Industry 4.0 are immersive technologies that enhance human-machine interaction and training processes. AR overlays digital information onto the physical environment, providing real-time insights and instructions, while VR creates simulated environments for training, design visualisation, and remote collaboration.	(Egger & Masood, 2020; Fernández, 2020; Masood & Egger, 2019a, 2020, 2021; Zheng et al., 2021)

2.3.3 Industry 4.0 Benefits for Shipbuilding

The following is a presentation of high-level potential benefits of I4.0 adoption within the Shipbuilding industry. Several key benefits have been highlighted in literature, these include cost reduction, increased competitiveness, higher quality, and increased efficiency and flexibility (Hoyer et al., 2020; Koch et al., 2014; Masood & Sonntag, 2020; Mohamed, 2018; Narula et al., 2020; Torres, 2018; Worrall & Spoehr, 2021).

The transition to digitised enterprises is expected to yield an average efficiency increase of 18% across all industry sectors over the next five years. Enhanced productivity is projected with operational efficiencies rising by an average of 3.3% annually, resulting in an annual cost reduction of 2.6%. Revenue growth is anticipated to surpass the costs of automation or digitisation under Industry 4.0 initiatives, as logistics and statistics are automatically generated and collected, enabling quicker response times (Koch et al., 2014; Mohamed, 2018). Cost reduction is facilitated by efficient resource use through smart networks and robotics, despite the high initial investment costs. Increased competitiveness is driven by globalisation-induced cost reduction and process enhancement, with digitisation and smart technology improving data analysis and process efficiency. The flexibility in manufacturing is enhanced through digitisation, reducing complexity, and enabling rapid production with real-time monitoring and flexible production capabilities provided by Cyber-Physical Systems. Additionally, digitised technologies improve resource efficiency and production scheduling, thereby enhancing quality and reducing defects through autonomous machinery communication (Torres, 2018). Industry 4.0 technologies have also helped manufacturers enhance efficiency, reduce downtime, cut costs, and improve service, delivery, and quality, providing market differentiation (Narula et al., 2020). The increased operational flexibility and efficiency, combined with improvements in quality, productivity, and competitive advantage, underscore the significant benefits of digitisation (Hoyer et al., 2020; Masood & Sonntag, 2020).

These benefits highlight how Industry 4.0 technologies contribute to efficiency, cost reduction, revenue growth, automation, flexibility, competitiveness, and quality enhancement in manufacturing processes.

2.4 Industry 4.0 Implementation Challenges within Shipbuilding

An investigation in the literature was undertaken to answer RQ3: Challenges and Opportunities, more specifically:

1. What are the primary challenges and barriers hindering the adoption of I4.0 in shipbuilding manufacturing?
2. What opportunities/gaps exist for implementation to enhance efficiency, quality, flexibility, and innovation through I4.0 initiatives?

The following sections look deeper into what methodologies or frameworks exist currently for I4.0 implementation, and the barriers or limitations these might have in the context of Shipbuilding.

2.4.1 Implementation Methodologies (Frameworks)

Several frameworks and methodologies exist for implementing Industry 4.0 across various industries. These provide structured approaches to guide organisations through the process of digital transformation and technology adoption. Some of the commonly used include those seen in ***Figure 4***:

Figure 4: Implementation Frameworks

These frameworks provide valuable guidance and best practices for organisations adopting Industry 4.0, helping them address challenges, seize opportunities, and achieve successful digital transformations. While organisations can adapt these frameworks to their specific needs, there is no framework specifically tailored for shipbuilding, which this report aims to develop.

2.4.2 Challenges

The adoption of Industry 4.0 (I4.0) and its associated technologies relies on numerous interrelated factors operating in tandem to achieve synergy. However, existing frameworks outlined in the literature often serve as general guidelines for adoption, remaining largely theoretical without substantial evidence of implementation within the shipbuilding industry, whether naval or commercial. For instance, three potentially suitable for I4.0 implementation include (1). IIRA, (2). RAMI 4.0, and (3). TOE. **Table 6** discusses why these three may be well-suited for adoption, yet also their limitations concerning the shipbuilding industry.

Table 6: Limitations in Potential Frameworks within Shipbuilding Industry.

Framework	Reason for Application	Key Strengths	Limitations	Customisation Needs	Technologies/ Tools to Address Limitations	Sources
IIRA (Industrial Internet Reference Architecture)	Facilitates IIoT integration to enhance productivity, operational efficiency, and maintenance within shipbuilding.	- Specifically designed for IIoT systems. - Highly scalable and interoperable. - Aligns closely with Industry 4.0 principles.	- Requires extensive customisation. - Complex integration across diverse subsystems. - Challenges related to long supply chains and stringent regulatory compliance.	- Adaptation for bespoke vessel designs. - Integration across multidisciplinary subsystems.	- Implementation of interoperability standards. - Integration of digital twins. - Deployment of robust cybersecurity measures.	Chuah & Wong (2011); Demir & Kocaoglu (2019); Jesus & Lima (2020); J. Li et al. (2020); Lin (2016); Radanliev et al. (2019); Yli-Ojanperä et al. (2019)
RAMI 4.0 (Reference Architecture Model for Industry 4.0)	Provides a standardised framework for Industry 4.0 adoption, ensuring interoperability across complex shipbuilding processes.	- Promotes compatibility across diverse system components. - Structured through clear layers (communication, modelling, protocols).	- Operates at a high level; lacks shipbuilding-specific detail. - Complex supply chain considerations are insufficiently addressed. - Requires tailoring for bespoke engineering solutions.	- Adaptations for unique systems such as propulsion and navigation.	- Advanced simulation technologies and digital twins. - Lifecycle management tools. - Enhanced supply chain management systems.	Jesus & Lima (2020); J. Li et al. (2020); Lin (2016); Resman et al. (2019); Ustundag & Cevikcan (2018); Yli-Ojanperä et al. (2019)
TOE (Technological, Organisational, Environmental)	Assesses the feasibility of Industry 4.0 technology adoption, taking into account organisational capabilities and environmental factors.	- Provides a holistic evaluation framework. - Aligns technological deployment with sustainability objectives. - Assists in gauging technological readiness.	- Insufficient consideration of human factors (skills gaps, cultural resistance). - Limited attention to shipbuilding-specific regulatory and compliance challenges.	- Emphasis on workforce development and enhanced safety measures.	- Workforce reskilling and training programmes. - Strengthened collaboration platforms. - Advanced IoT and cybersecurity infrastructures.	Jesus & Lima (2020); Masood & Egger (2019); Rafique et al. (2022); Zhong & Moon (2023)

Overall, these three frameworks offer valuable guidance and best practices for implementing Industry 4.0 in the shipbuilding manufacturing industry, but they may require customisation and adaptation to fully address the industry's unique challenges and requirements.

3. Summary of Review Questions and Answers

Several review questions were posed at the beginning of the SLR, in order to better understand shipbuilding, I4.0 and the opportunities and challenges associated with the combination of the two. Below is a summary of the review question sub-questions and the findings of the SLR.

Table 7: Summary of Review Question 1 and Answers Obtained via SLR.

RQ	Description	Findings
RQ1: Current State Analysis	1. What is the current state of Shipbuilding and/or their Manufacturing Processes?	***1. Shipbuilding and Manufacturing:*** • **Defence Spending:** UK's declining defence budget impacts ship production; the 2017 Shipbuilding Strategy aims to boost capacity with BAE Systems Maritime as a key player. • **Contracts:** Contracts like the Type 26 Global Combat Ship in Naval Shipbuilding sustain the industry, driving economic growth.
	2. What is the manufacturing/production lifecycle of Shipbuilding?	***2. Shipbuilding Lifecycle:*** • **Lifecycle Stages:** The process involves planning, design, production, quality control, safety, supply chain management, and HR. • **Functions:** Various organisational functions work together for integrated ship production.
	3. Where are the opportunities for optimisation and improvement through the integration of I4.0 technologies/current challenges in Shipbuilding?	***3. I4.0 Technologies and Challenges:*** • **Challenges:** Overcoming traditional methods and adapting to new technologies are key challenges; Japan sets an example with rapid tech adoption. **I4.0 Integration:** Using digitalisation and automation, I4.0 technologies offer efficiency improvements, requiring effective change management and collaboration.

In response to Review Question 1, the shipbuilding sector is keen to adopt Industry 4.0, focusing on complex, customised production. Challenges include the UK's declining defence budget, which affects naval shipbuilding, despite initiatives like the 2017 Shipbuilding Strategy and key projects such as the Type 26 Global Combat Ship.

The shipbuilding lifecycle involves planning, design, production, quality control, safety, supply chain management, and human resources, requiring coordination across functions. While Industry 4.0 technologies offer opportunities for optimisation through digitalisation and automation, overcoming traditional practices and adapting to new technologies remains challenging. Japan's rapid tech adoption highlights potential benefits example case study. Successful integration of I4.0 in shipbuilding demands effective change management and collaboration.

Table 8: Summary of Review Question 2 and Answers Obtained via Systematic Literature Review.

<table>
<tr><td rowspan="2">RQ2: Technological Enablers</td><td>1. What are the core technologies associated with I4.0, and how can they be applied in shipbuilding manufacturing?</td><td>1. Core I4.0 Technologies in Shipbuilding:
• I4.0 Overview: I4.0 integrates digital technologies to improve manufacturing efficiency and flexibility.
• Key Technologies: Includes CPS, IoT, Digital Twin, Additive Manufacturing, Cobots, AI, and AR/VR.
• Benefits: Enables real-time data exchange, predictive maintenance, customisation, and smart decision-making.</td></tr>
<tr><td>2. How does each technology contribute to improving efficiency, quality, and innovation in shipbuilding processes?</td><td>2. Technology Contributions to Shipbuilding Efficiency and Innovation:
• CPS: Facilitates modular production, enhancing adaptability to changing demands.
• IoT: Enables real-time monitoring, improving operational visibility.
• Digital Twin: Provides virtual representations for predictive maintenance and performance analysis.
• Additive Manufacturing: Allows rapid prototyping and customisation, reducing lead times.
• Cobots: Increases productivity and safety by working alongside humans.
• AI: Enables autonomous decision-making and predictive analytics, enhancing accuracy.
• AR/VR: Enhances training and collaboration, fostering innovation.
Overall Impact: These technologies reduce costs, increase competitiveness, and improve quality and flexibility in shipbuilding, aligning with I4.0 goals.</td></tr>
</table>

In response to Review Question 2, I4.0 technologies could greatly enhance shipbuilding processes. Core technologies like Cyber-Physical Systems (CPS) and the Internet of Things (IoT) enable better customisation, real-time data exchange, and smarter decision-making, to potentially improve efficiency, quality, and flexibility.

CPS supports modular production, IoT offers real-time monitoring, and Digital Twin enables predictive maintenance and performance analysis. Additive Manufacturing allows for rapid prototyping whilst Cobots enhance productivity and safety, AI facilitates autonomous decision-making and predictive analytics, and AR/VR improves training and collaboration. These technologies collectively reduce costs, boost competitiveness, and enhance quality and flexibility in shipbuilding, aligning with Industry 4.0's transformative goals.

Table 9: Summary of Review Question 3 and Answers Obtained via Systematic Literature Review

RQ3: Challenges and Opportunities	1. What are the primary challenges and barriers hindering the adoption of I4.0 in shipbuilding manufacturing?	1. **Challenges Hindering I4.0 Adoption in Shipbuilding:** • **Complexity of Manufacturing:** Intricate processes and machinery require IIoT systems for efficiency, but complexity hinders seamless I4.0 integration. • **Lack of Tailored Frameworks:** Existing frameworks like IIRA, RAMI 4.0, and TOE lack specificity for naval shipbuilding's unique challenges. • **Diverse Stakeholders and Supply Chains:** Complex supply chains and diverse stakeholders complicate I4.0 adoption, requiring customised approaches. • **Social and Systemic Dimensions:** Existing frameworks overlook social and systemic aspects critical to shipbuilding, requiring broader considerations. • **Customisation and Adaptation Needs:** Standard frameworks may not address industry-specific challenges, necessitating customisation for effective I4.0 integration.
	2. What opportunities/gaps exist for implementation to enhance efficiency, quality, flexibility, and innovation through I4.0 initiatives?	2. **Opportunities for I4.0 Implementation in Shipbuilding:** • **Enhanced Efficiency:** IIoT, data analytics, and automation streamline processes, improve resource utilisation, and cut costs. • **Quality and Maintenance Improvement:** Real-time monitoring and predictive maintenance enhance product quality and reduce downtime. • **Increased Flexibility:** I4.0 enables swift response to market trends, customer demands, and regulatory changes. • **Innovation and Collaboration:** Digital transformation fosters innovation, new business models, and growth opportunities. • **Sustainability Focus:** I4.0 optimises resource usage and reduces waste, aligning with industry sustainability goals. **Overall Impact:** I4.0 offers naval shipbuilding opportunities to boost efficiency, quality, flexibility, and innovation, but a tailored approach is essential to address challenges and leverage these benefits effectively.

In response to Review Question 3, adopting Industry 4.0 (I4.0) in shipbuilding faces challenges due to complex processes and machinery requiring Industrial Internet of Things (IIoT) systems, complicating integration. Existing frameworks like IIRA, RAMI 4.0, and TOE do not fully address the sector's unique needs, exacerbated by complex supply chains and diverse stakeholders. Customised frameworks are necessary to overcome these challenges.

Despite these hurdles, I4.0 offers significant advantages, including improved efficiency, quality, flexibility, and innovation. IIoT, data analytics, and automation streamline processes, enhance resource use, and cut costs. Real-time monitoring and predictive maintenance improve product quality and reduce downtime. I4.0 also supports rapid adaptation to market changes and regulatory demands, driving sustainability through efficient resource use and reduced waste.

In summary, while I4.0 provides substantial benefits for shipbuilding, tailored approaches are crucial to address adoption challenges and maximise these benefits.

4. Discussion

The integration of Industry 4.0 (I4.0) technologies within the shipbuilding sector offers numerous opportunities but also presents several challenges. A systematic literature review (SLR) conducted in this study identified significant gaps in the current understanding and application of these advanced technologies in shipbuilding. The SLR focused on three main areas: the current state of the sector, technological enablers, and challenges associated with I4.0 implementation.

4.1 Current State Analysis (RQ1)

The review provides a comprehensive evaluation of the current state of shipbuilding, highlighting critical issues such as declining defence budgets, particularly within naval shipbuilding, one of the largest sectors in the United Kingdom. It emphasises the significance of major contracts like the Type 26 Global Combat Ship and outlines critical stages in the shipbuilding lifecycle, including planning, design, production, quality control, safety, supply chain management, and human resources. These findings underscore the limitations of traditional practices and the necessity for effective change management and collaboration to integrate new technologies successfully. However, while the review presents a holistic overview of shipbuilding processes, it also suggests a need for more contemporary, industry-specific data to better reflect current perspectives.

4.2 Technological Enablers (RQ2)

Key I4.0 technologies identified through the review include digital twins, the Internet of Things (IoT), automation, and data analytics. These technologies are shown to enhance efficiency, quality, and innovation by enabling real-time monitoring, predictive maintenance, streamlined operations, and optimised resource utilisation. Although the potential contributions of these technologies are evident, the review highlights a gap in understanding regarding industry perceptions of these tools and the extent to which they have been practically implemented. Consequently, further empirical research is necessary to address these issues and capture the real-world application of I4.0 technologies within shipbuilding.

4.3 Challenges and Opportunities (RQ3)

The review identifies several major challenges to the adoption of I4.0 in shipbuilding, including high costs, workforce readiness, cybersecurity, and interoperability. It emphasises the need for tailored strategies to overcome these barriers and capitalise on I4.0 benefits such as increased efficiency, flexibility, and innovation. Nevertheless, the review also notes the lack of empirical, sector-specific data to substantiate these findings, as much of the existing evidence is either generalised across industries or lacks specificity. This highlights the need for further research targeted at the shipbuilding context.

4.4 Theoretical Contributions

This study makes three key theoretical contributions to the body of knowledge on Industry 4.0 implementation:

- It advances understanding of I4.0 adoption within the traditionally conservative and complex environment of shipbuilding manufacturing, which has been underrepresented in existing research.
- It contributes an initial theoretical framework for I4.0 integration, specifically tailored to the shipbuilding context, identifying the technological enablers, sector-specific challenges, and contextual factors critical for successful adoption.
- It builds a foundation for future research by defining clear research gaps, including the need for empirical, sector-specific evidence and a greater focus on organisational change management within digital transformation initiatives.

By producing insights from manufacturing, digital transformation, and shipbuilding studies, this research positions itself as a bridge between broad Industry 4.0 theories and their sector-specific application.

4.5 Managerial Implications

For industry practitioners and managers within shipbuilding, this study offers several practical insights:

- Strategic Focus: Managers should prioritise the integration of digital twins, IoT, and automation technologies, particularly within supply chain, production planning, and maintenance functions.
- Change Management: Given the complexity and tradition-bound nature of shipbuilding, strong leadership in change management and cross-disciplinary collaboration is essential for successful digital transformation.
- Workforce Development: Workforce readiness remains a critical barrier. Targeted training and reskilling programmes are necessary to build capabilities in data analytics, cybersecurity, and systems integration.
- Cybersecurity Preparedness: As digital integration increases, cybersecurity risks become more prominent. Managers must integrate cybersecurity strategies early within digital initiatives.

- Supply Chain Integration: Digital supply chain platforms should be adopted to address the unique logistical challenges in shipbuilding manufacturing, ensuring real-time visibility and improved resilience.

These implications provide actionable guidance for shipbuilding managers seeking to transition towards Industry 4.0 readiness.

4.6 Limitations and Future Research Directions

Although this study provides valuable insights into the integration of Industry 4.0 technologies within shipbuilding manufacturing, certain limitations must be acknowledged. First, the scope of the systematic literature review was largely confined to the UK naval shipbuilding sector, potentially limiting the generalisability of the findings to other regions or to commercial shipbuilding contexts. Second, the research to date remains primarily conceptual, drawing on secondary data rather than first-hand empirical evidence. Third, the rapid evolution of I4.0 technologies implies that continuous updates to the findings and frameworks proposed here will be necessary to maintain relevance.

Future research should aim to address these limitations through empirical investigation. In particular, structured surveys and semi-structured interviews with industry practitioners will be essential to validate and refine the proposed theoretical framework. Further work should expand the geographical scope to incorporate comparative studies across different national shipbuilding industries and explore sector-specific applications of emerging technologies such as AI, digital twin, and machine learning.

In addition, greater emphasis is required on the organisational and human factors underpinning successful I4.0 adoption, particularly in relation to workforce reskilling, change management, and cultural transformation. These themes will be explored in subsequent stages of the broader research project, which are designed to empirically validate the initial findings and further enhance the practical applicability of the proposed framework for digital transformation in shipbuilding.

5. Conclusion

This systematic literature review highlights the transformative potential of Industry 4.0 technologies in the naval shipbuilding industry. The findings emphasise the need for customised solutions that cater to the unique complexities of shipbuilding, including multidisciplinary coordination, regulatory compliance, and supply chain management.

The review offers an in-depth analysis of the current shipbuilding processes, highlighting areas for improvement through I4.0 technologies. It emphasises the lifecycle stages and organisational functions necessary for integrated ship production. By identifying and evaluating core I4.0 technologies, the review provides valuable insights into how these technologies can be practically applied in shipbuilding to enhance efficiency, quality, and innovation. Additionally, the review outlines the primary challenges to I4.0 adoption and identifies opportunities to enhance shipbuilding processes through these technologies. It stresses the importance of addressing specific industry challenges to effectively implement I4.0 initiatives.

The review also identifies that while existing frameworks like RAMI 4.0 and the TOE framework offer valuable guidance, they require customisation to address the unique challenges of the shipbuilding industry. The need for broader considerations, such as human factors, organisational culture, and comprehensive stakeholder engagement, is emphasised. This defines the gap in current research and highlights the necessity for tailored approaches to fully leverage I4.0 technologies in naval shipbuilding.

In conclusion, the systematic literature review provides a robust foundation for understanding and advancing the integration of I4.0 in shipbuilding, addressing critical gaps, and offering a clear path forward for future research and practical implementation. Future research should focus on the creation of a new framework for use in I4.0 implementation in shipbuilding through empirical studies and exploring the integration of emerging technologies. By advancing the understanding and implementation of I4.0 in shipbuilding, this research contributes to enhancing efficiency, productivity, and innovation in this critical sector.

References

Ang, J. H., Goh, C., & Li, Y. (2016). Smart design for ships in a smart product through-life and industry 4.0 environment. *2016 IEEE Congress on Evolutionary Computation (CEC)*, 5301–5308. https://doi.org/10.1109/CEC.2016.7748364

Bierer, A., Götze, U., Köhler, S., & Lindner, R. (2016). Control and Evaluation Concept for Smart MRO Approaches. *Procedia CIRP*, *40*, 699–704. https://doi.org/10.1016/J.PROCIR.2016.01.157

Bruce, G. (2021). *Shipbuilding Management*. Springer Singapore. https://doi.org/10.1007/978-981-15-8975-1

Buer, S.-V., Strandhagen, J. O., & Chan, F. T. S. (2018). The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. *International Journal of Production Research*, *56*(8), 2924–2940. https://doi.org/10.1080/00207543.2018.1442945

Chuah, M.-H., & Wong, K.-L. (2011). A review of business intelligence and its maturity models. *African Journal of Business Management*, *5*, 3424–3428. https://doi.org/10.5897/AJBM10.1564

Cil, I., Arisoy, F., Kilinc, H., Ozgurbuz, E., Cil, A. Y., & Uysal, E. (2021). Challenges and Trends in Shipbuilding Industry: Digitization of SEDEF Shipyard in Turkey. *2021 5th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, 799–804. https://doi.org/10.1109/ISMSIT52890.2021.9604757

Demir, E., & Kocaoglu, B. (2019). THE USE OF MCKINSEY'S 7S FRAMEWORK AS A STRATEGIC PLANNING AND ECONOMIC ASSESTMENT TOOL IN THE PROCESS OF DIGITAL

TRANSFORMATION. *PressAcademia Procedia*, *9*(1), 114–119. https://doi.org/10.17261/Pressacademia.2019.1078

Department for Business, E. & I. S. (2017). *Made Smarter Review*. https://www.gov.uk/government/publications/made-smarter-review

Drath, R., & Horch, A. (2014). Industrie 4.0: Hit or Hype? [Industry Forum]. *IEEE Industrial Electronics Magazine*, *8*(2), 56–58. https://doi.org/10.1109/MIE.2014.2312079

Egger, J., & Masood, T. (2020). Augmented reality in support of intelligent manufacturing – A systematic literature review. *Computers & Industrial Engineering*, *140*, 106195. https://doi.org/10.1016/J.CIE.2019.106195

Fernández, R. P. (2020). How the industry 4.0 could affect the shipbuilding world. *Journal of Maritime Research*, *17*(3), 18–27.

Geissbauer, R., Vedso, J., & Schrauf, S. (2016). *Industry 4.0: Building the digital enterprise*.

GOV.UK, & Statista Inc. (2022). *Defense Expenditure as a share of GDP in the United Kingdom from 1980 to 2021*. https://www.statista.com/statistics/298527/defense-spending-as-share-of-gdp-united-kingdom-uk/

Hoyer, C., Gunawan, I., & Reaiche, C. H. (2020). The Implementation of Industry 4.0 – A Systematic Literature Review of the Key Factors. *Systems Research and Behavioral Science*, *37*(4), 557–578. https://doi.org/10.1002/sres.2701

Iwańkowicz, R., & Rutkowski, R. (2023). Digital Twin of Shipbuilding Process in Shipyard 4.0. *Sustainability*, *15*(12), 9733. https://doi.org/10.3390/su15129733

Jesus, C. de, & Lima, R. M. (2020). Literature Search of Key Factors for the Development of Generic and Specific Maturity Models for Industry 4.0. *Applied Sciences*, *10*(17), 5825. https://doi.org/10.3390/app10175825

Kim, H., Lee, J., Park, J., Park, B., & Jang, D. (2002). Applying digital manufacturing technology to ship production and the maritime environment. *Integrated Manufacturing Systems*, *13*(5), 295–305. https://doi.org/10.1108/09576060210429748

Kim, H., Lee, S.-S., Park, J. H., & Lee, J.-G. (2005). A model for a simulation-based shipbuilding system in a shipyard manufacturing process. *International Journal of Computer Integrated Manufacturing*, *18*(6), 427–441. https://doi.org/10.1080/09511920500064789

Koch, V., Kuge, S., Geissbauer, R., & Schrauf, S. (2014). *Industry 4.0: Opportunities and challenges of the industrial internet*. https://docplayer.net/1730012-Industry-4-0-opportunities-and-challenges-of-the-industrial-internet.html

Kunkera, Z., Željković, I., Mimica, R., Ljubenkov, B., & Opetuk, T. (2024). Development of Augmented Reality Technology Implementation in a Shipbuilding Project Realization

Process. *Journal of Marine Science and Engineering*, *12*(4), 550. https://doi.org/10.3390/jmse12040550

Lee, J., Bagheri, B., & Kao, H.-A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, *3*, 18–23. https://doi.org/10.1016/j.mfglet.2014.12.001

Li, J., Qiu, J.-J., Zhou, Y., Wen, S., Dou, K.-Q., & Li, Q. (2020). Study on the Reference Architecture and Assessment Framework of Industrial Internet Platform. *IEEE Access*, *8*, 164950–164971. https://doi.org/10.1109/ACCESS.2020.3021719

Li, Z., Wang, Y., & Wang, K.-S. (2017). Intelligent predictive maintenance for fault diagnosis and prognosis in machine centers: Industry 4.0 scenario. *Advances in Manufacturing*, *5*, 1–11. https://doi.org/10.1007/s40436-017-0203-8

Lin, S.-W. (2016). The Industrial Internet of Things Volume G1: Reference Architecture. *Industrial Internet Consortium*, *G1*(1.9). Industrial Internet Consortium

Masood, T., & Egger, J. (2019). Augmented reality in support of Industry 4.0—Implementation challenges and success factors. *Robotics and Computer-Integrated Manufacturing*, *58*, 181–195. https://doi.org/10.1016/J.RCIM.2019.02.003

Masood, T., & Sonntag, P. (2020). Industry 4.0: Adoption challenges and benefits for SMEs. *Computers in Industry*, *121*, 103261. https://doi.org/10.1016/j.compind.2020.103261

Mohamed, M. (2018). Challenges and Benefits of Industry 4.0: an overview. *International Journal of Supply and Operations Management*, *5*(3), 256–265. https://doi.org/10.22034/2018.3.7

Narula, S., Prakash, S., Dwivedy, M., Talwar, V., & Tiwari, S. P. (2020). Industry 4.0 adoption key factors: an empirical study on manufacturing industry. *Journal of Advances in Management Research*, *17*(5), 697–725. https://doi.org/10.1108/JAMR-03-2020-0039

Oxford Economics. (2015). *The Impact of BAE Systems on the UK Economy*. 93digital (2015). The impact of BAE Systems on the UK economy. [online] Oxford Economics. Available at: https://www.oxfordeconomics.com/resource/the-impact-of-bae-systems-on-the-uk-economy/.

Oxford Economics. (2023). *BAE Systems' Contribution to the UK Economy*. https://www.baesystems.com/en-media/uploadFile/20230629160020/1573692835722.pdf

Price Waterhouse Coopers. (2016). *Industry 4.0: Building the Digital Enterprise*. https://www.pwc.nl/nl/assets/documents/industry-4.0-building-your-digital-enterprise-april-2016.pdf

Radanliev, P., de Roure, D., Nicolescu, R., & Huth, M. (2019). *A reference architecture for integrating the Industrial Internet of Things in the Industry 4.0*. https://www.macs.hw.ac.uk/~yjc32/project/ref-Industrial%204.0/201903-David%20De%20Roure-Ind%204.0%20Iot.pdf

Rafique, M. Z., Haider, M., Raheem, A., Ab Rahman, M. N., & Amjad, M. S. (2022). Essential Elements for Radio Frequency Identification (RFID) adoption for Industry 4.0 Smart Manufacturing in Context of Technology-Organization-Environment (TOE) Framework – A Review. *Jurnal Kejuruteraan*, *34*(1), 1–10. https://doi.org/10.17576/jkukm-2022-34(1)-01

Resman, M., Pipan, M., Simic, M., & Herakovic, N. (2019). A new architecture model for smart manufacturing: A performance analysis and comparison with the RAMI 4.0 reference model. *Advances in Production Engineering & Management*, *14*(2), 153–165. https://doi.org/https://doi.org/10.14743/apem2019.2.318

Schneider, P. (2018). Managerial challenges of Industry 4.0: an empirically backed research agenda for a nascent field. *Review of Managerial Science*, *12*(3), 803–848. https://doi.org/10.1007/s11846-018-0283-2

Soori, M., Arezoo, B., & Dastres, R. (2024). Virtual manufacturing in Industry 4.0: A review. *Data Science and Management*, *7*(1), 47–63. https://doi.org/10.1016/J.DSM.2023.10.006

Spoehr, J. D., Jang, R., Manning, K., Rajagopalan, A., Moretti, C., Hordacre, A., Howard, S., Yaron, P., & Worrall, L. (2021). *The Digital Shipyard Opportunities and Challenges*. https://api.semanticscholar.org/CorpusID:238864711

Stott, P. (2023). Shipbuilding Policy in the UK: The Legacy of a Century of Decline and its Influence on Naval Procurement. *The RUSI Journal*, *168*(5), 54–67. https://doi.org/10.1080/03071847.2023.2250389

The Global Combat Ship Programmes (Type 26 Frigate, Hunter Class Frigate, Canadian Surface Combatant). (2021, February). https://doi.org/10.24868/issn.2515-818X.2020.063

Torres, A. (2018). Identifying Challenges and success factors towards Implementing Industry 4.0 technologies in the Shipbuilding Industry. *Delft University of Technology*.

Trappey, A. J. C., Trappey, C. V., Hareesh Govindarajan, U., Chuang, A. C., & Sun, J. J. (2017). A review of essential standards and patent landscapes for the Internet of Things: A key enabler for Industry 4.0. *Advanced Engineering Informatics*, *33*, 208–229. https://doi.org/10.1016/J.AEI.2016.11.007

Ustundag, A., & Cevikcan, E. (2018). *Industry 4.0: Managing The Digital Transformation* (1st ed.). Springer International Publishing. https://doi.org/10.1007/978-3-319-57870-5

Waschull, S. (2022). *The impact of Industry 4.0 on work design* [University of Groningen]. https://doi.org/10.33612/diss.238472479

Worrall, L., & Spoehr, J. (2021). Naval Shipbuilding and Industry 4.0 Building the Value Chain and Industry Capability. *Flinders University Australian Industrial Transformation Institute*. http://www.flinders.edu.au/aiti/

Yli-Ojanperä, M., Sierla, S., Papakonstantinou, N., & Vyatkin, V. (2019). Adapting an agile manufacturing concept to the reference architecture model industry 4.0: A survey and case study. *Journal of Industrial Information Integration*, *15*, 147–160. https://doi.org/10.1016/J.JII.2018.12.002

Zacharaki, N., Dimitropoulos, N., & Makris, S. (2022). Challenges in human-robot collaborative assembly in shipbuilding and ship maintenance, repair and conversion (SMRC) industry. *Procedia CIRP*, *106*, 120–125. https://doi.org/https://doi.org/10.1016/j.procir.2022.02.165

Zheng, T., Ardolino, M., Bacchetti, A., & Perona, M. (2021). The applications of Industry 4.0 technologies in manufacturing context: a systematic literature review. *International Journal of Production Research*, *59*(6), 1922–1954. https://doi.org/10.1080/00207543.2020.1824085

Zhong, Y., & Moon, H. C. (2023). Investigating the Impact of Industry 4.0 Technology through a TOE-Based Innovation Model. *Systems*, *11*(6), 277. https://doi.org/10.3390/systems11060277