Flinders University
Australian Industrial Transformation Institute

The Digital Shipyard

Opportunities and Challenges

John Spoehr, Ryan Jang, Kosta Manning, Arvind Rajagopalan, Cecilia Moretti, Ann-Louise Hordacre, Sara Howard, Peter Yaron and Lance Worrall

Australian Industrial Transformation Institute

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College of Business, Government and Law
Flinders University of South Australia

1284 South Road
Clovelly Park
South Australia 5042

www.flinders.edu.au/aiti

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Preamble

Large scale shipbuilding projects like the Hunter Class Future Frigate program can benefit greatly from accelerated application of advanced digital and manufacturing technologies in tandem with lean manufacturing and high performance workplace practices. So too can the supply chains working in support of this national endeavour. The vision to establish a world class 'digital shipyard' is a major driver toward achieving sovereign shipbuilding capability. Flinders University is proud to be working in collaboration with BAE Systems Maritime Australia and its supply chain to examine the role that human factors and ergonomics (HFE) play in the uptake and diffusion of advanced manufacturing and digital technologies.

With support from the Department of Industry, Science, Energy resources (Innovative Manufacturing CRC (IMCRC)) the partners have embarked on a multi-year program of HFE technology research and trials designed to support the successful and timely uptake of advanced manufacturing and digital technologies in Australian shipbuilding. A unique transdisciplinary research capability has been assembled at the Flinders at Tonsley campus to drive this work. BAE Systems Maritime Australia staff are working alongside Flinders researchers on an ambitious research program based in fit-for-purpose collaborative research labs and the Pilot Factory of the Future – Line Zero trial and test facility.

In line with all other forms of manufacturing, Industry 4.0 offers a vision for transformation of the shipbuilding industry though the establishment of 'Digital Shipyards' and adoption of a 'Shipyard 4.0' agenda. It is important to acknowledge just how transformative such a vision is and how challenging it will be to realise. The motivations and drivers must be powerful and the benefits very large. The ideal of Digital Shipbuilding and importantly, sustainment, is propelled by the prospect of significant improvements in productivity, efficiency, reliability, quality and safety over the lifecycle of vessels. This is the promise that the Industry 4.0 agenda makes and that HFE can enable.

This report is one of a series of reports arising from our IMCRC project with BAE Systems Maritime Australia. It's aim is a specific one - to help develop among key stakeholders a deeper understanding of the significance of human factors as determinants of the uptake and diffusion of advanced manufacturing and digital technologies. This work is the foundation for development, trialling and evaluation of appropriate HFE technology assessment and adoption processes in shipbuilding.

Our lead industry partners involved in the implementation of this project include Sharon Wilson (Continuous Naval Shipbuilding Strategy Director), Evangelos Lambrinos (Exports and Innovation Manager), Andrew Sysouphat (Principal Technologist - Hunter Class), Ivor Richardson (Project Manager – Strategic), Tom Snowden (Project Manager – Industry 4.0 Trials), and Mark Francis (Project Manager). Collectively we thank the Board of the IMCRC and David Chuter, CEO for their support for this project. We share their vision for growth of advanced manufacturing in Australia.

Professor John Spoehr,
Director,
Australian Industrial Transformation Institute

Executive Summary

The ambition to establish a world class 'digital shipyard' in South Australia is driven by the Australian Government's objective of modernising shipbuilding in Australia in support of constructing the most advanced surface and underwater vessels for the Australian Navy. More broadly it draws inspiration from the global Industry 4.0 agenda underpinning the modernisation and transformation of manufacturing. Industry 4.0 is underpinned by digital systems including the internet of things (IoT), internet of services (IoS), master data management (MDM), 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).

The fundamental premise of the digital shipyard is the vertical and horizontal integration of the shipyard infrastructure and processes. This connectivity provides a platform for the development of technical or digital functionalities that enable smart production, for example analytics, process automation and simulation and real-time monitoring through extensive use of sensors enabling control, condition monitoring and predictive maintenance.

Advanced manufacturing and digital technologies have the potential to transform the shipyard through improvements in productivity, accuracy and repeatability, traceability/visibility and health and safety. This is all dependent upon the successful uptake and diffusion of technologies and processes which is heavily influenced by a range of human factors.

There are likely to be many potential productive applications of advanced manufacturing and digital technologies in the shipyard. Shipbuilding can learn a great deal from other industry sectors where digital technologies are well established but the lessons from this cannot be slavishly applied in shipyards, particularly maritime shipyards where security and risk management are of paramount importance.

To promote discussion around what might constitute a digital shipyard this report discusses some of the core technologies and processes associated with digital transformation of manufacturing that might be applied in various ways in the shipyard and shipbuilding and sustainment processes.

Impact on physical work processes

Historically, shipbuilding has comprised labour intensive, complex, and hazardous tasks due to its scale, high level of customisation and harsh production environment. Most tasks are time intensive and demand high precision due to the large volume of parts manually installed and the requirement for high quality standards. Applications of advanced manufacturing technologies are likely to help deliver significant benefits where sufficient attention is given to human and ergonomic factors in technology assessment, trial and application processes.

Industrial robots are frequently fast-moving, heavy-lifting machines that require a deep understanding of robotic science in order to operate. **Cobots** have greater flexibility and applicability to tasks with higher variability, hence their increasing use in a variety of manufacturing tasks such as machine tending and assembly. They are designed to work collaboratively with human operators and have the benefit of reducing exposure to hazardous elements and ergonomic problems. Shipbuilding requires rigorous inspection and quality testing of tasks in often harsh and hazardous environments, for which there are specialist-designed **inspection robots** (e.g. snake-armed, four-legged, multi-limbed and swarm robots).

Automated guided vehicles (AGVs) are robotic platforms used predominantly as agents for logistical processes. They automate the manual tasks of transporting and processing goods, improving efficiency and productivity in manufacturing environments. A limitation of AGVs is their low capability for handling non-repetitive tasks as they have generally been programmed to move along designated routes. **Track and trace** technologies (e.g. barcodes, RFID transponders and GPS) facilitate real-time location and status updates on items in a process chain. Cobots and AGVs can be equipped with peripheral devices to enable them to read RFID tags or barcodes, expanding their functionalities within manufacturing processes.

Additive manufacturing, or 3D printing, is a process of fabricating digitally represented objects, enabling businesses to rapidly prototype tools or components prior to production. This offers value to shipbuilding and lifecycle management owing to the efficiency of producing components using 3D printers compared with sourcing them through a complex supply chain. Challenges include applying the technology at the vast scale and in the complex context of shipbuilding; and managing the requirement for accredited certification of components.

Impact on workflow

Physical tasks in the shipbuilding process rely on information provided by different organisations involved in engineering, design, and procurement among other functions. It is important to achieve an efficient and continuous data flow across the project lifecycle, from engineering through to operation, and across various systems in the production process, including supply chains. Digital work management (DWM) converts the workflow from ‘paper-based’ to ‘digitalised’ for optimal workflow management. It provides access to real-time digital data, allowing effective work management and paperless communication that leads to time saving and improved productivity.

Information management software involved in the digital transformation of shipyards includes Digital Work Management (DWM), product data management (PDM), and product lifecycle management (PLM). Data attributes of work are updated either manually or autonomously on digital platforms, providing paperless instructions (and other information) in real time. A potential drawback is the need to carry additional smart computing devices in sometimes harsh and unaccommodating environments.

Big data refers to a set of tools and methods used to harvest, manage, and systematically extract useful information from data that is too large or complex for traditional statistical methods. In the digital shipyard, industrial data are collected from a range of data sources. Human and AI **analytics** is performed on the data generating summary data (e.g. mean cycle-times for production), enabling prediction (e.g. predicting time-to-failure of production machines) and generating prescriptive actions in order to streamline production and management of the enterprise. **Data visualisation** is a means of presenting data pictorially or graphically and reduces the amount of time and resources needed to capture, communicate and act on critical information.

Impact on design and quality

Advancements in modern computing have given the IT industry access to advanced graphical computational capability. This makes it possible to simulate an entire manufacturing process in a virtual environment that does not physically exist. A **digital twin** is a virtual representation of an IoT device, giving a detailed representation of how it operates throughout its lifecycle. Modelling and simulation of a product can validate and support design choices and system properties, assist in the early identification of potential flaws in the development cycle and reduce time to market. In a legacy shipyard, work status or progress is manually updated on systems by taking photos and through repetitive site visits. Strategically positioned **3D laser scanners** can bypass these time-consuming activities by quickly and accurately capturing existing physical objects and tasks and feeding updated data into the digital twin.

Virtual reality (VR) tools such as VR Headsets or VR ‘domes’ can be used to visualise a simulated process through a first-person perspective, as if it was real. **Augmented reality (AR)** can visualise a simulated process projected into an area. **Light virtual construct (LVC)** is a more complex method that mixes real-world events into the AR simulation and display. Useful applications for these technologies include training and education, enabling risk-free simulated exposure to complicated scenarios and hazardous tasks. Legacy shipyards involve extensive inspection processes, both automated and manual. AR can support human inspection tasks through mobile devices and AR headsets, enabling inspectors to access, collect and process data while leaving the hands free. VR provides real-time information that can support remote and proactive maintenance without the need for physical site surveys.

Opportunities and challenges

The digital shipyard presents a multitude of benefits and opportunities as well as challenges that need to be addressed for the vision to be fully realised. Digital transformation has the potential to deliver improvements at every stage of a project cycle, through better integrated systems, smart allocation of resources and instant feedback loops. In the shipyard, the value proposition is evident both vertically and horizontally. Digital transformation increases safety and quality, improves accuracy and reduces paperwork, and replaces mundane, repetitive tasks. These advancements can lead to improved worker wellbeing, alongside substantial business improvements.

Digital transformation involves networking physical entities to digital entities and vice versa, which exposes businesses to the threat of cyber-attack. Effective counter measures include methods to rapidly decouple networked systems and **powerful data encryption**; internal and external collaboration with partners, including government agencies, large companies and international bodies to develop overarching cybersecurity frameworks; and enterprise-wide understanding of applicable information security standards, such as IEC/ISO 27001.

Small and medium size enterprises carry financial and business risks such as significant capital investment in digital infrastructure and exposure to new competitors through horizontal integration. Organisations must develop risk management capabilities, and the competencies embedded in its people and processes to complement technology investments

Transformation to a digital shipyard represents a profound organisational change and requires a rigorous **change management** approach. Contemporary naval shipbuilding is transforming from practices inherited from traditional heavy engineering and manufacturing to the digital integration of research and development, design, production, systems integration and through-life support, together with collaboration along the value chain. Naval shipbuilding is also one of the most complex and knowledge-intensive value chains of industrial activity, characterised by high levels of organisational, functional and production interdependency within and between firms in the value chain. Given this complexity, the processes of modern shipbuilding are replete with positive dynamic knowledge spill-overs. Shipbuilding often requires intensive experimentation and near-concurrent design, testing and production of some components.

The development of Industry 4.0 capabilities through the application of advanced technologies and management competencies will change the **nature of work**, *what* people do, *where* they work, and *how* work is done. Trends in automation have significant implications for people in occupations involving predictable physical work. Routine tasks are more easily automated requiring consideration of the implications of automation for work roles/duties. While some tasks may no longer be required others are often created. This has industrial, career development and education/training implications. Skills in demand will increasingly be those requiring the application of cognitive expertise, interaction with complex systems, stakeholder management and problem solving. Human-machine interactions will be more central to the workday, signalling demand for easy to use human/machine interfaces that have a high level of employee acceptance, enhance learning, and maintain engagement and satisfaction. A sophisticated training and skills management regime is required to deliver the vision of Industry 4.0, together with necessary organisational and cultural changes to support these key capabilities. Effective knowledge management systems and practices are necessary to value, capture and codify tacit knowledge and skills.

The successful uptake of Industry 4.0 technologies such as AGVs, RFID and cobots requires novel capabilities and introduces new skills requirements in the **workforce**, even among highly technical employees. An inherent challenge is to develop and align human skills to optimise technological outputs, ranging from fabricated products to production processes and decisions. For fabricated products, the emphasis is on optimising collaboration with robots and automation; in the production of processes (e.g. procurement and logistics) and decision-making, the emphasis is on effective human-AI collaboration.

A major challenge for shipbuilding capability is the fabrication of low-volume/high-value customised components for the ship across **the supply chain**. Aligned frameworks for quality, compliance, cost, efficiency, and flexibility are needed across all organisations involved in the manufacturing process, as well as the various sub-components and interim products. To counter affordability constraints, SMEs in the supply chain need to develop internal and external collaboration strategies to support the production of sufficiently complex components and integrated interim products. A key challenge is the lack of standards and norms relating to the integration of interfaces and IT systems between organisations (horizontal integration). Without consistency in requirements, organisations may be limited in the value networks they can join, which may impede their competitiveness and future viability.

Interconnection, instrumentation, and intelligence are identified as key properties of smart systems. These three properties represent functionalities for **acquisition, transmission, processing, and utilisation of data**. In the digital shipyard, The Internet of Things (IoT) provides key instrumentation and interconnection functionalities using data collection capabilities. The mass deployment of IoT devices in the shipyard creates the platform for big data capabilities which supports analytics, autonomy, flexibility, and value chain integration. Big data enables track and trace applications for equipment and people, thereby facilitating optimised inventory management, operational agility and safety. Big data from cyber-physical systems facilitates predictive capabilities for product maintenance, asset management and supply chain efficiency.

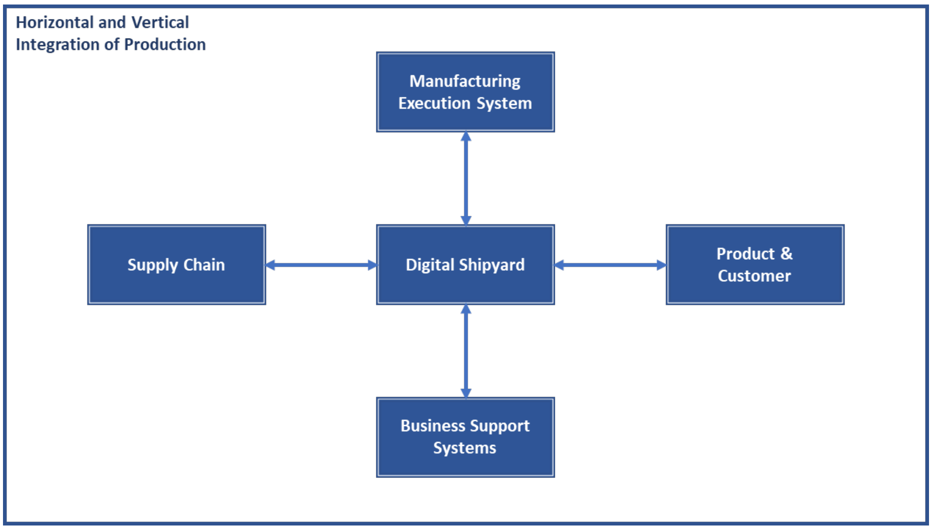
The digital shipyard is the Industry 4.0 blueprint for the modern shipyard. It is characterised by the integration of people, processes, tasks, and technologies that enable the digital transformation of shipbuilding and sustainment. The vision promises great benefits in terms of quality, effectiveness, efficiency, safety and reliability. There are challenges to overcome in the pursuit of these benefits, including issues relating to cybersecurity, technology acceptance, work roles/tasks, capability building and leadership. All of these require attention in pursuit of the vision of the Digital Shipyard

1 The digital shipyard in the age of Industry 4.0

The vision of the ‘digital shipyard’ aligns with the wider Industry 4.0 agenda that 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, Industry 4.0 transforms production systems and products into inter-connected, intelligent systems and products by embedding digital functionalities into production processes and products (Lichtblau et al., 2015; Wang, Törngren, & Onori, 2015).

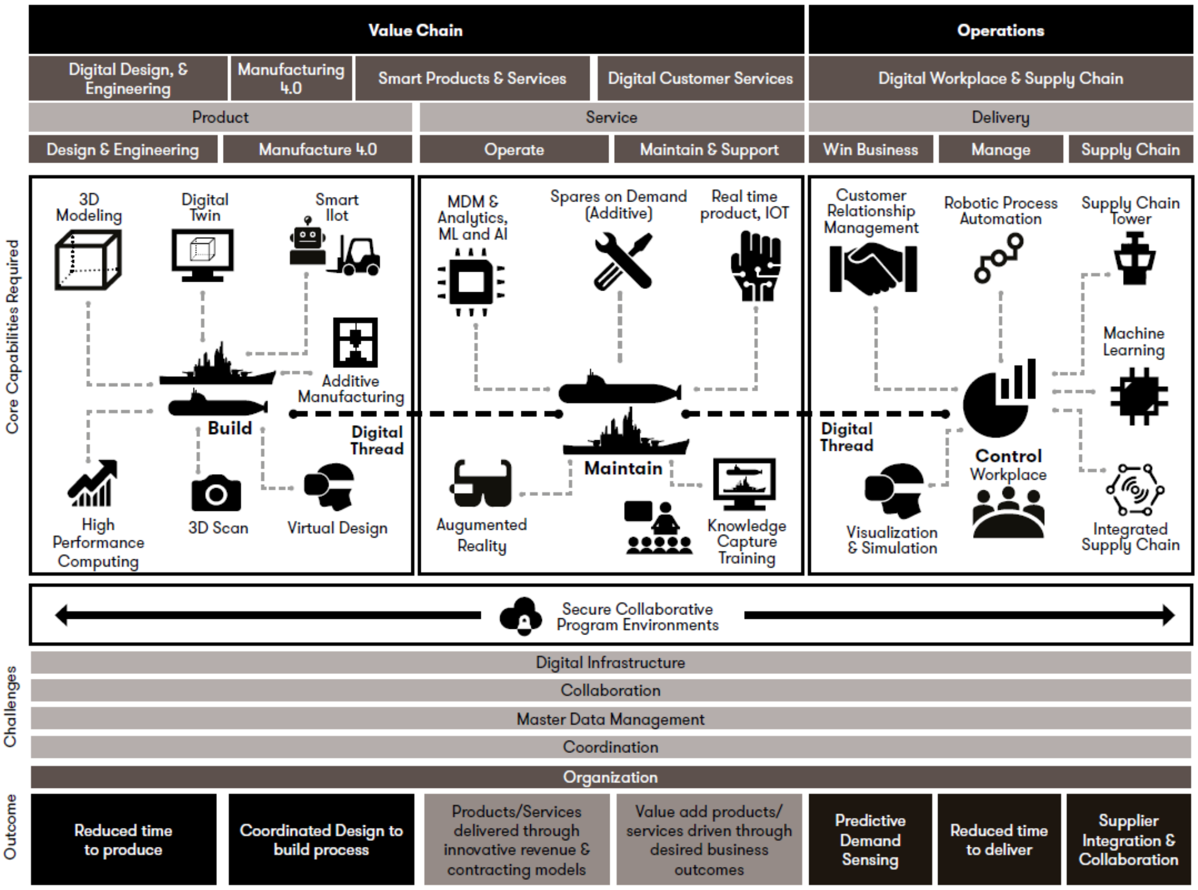
The digital shipyard represents a significant evolution of shipbuilding. For most of the last century maritime shipbuilding has been a siloed and largely analogue process. The fundamental premise of the digital shipyard is the vertical and horizontal integration of shipyard infrastructure and shipbuilding processes (see Figure 1). Vertical integration transforms the production process by connecting production system components, enabling cyber physical systems functionalities within an organisation. It facilitates information exchange across business functions, resulting in more accurate production planning and greater capability to produce low volume/high mix products (i.e. customisation) (Liere-Netheler, Packmohr, & Vogelsang, 2018; Muller, Kiel, & Voigt, 2018). Horizontal integration refers to the “exchange of materials, energy and information within a company (e.g. inbound logistics, production, outbound logistics, marketing) and between several different companies (value networks)” (Kagermann, Wahlster, & Helbig, 2013, p. 20). It connects the value chain from the customer to the supply chain, enabling the entities that compete and cooperate in the process to be organised into a functional ecosystem. This connectivity provides a platform for the development of technical (or digital) functionalities that enable smart production, for example analytics, process automation and simulation.

Figure 1: Horizontal and vertical integration of production



A digital shipyard integrates industry 4.0 technologies and systems to manage, monitor and optimise all shipbuilding processes from engineering to maintenance, as well as encompassing the entire supply chain (see Figure 2). The impact of digital transformation on shipbuilding processes can vary and different values and implications can be expected. For instance, industrial robots can provide value in undertaking labour intensive and high-risk tasks whereas digital technologies optimise the workflow from engineering to delivery.

Figure 2: Digital shipyard Value Chain Vision



Source: Ash (2018)

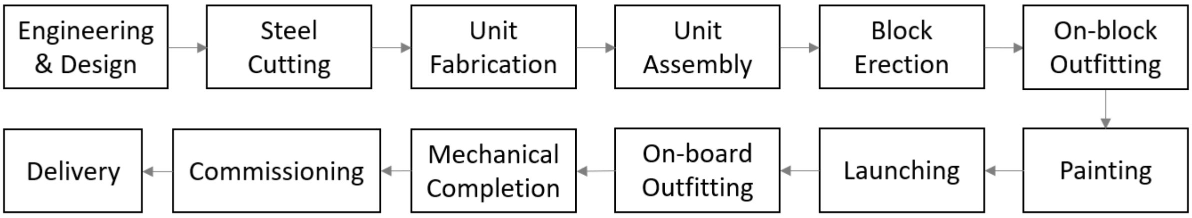
The digital shipyard vision involves the establishment of smart infrastructure designed to create a smart product and a delivery model that provides ongoing operational support and support services to customers. Product lifecycle management (PLM), digital twins and 3D modelling functionalities in shipbuilding enable a ‘360 degrees integration’ of the product (production and design processes) enabling the complete and continuous inspection of the product and parts from the design phase through to when the product is decommissioned.

The following sections of the report explore various technologies and processes commonly associated with Industry 4.0. The potential application of some of these in support of digital shipbuilding is the subject of research trials underway in partnership with BAE Systems Maritime Australia and the Innovative Manufacturing CRC.

2 Digitalisation and shipbuilding

While there are opportunities for the application of advanced manufacturing and digital technologies throughout design, build and sustainment processes, these vary enormously from product to product. Shipbuilding is a complex, large scale production process similar to other heavy manufacturing industries, sharing issues such as project-based production and overall product complexity (Bock, 2015; Castro-Lacouture, 2009). Production is undertaken in various stages ranging from steel cutting to launching (see Figure 3). Advanced manufacturing technologies such as automated welding and task setting have already been introduced into some traditional shipbuilding stages (Maharjan, 2019).

Figure 3: Shipbuilding process



The shipbuilding process involves a range of hazardous tasks requiring special skills and can be physically and psychologically demanding. Typical scenarios include handling pipe spools to make alignments, pulling and installing cables, painting, and touching up large area surfaces, and erecting and dismantling a large amount of scaffolding to support construction. Other activities include the shifting of heavy steel by cranes and forklifts, handling of heavy tools and equipment, using gas and oxygen, and working at great heights and within confined spaces. Blocks (or assembled units) can easily weigh hundreds of tons or more, and crane operations involve lifting several of these during block assembly. Consequently, various safety rules and procedures are commonly used in the shipbuilding process.

A further consideration is that many shipbuilding processes are often performed outdoors and are impacted by weather conditions. Climate is an important factor in deciding a shipyard's location and even though most shipyards are in geographically desirable locations, temperature, wind, and rain can easily influence productivity. Additionally, most ships are made of steel and require a great deal of welding, cutting, and pulling tasks under specific work categories. These tasks consist mostly of structure, pipe and cable work.

The legacy[1] shipyard is thus a large landscape of analogue, and very physically exerting activities taking place at scale, lending it to optimisation using digital tools and methods. Opportunities for transformation exist on three levels: (1) digitising systems and processes by introducing sensors, actuators and network connectivity, thereby enabling IoT implementation for vertical integration of the factory; (2) implementing digital business support systems such as supply chain management (SCM), analytics and enterprise resource planning (ERP) to integrate the value chain (horizontal integration) and optimise processes; and (3) developing smart functionalities such as autonomy and flexibility.

2.1 Impact on the physical work environment

Shipbuilding is comprised of labour intensive, complex, and hazardous tasks due to its scale, high level of customisation and harsh production environment. For instance, a single ship project can contain millions of parts and hundreds of heavy components including steel, pipe, cables, mechanical equipment and outfitting (Gourdon & Steidl, 2019). The overall production of a single ship takes an average of one to two years, translating to millions of labour hours on a single project. The resource intensiveness is attributed to industry-intrinsic issues of heavy and low volume manufacturing (Bock, 2015). During the production stage, physical tasks include cutting,

[1] Legacy shipyard is used to describe shipyards that largely use traditional non-digital shipbuilding techniques.

bonding, welding, task setting, assembling, blasting, painting, pulling, bolting, installing, and transporting. Most tasks demand high precision and are time intensive due to the large volume of parts manually installed into the ship blocks and requirement for high quality standards.

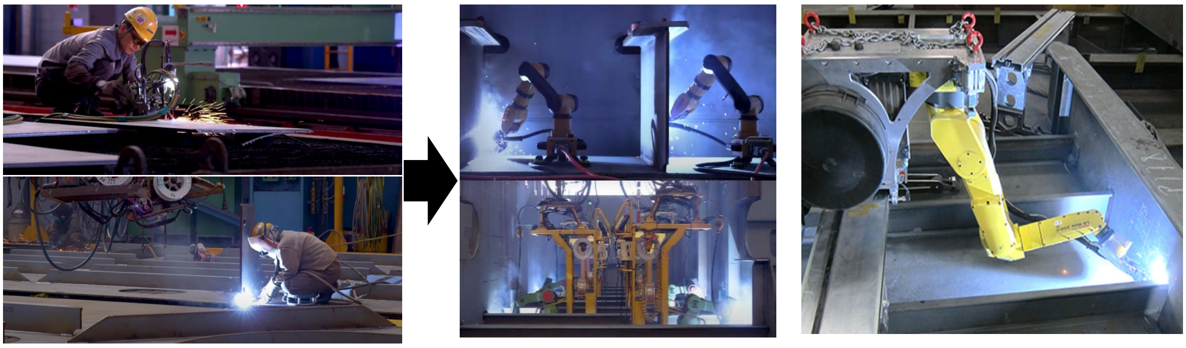
Robotics is useful technology to support shipyard transformation as machines can be designed to undertake tasks autonomously, with high speed and accuracy. A wide range of robots with diverse applications have been developed to improve industry performance. Industrial robots are widely used for repetitive tasks in high-volume manufacturing (e.g. in the automotive industry) whereas collaborative robots (cobots) are commonly used for tasks that require high flexibility in close proximity and collaboration with workers. In the advanced digital shipyard context, there is potential for robots to improve physical task performance, thereby influencing business outcomes relating to productivity, quality, cost and safety. For illustrative purposes, the following sections outline relevant applications of robots and autonomous systems in different industrial contexts.

2.1.1 Industrial robots and cobots

For repetitive tasks (e.g. bonding, cutting, setting) or time-consuming tasks (e.g. thick welding), workers spend a significant amount of time completing tasks. Industrial robots or cobots can reduce working time by performing high-speed, repetitive and lengthy tasks with a high level of accuracy. Structural work in the shipyard is often ergonomically challenging and hazardous as steel is extremely large and heavy. Robotic applications can significantly improve worker productivity and reduce exposure to hazards (see Figure 4). Prime candidates for industrial robotic applications are quality inspection tasks following task completion, including visual examination and non-destructive examination (NDE).

Figure 4: Transformation from manual structural work to robot structural work

Traditional Shipyard	Digital Shipyard	
Manual structural work	**Robot structural work**	**Inrotech's industrial robots**



Source: DSME (2020) | Source: DSME (2020) | Source: Inrotech (2020)

Industrial robots are often fast-moving, heavy-lifting machines that often require a deep understanding of robotic systems and programming to operate. This level of understanding is generally gained through years of advanced scientific study or training. Furthermore, industrial robots create a degree of disorder in their immediate environment that can present safety issues for humans. Cobots on the other hand are slower-moving, generally very safe to operate, and are regulated by different standards (ISO, 2014). The cobotic platform does not require deep scientific knowledge to operate, lowering barriers to its uptake and application, particuarly because it requires less user training and is less expensive to install.

Compared with industrial robots, cobots have greater flexibility and applicability to tasks with higher variability, hence their increasing use in a variety of manufacturing tasks such as machine tending and assembly (Cherubini, 2016). Cobots have distinctive features that allow humans to work collaboratively, safely, and flexibly within narrow spaces. This collaborative feature can mitigate ergonomic and safety problems, for example cobots can be trained at a distance by humans using AR/VR, thus reducing the frequency of direct contacts with harmful elements. This has important workforce health and wellbeing implications. Integration of cobots into industrial processes can also address human ergonomic factors such as posture and physical and cognitive loads, further eliminating hazards.

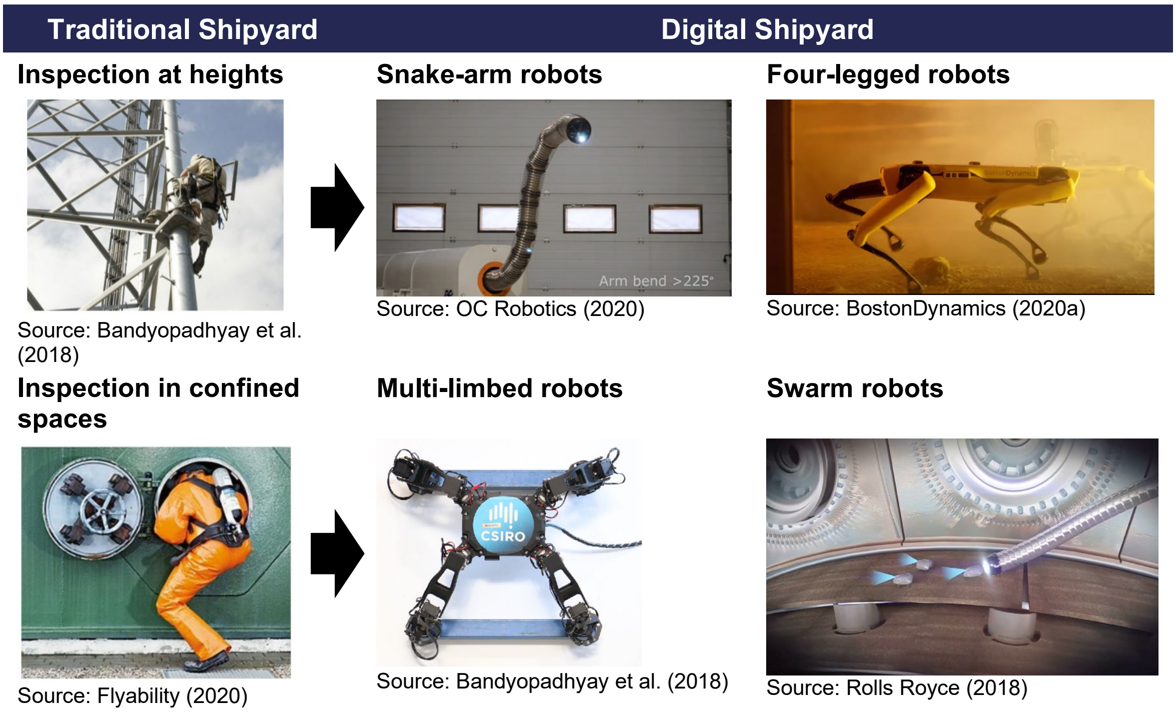
The size of the shipyard, the ship block and the size of materials such as pipes and steel influence work design in shipbuilding. Many tasks are undertaken in large areas in the shipyard, so portability and traceability of tools is an important consideration. In this context, the ability of a robotic agent to move around in shipyard terrain safely without human involvement is likely to be valuable.

2.1.2 Inspection robots

Following completion, most tasks require quality testing and inspection for completeness and correctness by quality management teams. The inspection can be physically demanding and hazardous as many locations in the shipyard are harsh environments. Inspections may require extraordinary human efforts such as working at heights, entering confined spaces with complex safety procedures, dismantling parts and installing scaffolding to access inspection points.

Inspection robots have the flexibility to eliminate the need for extraordinary human physical efforts and serve to optimise the inspection process. Snake-arm robots or four-legged robots can be used for inspections in harsh environments, for example blasting inspection in confined spaces. Magneto robots are suitable for inspection at heights while swarm robots can be used to inspect small mechanical components such as turbine engines (see Figure 5).

Figure 5: Transformation from manual inspection to inspection robots



Shipbuilding is a low volume, high mix industry with a high level of flux in work and production over time. Site surveys are undertaken to monitor and report on the production progress, identifying issues such as task delays, quality issues and the need for preventive maintenance (Torres Saenz, 2018). Production progress monitoring can be optimised using inspection robots such as four-legged robots, which are capable of delivering effective and efficient assessments and streamlining the allocation of tasks and resources (Balasingham, 2016). Inspection robots allow real-time data collection and remote visual inspections, thereby reducing human operator safety issues and improving inspection efficiency.

2.1.3 Automated guided vehicles (AGVs)

Automated Guided Vehicles (AGVs) are robotic platforms used predominantly as agents for logistic processes in a wide variety of industries such as manufacturing, mining, and agriculture (Ullrich, 2015). Logistic requirements are a key consideration in the shipyard due to its physical size and many moving parts and destinations. The logistical complexity of the shipyard extends across warehouses, work sites, various parts and components, and project parameters. During the shipbuilding process a wide range of components including structural steel, pipes, cables, valves and outfitting are supplied, handled and transported. Shipyards do not typically employ just-in-time scheduling of supplies, so these components need to be stored in warehouses until the work order is issued by production teams. This operation requires mechanical supports such as forklifts depending on the size, weight or height of the objects (Figure 6).

Figure 6: Transformation from manual to AGV forklifts

Traditional Shipyard	Digital Shipyard
Manual forklift	**Forklift-type AGV**

Source: Depositphotos (2020)

Source: Casun (2020)

AGVs automate the manual tasks of transporting and processing goods, thereby improving productivity in the manufacturing environment. AGVs are a smart solution capable of "making decentralised decisions to avoid collisions and establish the best path planning possible to reach its destination" (Sánchez-Sotano, Cerezo-Narváez, Abad-Fraga, Pastor-Fernández, & Salguero-Gómez, 2020a, p. 8). Many OEMs and equipment suppliers of robotics and automation equipment also now typically offer many brands of modern AGVs. The current state of the AGV market can be categorised into two classes. The first are lower cost and utilise older navigation methods such as following strips of magnetic tape. The second are more expensive, offer powerful on-board processing capability and network connectivity options which allow for smarter navigation capabilities among other 'smart' benefits (Clark, 2019). These navigation capabilities are implemented through robust map creation and navigation algorithms such as simultaneous localisation and mapping (SLAM) (Smith, Self, & Cheeseman, 1990). The flexibility and autonomous functionalities of AGVs can contribute to key efficiencies and productivity improvements in the smart factory.

In the shipbuilding warehouse, outfittings and consumables are commonly organised by warehouse personnel. Given the large volume of components, rework is often required to reorganise various materials and outfittings into order. Warehouse operations receive site requests for outfitting components on a daily or weekly basis and it can take time for the ordered components or consumables to be picked up and transported back to the site area. AGV adoption can reduce the material preparation time improving work efficiency and address "inaccurate workflows, ultimately reducing waste and increasing output, allowing operations to become more productive and accurate" (Conveyco, 2019). The autonomous function of AGVs can reduce the processing time, particularly where components are traceable by AGVs.

While AGVs can improve work efficiency in some cases, they can have limited flexibility (see Table 1). For example, a human forklift operator can detect obstacles and address issues immediately to prevent accidents, whereas this is not always the case with AGVs. Non-repetitive tasks can be challenging because AGVs are generally programmed to move along designated routes. More research is needed to ascertain the most efficient means of addressing transportation tasks.

Table 1- Different features between AGV and Existing method

	Operation	Process	Flexibility	Suitability	Safety
AGV	Autonomous (Slow reaction)	Algorithm	Programmed route	Repetitive	Navigation Sensor
Existing (Forklift)	Manual control (Quick reaction)	Human decision	Human control	Ad hoc	Human error (Tipping)

2.1.4 Additive manufacturing

Additive manufacturing (or 3D printing) is a process of fabricating digitally represented objects with geometrical dimensions that are well defined by producing 2D slices of the complete 3D model in layers. Throughout the 2010s, 3D printing technologies became vastly cheaper and more advanced. This now presents the opportunity for businesses to rapidly prototype tools or components before machining or fabrication.

The main benefits of using 3D printing as a prototyping method include reduction of cost, freedom of design and rapid prototyping. Applications of 3D printing extend to the biomedical, aerospace and construction industries (Ngo, Kashani, Imbalzano, Nguyen, & Hui, 2018). Smaller, cheaper 3D printers are a useful starting point for smaller businesses, 3D printers with large print beds and automatic material management are ideal for larger businesses whereas large industrial printers offer capacity to print at very fine resolutions, self-clean and utilise pre-mixed composite materials or mix materials as needed for more complex operations. Additive manufacturing for metallic materials is also available through some providers and creates opportunities for wider applications.

There are hundreds of thousands of components used in a single ship production. In addition to the essential components installed in the production phase, temporary parts such as dummy spools are also manufactured, to be replaced by valves in later stages. Many spare parts are required for maintenance activities such as replacement of gaskets or filters in the operations phase. The procurement of components introduces complexity into the shipbuilding process as they are sourced from many different suppliers across the globe. Additive manufacturing can offer value to shipbuilding and ship lifecycle management as it is more efficient to produce some components using 3D printers rather than sourcing them through complex supply chain.

The development of metallic 3D printing capabilities has increased the relevance of additive manufacturing in the shipbuilding sector. For example, US based Newport News shipbuilding company has adopted 3D assitive manufacturing systems with a 3D metal printer (see Figure 7) to produce “marine-based alloy replacement parts for castings, as well as valves, housings, dummy spools, and brackets, for future nuclear-powered warships” (CISION, 2018).

Figure 7: Transformation from metal component manufacturing to Metal 3D printing

Traditional Shipyard	Digital Shipyard
Metal component manufacturing	**Metal 3D printer ProX DMP**

Source: 3DEO (2017)

Source :

There are considerable challenges involved in adopting additive manufacturing in ship production. Ships are larger in size and scale than products in most other industries, and the size of their parts and components is a key factor as 3D printed products are limited to the 3D printer's capacity. Although there are some applications involving large size projects, for example the production of a 3D printed house, challenges persist due to the vast scale and complexity of shipbuilding. Additionally, due to the complex operation and extended lifecycle of ships, most components are required to be certified by an accredited certification body such as DNV-GL and Bureau Veritas (BV). This has led to a new additive manufacturing certification approach including "certification, qualification, verification, classification, advisory, design approval, product testing, inspections and consulting" (DNV-GL, 2020).

2.2 Impact on workflow

The majority of physical tasks in the shipbuilding process rely on information provided by different organisations involved in engineering, design and procurement among other functions. Various digital forms of data are created and managed using different IT software and systems. The information exchange involves thousands of stakeholders, however the process is still predominantly paper-based, including drawings. Coordinating document controls requires tremendous effort from workers across the entire project lifecycle. For instance, at the handover phase, numerous paper-based records are transferred to clients, requiring manual processes to import the information into the recipient's maintenance and operation processes.Thus, a major challenge is to have an efficient and continuous data flow across the project lifecycle, from engineering through to operation. The holistic integration of various systems in the production process, including supply chains, is essential (Michaud, 2018).

Digital work management (DWM) converts a workflow from "paper-based" (including workorders, drawings, work permits etc) to "digitalised" for optimal workflow management. DWM can support employees to gain full access to real-time digital data which allows effective work management and paperless communication. This can reduce the time spent on preparing extensive documentation and mitigate poor communication, resulting in time saving and improved productivity.

2.2.1 Information management software

A wide range of information management software is available for use in the digital transformation of shipyards, including product data management (PDM), work order management and product lifecycle management (PLM) applications. Information management solutions are widely used for digital information integration of processes, people, data and systems. Various suppliers (e.g. AVEVA, Siemens, Dassault Systems) provide solutions targeting diverse digital shipyard requirements.

In legacy shipyards, supervisors or forepersons prepare daily work orders using paper-based drawings, procedures, work permits, lists of materials, tools required and so forth. Work orders are distributed with required documents such as drawings and specifications. During task performance, most communication on task status and progress is updated on paper-based work orders.

Introducing advanced information management systems allows work orders to be managed digitally. Data attributes of work are updated either manually or autonomously on the digital platforms, making instructions and other information available to workers in real time and without paper and its associated tasks. This digital work order system can improve productivity and work quality as well as facilitate decision making. The application has potential to span all phases of the shipbuilding process.

Figure 8: Transformation from paper-based to digital work ordering

Traditional Shipyard	Digital Shipyard
Paper-based work	**Digital work order**

Source: Benarroche (2020)

Source: Melo (2019)

Digital Work Management can be challenging in a harsh environment as it requires workers to physically carry additional computing devices (e.g. Smart Phone, Tablet, etc). The shipyard working environment involves working at heights and in confined, narrow spaces, dealing with hazardous environments and wearing personal protective equipment (PPE). The ergonomic and process impact of using digital work management devices in harsh environments has not been established.

2.2.2 Big data, analytics, visualisation

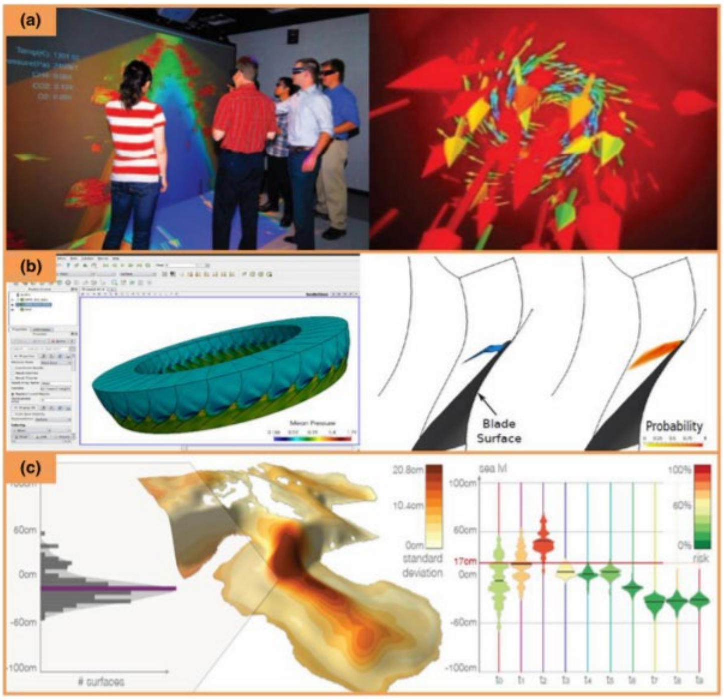
Big data refers to a set of tools and methods used to harvest, manage and systematically extract useful information from data that is too large or complex for traditional statistical methods. The size and complexity of these datasets are important characteristics, and ultimately determine the data's utility. Analytics is the application of computational and statistical methods to data to identify patterns and generate predictive capability. It is fundamental to machine learning and artificial intelligence which underpins smart systems. Data visualisation is a means of presenting data pictorially or graphically. Whereas the utilisation of big data involves exploration and analysis, the objective of visualisation is to provide users with a mechanism for engaging with data in a manner that exploits human intuition and enables human interpretation (Bikakis, 2018).

In the context of Industry 4.0, industrial data are collected from a range of data sources and captured in a 'data lake'[2]. Human and AI analytics is performed on the data to generate summary descriptors (e.g. mean cycle-times for production), enable prediction (e.g. predicting time-to-failure of production machines) and to generate prescriptive actions to streamline production and management of the enterprise. Data visualisation reduces the amount of time and resources required to capture and communicate critical information to translate into prescriptive actions. Data complexity can be made accessible, understandable and usable through visualisation approaches.

[2] A scalable centralised data repository for storage of both structured and unstructured data.

In smart manufacturing settings such as the digital shipyard, shopfloor data visualisation may be presented to the user through augmented reality, virtual reality and screen-based interfaces, such as is shown in Figure 9.

Figure 9: Examples of data visualisation in smart manufacturing settings



(a) Augmented reality (b) virtual reality (c) screen-based interfaces
Source Zhou et al. (2019)

2.3 Impact on design and quality

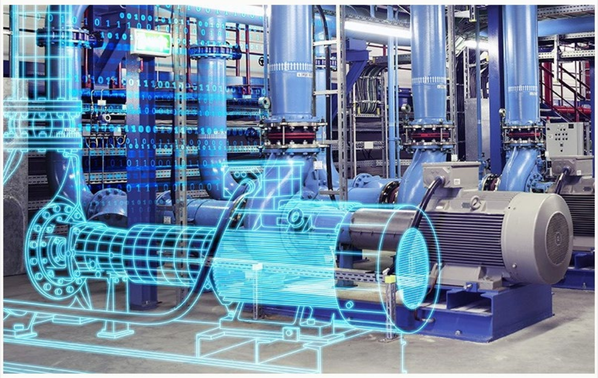
2.3.1 Digital twin technology

Advancements in modern computing have given the IT industry access to advanced graphical computational capability. This makes it possible to simulate an entire manufacturing process in a virtual environment that does not physically exist. A digital twin has been described as *"a virtual representation of the elements and dynamics of how an IoT device operates, works and lives throughout its lifecycle"* (IBM Internet of Things, 2017). A well planned and implemented digital twin solution should influence product design, manufacturing process and operation of the product in its lifecycle.

The complete 3D model of a digital twin can also serve as a simulation tool at a high level of detail, down to nuts and bolts or even electrons where scanning is undertaken. Modelling and simulation of a product can not only validate and support design choices but also validate system properties. Simulation of product use over a lifetime can assist in the early identification of potential flaws in the development cycle and reduce time to market (Boschert & Rosen, 2016).

The value of digital twin simulation is that it can be performed in advance of any physical build process, including operational prototypes. Scenarios such as a disaster can be simulated to provide more complete information in the design phase (see Figure 10). Although the simulation is based on a physical layout, it can confirm various extraneous factors such as "compartment materials, flammable substances, ventilation, installed fire-suppression systems" (DXC.technology, 2020). Problems can be identified before a single piece of steel is cut.

Figure 10: Simulated scenarios using digital twin and AI technology

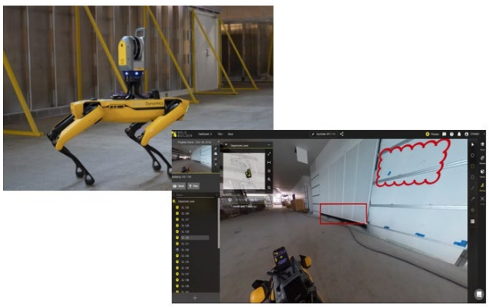
Simulation of fire spread using digital twin and AI	Digital twin in production phase
	
Source: DXC.technology (2020)	Source: Standford (2020)

In shipbuilding, digital twin technology has scope to mitigate costs associated with change and development. In the engineering and design phase, errors often arise due to poor communication between disciplines, poor understanding of the product operations context and/or changing customer requirements. A digital twin has the potential to improve the quality of communication by providing an accurate representation of functionality and an opportunity for internal stakeholders to identify and review potential challenges before they are actualised.

In the production and operation phase, a digital twin can provide visual guidance concerning production activities. This assists workers to plan and collaborate more effectively with other involved disciplines. Also, a digital twin can capture all operational data collected from the physical twin using hundreds of sensors on site. This facilitates real-time operation or maintenance by sharing all relevant information about issues and interactions in a ship's operation.

3D laser scanners can be used to capture and update all changes made across the project lifecycle. In a legacy shipyard, work status or progress is manually updated on systems by taking photos and through repetitive site visits (see Figure 11). 3D laser scanners can bypass these time-consuming activities as they are able to quickly and accurately capture existing physical objects. The scanners can reduce the level of effort involved in capturing changes in physical objects, with captured data used to update digital information for the latest digital twin. Updated information can be used for various activities in shipbuilding processes, for example dimensional control can be achieved by ensuring the scanned dimensions align with the intended design.

Figure 11: Transformation from manual to autonomous progress updates

Traditional Shipyard	Digital Shipyard
Manual progress update	**Autonomous progress update**
	
Source: BostonDynamics (2020b)	Source: BostonDynamics (2020b)

2.3.2 Virtual reality (VR), augmented reality (AR) and light virtual construct (LVC)

Virtual reality (VR) tools such as VR Headsets or VR domes can be used to visualise a simulated process through a first-person perspective, as if it was real. Augmented reality (AR) can be used to visualise a simulated process projected into an area. AR uses live input video from a camera(s), mixes the input with simulated images and displays the information for the user through projections onto a visor, smart glasses, edge computing device or similar headset technology such as VR. Light virtual construct (LVC) is more complex and is a method to mix real-world events into the AR simulation and display.

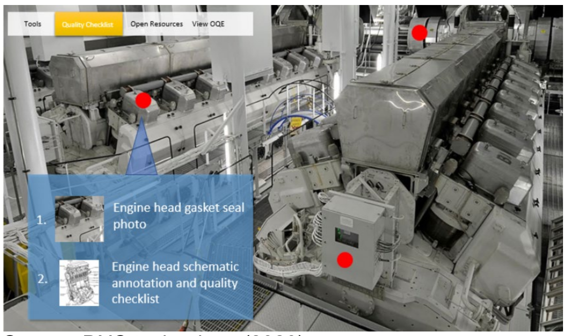
Safety education is critical in legacy shipyards, with employees frequently required to update their awareness of safety procedures, practice and guidance for ship production. The education process itself can be hazardous, with potential exposure to high-voltage cables, heavy pipes and sharp or flammable objects. Other technical trainings and skill development exercises contain similar risks.

VR and AR can improve safety, quality, cost and efficiency by optimising training procedures and processes. VR can improve safety training for all employees by enabling risk-free exposure to simulated risky tasks (VREDDO, 2020). The technology also allows exposure to more complicated scenarios and provides accurate assessment for learners (VREDDO, 2020). Training in virtual spaces reduces the size requirement of training facilities and need for tools, equipment and supplies. AR can usefully provide skills training for welders, electricians and others. A further argument in support of VR and AR training is heightened participant engagement due to the novelty of the format and participant enjoyment working with the technologies (Singh, 2018).

Inspection tasks are a fertile area for the application of AR. In legacy shipyards, inspectors need to document and revisit inspection histories which involve managing multiple documents such as checklists, drawings, specifications and so forth. AR can support the inspection task by reducing the level of effort involved. Mobile devices and AR headsets enable inspectors to access, collect and process data while leaving the hands free. The headset displays inspection checklists and information that can be managed by gesture alone and can also perform image analysis and comparison with digital twins to detect and highlight potential anomalies. This assurance functionality can also be applied to implementation, maintenance and operation activities as these share similar characteristics with inspection on site. AR technology overcomes the reactive nature of traditional maintenance, particularly its reliance on manual site indicators such as gauges and tags. VR provides real-time information that can support remote and proactive maintenance without the need for physical site surveys (see Figure 12).

Figure 12: AR and VR views of machinery space

AR view of machinery space	VR view of machinery space



Source: DXC.technology (2020)

Source: DXC.technology (2020)

3 Opportunities and challenges

Digital transformation promises benefits for individual employees, organisations and society more broadly. Very large-scale enterprises like shipbuilding could see substantial productivity, reliability and health and safety improvements flow from pursuing a digital shipyard ambition. For individuals, digital transformation is expected to lead to improvements in workplace conditions, typically regarding safety, ergonomics and job satisfaction (Liere-Netheler et al., 2018; Muller et al., 2018). A reduction in physically demanding and ergonomically unfavourable tasks is anticipated to promote long-term employee health and increased productivity. Decreases in monotonous and repetitive tasks alongside increased need for monitoring, collaboration and training are likely to increase worker motivation and satisfaction through more interesting work (Muller et al., 2018).

At an organisational level, the benefits of digital transformation can be both strategic and operational (Muller et al., 2018). New business models can be created through vertical and horizontal integration (Muller et al., 2018; Schroder, 2016). This facilitates transparency and flexibility across the supply chain, allowing better coordination of production stages (including shorter lead times and accelerated time-to-market, ensuring stock levels are consistent with demand), optimised logistics, traceability of products and improved quality assurance for customers, including a reduction in damaged goods and wrong deliveries (Liere-Netheler et al., 2018; Moktadir, Ali, Kusi-Sarpong, & Shaikh, 2018; Muller et al., 2018; Schroder, 2016).

Gains in process efficiencies (and thereby cost reductions) are also likely through smart components and products, which can monitor quality autonomously and enable predictive maintenance. This can result in reduced process faults and error rates, lower scrap rate and minimised downtime via a more reliable production system (Muller et al., 2018). The optimisation of task scheduling, processes and logistics can lead to reduced waste and energy consumption thereby improving overall environmental sustainability. Moreover, organisational carbon footprints are likely to be more traceable, potentially leading to reduced greenhouse gas emissions in alignment with social responsibility and reputational pressures (Moktadir et al., 2018; Muller et al., 2018).

However, the extent of such benefits is difficult to predict, given digital transformation relies on the implementation of a combination of technologies rather than a single system or technological development (Schroder, 2016). In addition, requiring the implementation of a suite of technologies presents a range of challenges that need to be overcome, largely by organisations, although individuals (employees) and external stakeholders (e.g. government) can also influence the capacity to do this. Consideration of the challenges prior to commencing or progressing the digital transformation journey may assist organisations to minimise any negative impacts (e.g. resistance to or rejection of the digital strategy). Underlying all challenges is the need for a clear digital strategy and suitable change management practices (Gobble, 2018; Kane, Palmer, Phillips, Kiron, & Buckley, 2015).

A range of challenges associated with the digital shipyard are addressed in the following sections.

3.1 The value proposition

The value proposition for digital transformation varies between stakeholders. We have given much consideration to the HFE value for workers focusing on improvements in technical and physical work practices leading to safer environments and fewer errors. These outcomes benefit employers who also gain from the availability of reliable, real time data, faster routine and bespoke processes. Moreover, they contribute to more dynamic, flexible organisations that can both predict and respond swiftly to challenges and opportunities.

Increasingly, adapting to Industry 4.0 technologies is no longer an optional path for business but a necessity. Digital transformation has the potential to deliver improvements at every stage of a project cycle, through better integrated systems, smart allocation of resources and instant feedback loops. Many customers are seeking smart and digital solutions and looking to engage with businesses that can provide these.

In the shipyard, the value proposition is evident both vertically and horizontally. Digital transformation increases safety and quality, improves accuracy and reduces paperwork, and replaces mundane, repetitive tasks. These advancements can lead to improved worker wellbeing, alongside substantial business improvements. For example, while shipbuilding has embraced three-dimensional (3D) computer aided design (CAD) for well over twenty years (Sánchez-Sotano, Cerezo-Narváez, Abad-Fraga, Pastor-Fernández, & Salguero-Gómez, 2020b) assembly, outfitting and inspection is often still conducted using two-dimensional (2D) drawings. As a result of this legacy process, valuable information is often lost or does not get translated efficiently through to equipment and personnel on the manufacturing shop floor. Sharing digital diagrams between trades workers, supervisors and management mean changes are instantly updated and the available version is always the most current (Sánchez-Sotano et al., 2020a).

At an enterprise level, the value proposition involves numerous areas of the business. Digitisation and integration of purchasing, supply chain and quality assurance can reduce duplication points and facilitate information sharing across the business. Digitisation can also act as a catalyst for streamlining fractured 'document-driven' enterprise resource planning (ERP) systems often found in SMEs with contemporary data-driven agile offerings (Ingram, 2019; Thomassen, 2019).

In order to make appropriate and sustainable decisions about the introduction of digital technologies and processes, businesses need to have a clear understanding of the value proposition for their enterprise. This requires assessment at multiple levels across the different streams of the business. We note that the value may be focused in one or two areas, with value in other areas less evident. However, we also note that in an integrated business, improvements in, for example, safety and quality may simplify compliance with the regulatory framework in which businesses operate and benefits are likely to flow through to customers, workers and supply chain.

The barrier to conducting such comprehensive assessments occurs in enterprises of all sizes and structures. For SMEs and start-ups, the issue is often a lack of internal research and development capabilities, expertise, and funding to support such assessments. Additionally, in large enterprises barriers to the uptake of innovations include a compartmentalised business model and poor communication between management levels and departments.

One approach to reducing this barrier is the creation of externally supported facilities which contain the equipment and expertise to help conduct such assessments. Multiple examples now exist around the globe with aim of de-risking the technology assessment process. Two such models of interest are the 'Factory of the Future' (Daniel, Kuhlmann, Köcher, Dauner, & Burggraaff, 2016) and 'Catapult' (Network, 2019) model concepts. These models aim to connect and align needs of government, academia, and industry to create a mutualistic environment where all parties benefit. Government outlines certain mandates and stretch goals to achieve and provides infrastructure and funds to help accomplish this. The value proposition can then be identified through academic and industry partnerships. This model provides a central repository of expertise and capital equipment which is available (at very low cost) to test its utility to business. Such facilities provide opportunities for academics to address both research and education gaps and upskill students and industry via new coursework, accreditations, and internships, amongst other things. Line Zero Factory of the Future at Flinders at Tonsley is modelled on such facilities. It is providing facilities and expertise to support innovation in the shipyard and SMEs and scoping activities to potentially expand into other industry sectors identified as high priority to South Australia and the Commonwealth (CSIRO, 2020).

3.2 Security and risk

The digital shipyard vision is fundamentally underpinned by the networking of physical entities to digital entities and vice versa. In pursuit of greater competitive advantage, digital transformation represents a profound shift in positioning critical data, information and functionality integral to the shipyard, and exposure to the digital space. This greatly increases the risk of cyberattack and necessitates extraordinary efforts to mitigate such risk. Such attacks can substantially impair business operations in the shipyard and result in the theft of highly confidential data and information.

Risk mitigation involves assessing specific systems and with the wider network of systems to which they belong, and then evaluating any changes to the risk/return proposition associated with introducing digital transformation. These processes need to be ongoing as they function within a dynamic and evolving cyber threat environment. In the event of a cyber-attack, methods to rapidly decouple networked systems need to be considered. Encryption of data is another important consideration. If it is inevitable that data will be decrypted, the goal is to make the encryption powerful enough to buy sufficient time to manage the risk. There is also the context of collaboration among organisations with different capabilities working together, signalling a need to protect partners in the channels and domains linking the organisations. Finally, government agencies, large companies and international bodies with bigger picture missions (e.g. anti-trust and protecting lives) need to play policy roles in managing the whole landscape of shipyards and affiliated agencies, including extending across borders in order to disincentivise competitive strategies based on cyberattacks.

In recent times, there have been concerted efforts to build knowledge for assessing cybersecurity risk and developing suitable cybersecurity strategies (Culot, Fattori, Podrecca, & Sartor, 2019; Schwab & Poujol, 2018). Key messages are that firstly, while all attacks cannot be stopped, cybersecurity risk prioritisation and mitigation practices ought to be a focus area for effective protection. Secondly, collaboration between the operational technology (OT) teams and information technology (IT) teams of a business are critical to create an overarching cybersecurity framework necessary to protect the digital organisation. Thirdly, there needs to be an enterprise-wide understanding of applicable information security standards. Finally, the shipyard needs to have the support of a wider ecosystem such as relevant industry associations, affiliated government bodies and academic institutions in promoting awareness of cybersecurity practices and to address risks associated with increasing connectedness of the value chain and the end product.

Beyond security risks, digital transformation introduces financial and business risks into the enterprise. Significant capital investment may be required in digital infrastructure, to support large hardware processor and memory requirements as well as broadband internet connection for enhanced utilisation of large data-sets in real-time (Schroder, 2016). Horizontal integration and new business models (with the potential to create entirely new industries) can expose established businesses to new competitors (Muller et al., 2018). Therefore, organisations may be reluctant to participate in the transformation process due to associated financial, technological and operational risks. This is particularly salient for SMEs that face increased resource scarcity relative to larger organisations (Schroder, 2016). The degree of capital investment required also varies by location and is dependent upon government provision of base infrastructure.

According to Gobble (2018, p. 68), “true digital transformation is risky, and successful organisations must develop a culture that encourages risk-taking and enables autonomy”. Organisations must develop risk management capabilities, and the competencies embedded in its people and processes to complement technology investments.

3.3 Change management

Naval shipbuilding is one of the most complex and knowledge-intensive value chains of industrial activity, characterised by high levels of organisational, functional and production interdependency within and between firms in the value chain. Given this complexity, the processes of modern shipbuilding are replete with positive dynamic knowledge spill-overs. Shipbuilding often requires intensive experimentation and near-concurrent design, testing and production of some components. These are highly positive features of this knowledge-intensive sector to the potential benefit of the ultimate customer (government) and the lead customer (prime), the participating enterprises along the value chain, and the economy generally.

However, these benefits can be realised only to the extent that there exists the structures, practices and governance not just to help create but also to capture these spill-overs. These governance structures and practices for knowledge- and innovation-management concern the internal organisation of individual enterprises and structured collaboration between enterprises in a value chain. The introduction of digital technologies and processes to naval shipbuilding have changed and augmented the importance of governance requirements and imperatives.

Lead customers and their suppliers transmit information and their issues, challenges and requirements along the value chain. Demanding lead customers can drive technological improvement and innovation along the value chain, whilst their suppliers feedback issues and potential opportunities as well as problems. These will often include new products, processes, technologies and organisational innovations. Beneficial spill-overs are created by this constant process of iterative problem definition and problem solving. This process has been described in a detailed case study by Eliasson (2010), who characterises such major large scale defence projects as creating ‘a technical university’, in which new knowledge is created and circulated on a larger scale and at a quicker pace as a result.

Such knowledge and competence transfer, feedback and flow is not only technical, but also deeply based in an understanding of human factors including management and organisational dynamics and leadership. It includes tacit as well as formal (codified) knowledge, requiring attention to informal organisational dynamics (Massa & Tucci, 2014, pp. 420-441).

The integration of digital technologies across the value chain presents major challenges as well as opportunities for the greater co-creation and capture of positive spill-overs. The challenges of digital collaboration are amplified in the defence industry, where national security concerns overlay normal commercial imperatives of value creation, capture and protection through intellectual property (IP) law.

Further, contemporary naval shipbuilding is transforming from practices inherited from traditional heavy engineering and manufacturing to the digital integration of R&D, design, production, systems integration and through-life support, together with collaboration along the value chain. The greater weight of legacy issues and investments in shipbuilding constitutes a significant impediment and source of inertia. This is discussed as a general economy-wide issue in Chesbrough (2010) and Massa and Tucci (2014), who also refer to ‘cognitive’ or ‘paradigmatic’ impediments as the other major barrier to changes in business models.

The weight of legacy investments and business models is a major issue in shipbuilding, requiring active “business model reconfiguration” (Massa & Tucci, 2014, pp. 427-429). The digital shipyard is a way of helping to reconfigure relationships, models and practices to the new requirements. The introduction of digital to shipbuilding vastly increases the size, velocity (‘real time’ relationships and decision-making) and scope for collaboration and sharing along the value chain, together with the creation and capture of beneficial knowledge spill-overs. It also raises potential risk.

All of the above considerations have a key concomitant: the necessity of structured governance and processes for innovation- and knowledge-management. Issues of innovation- and knowledge-management in support of the digital transformation of shipbuilding should be viewed from within the broader analysis of business models. A business model concerns four elements: products, processes, positioning with respect to the market, and organisation (firm and value chain). Business model innovation happens with changes at the intersection of two or more of these elements (European Commission: 2014; see also the more extensive discussions in Chesbrough (2010) and Teece (2010).

Spill-overs are not simply about discrete products or components, but all four elements – products, processes, markets and organisation. Any and all of these can generate new value. All need to be the focus of innovation- and knowledge-management, which must be guided by structured governance principles and practices. Without adequate governance and strategy for innovation- and knowledge-management, the potential will be reduced for generation and capture of spill-overs within and between firms in the value chain. Structures and processes are required that underpin trust and confidence that the collaborative efforts and contributions of each will be protected and rewarded. Without this there will be underperformance in spill-over production and benefit capture.

This is particularly important for largescale, long-term defence projects, requiring experimentation and involving stochastic outcomes. Such long-term projects cannot function on adversarial supplier relationships geared to short-term costs and discrete products or components. Instead, governance must be structured to allow co-creation, experimentation, collaboration and sharing of benefits along the value chain, recognising that specific forecast outcomes cannot be prescribed (Massa & Tucci, 2014). However, these must also ensure the necessities and hierarchies inscribed in lead customer relationships are recognised.

The ideal sought is a governed “network of exchange partners” (Massa & Tucci, 2014), allowing collaboration, experimentation and iteration along the value chain, whilst being organised around hierarchical lead customer relationships and vertical integration. This is a framework of “co-creation and lead-user innovation” (Paasi, Luoma, Valkokari, & Lee, 2010, pp. 629-654).

It should be noted that standard IP protection contractual approaches have a continuing role and are not antithetical to more fluid longer-term collaborations. However, by themselves, they are usually about protecting an individual firm’s position and interests at a particular point in time, rather than how these might evolve in future. Further, there are imbalances of power between primes and SMEs which condition disputes on provenance and ownership. Approaches suggested below might reduce but not abolish such conflicts.

At the commencement of the process, participants’ existing knowledge and IP should be codified. But given the open-ended and stochastic nature of the process, attribution of outcomes to partners is often difficult, and reliance on the IP law model, such as joint ownership of patents, is seen as suboptimal (Paasi, Luoma, Valkokari, & Lee, 2010, pp. 629-654). This is because only codified knowledge, rather than tacit or evolving knowledge, can have unambiguous legal protection. Whilst the customer usually owns the results, certain rights of use can be extended to partners, as these can often improve and build upon the results and improve the long-term value chain relationships.

It is also important to distinguish the nature of knowledge-management according to two key stages:

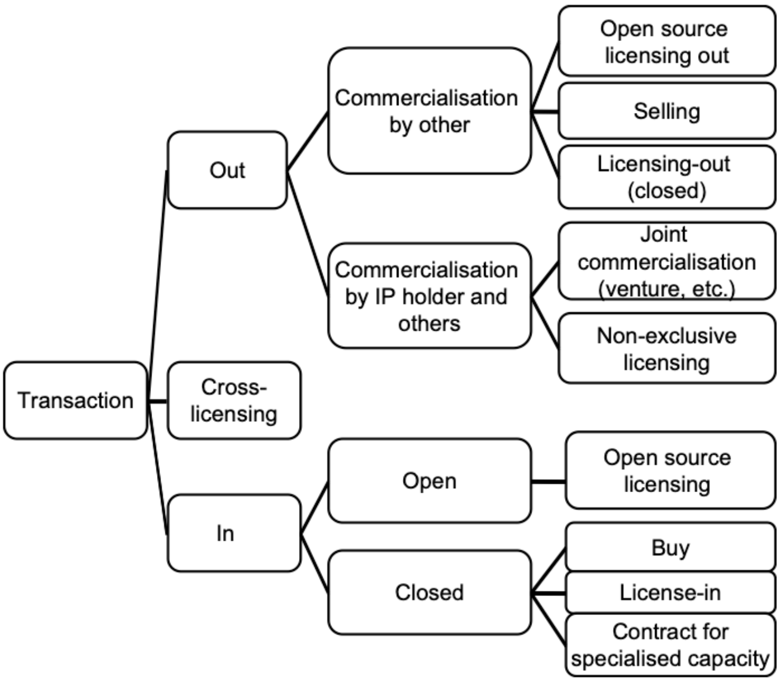
1. Knowledge *generation*: exploration for the purpose of knowledge co-creation, and
2. Knowledge *application*: exploitation of the knowledge for commercial benefit, using knowledge transactions, or knowledge-acquiring alliances.

Generally speaking, knowledge sharing between customers and suppliers is stronger in the generation phase during which ideas are being evaluated, ahead of application of the selected ideas to specific commercial ends. In knowledge generation, the focus is on creation of new knowledge and IP (including commercialisation of tacit knowledge). In knowledge application, the objective is to exploit existing knowledge. However, largescale defence projects often have the character of mission-oriented projects, exhibiting much higher levels of translation from exploration to exploitation (see for example (Mazzucato, Kattel, & Ryan-Collins, 2020).

The exploration stage should commence with a “brief but adequate formal agreement” covering the intent of the collaboration, the main features of the project, and potential types of exploitation of the potential innovation, and the definition of in-scope IP. This exploratory stage needs to anticipate the exploitation phase and the advent of particular innovation outcomes, and their lifecycles (Paasi et al., 2010, pp. 647-649).

Figure 13 presents key relationship types in innovation- and knowledge-management, divided between decisions to internalise or subcontract out the process. In defence industry, there is little use of open source and far greater use of ‘closed’ methods, including closed or exclusive licensing out, joint commercialisation projects, buying- and licensing-in, and contracts for specialised capacity and expertise. Non-disclosure agreements are a mandatory element throughout.

Figure 13: Knowledge and intellectual property management in customer-supplier relationships



Reproduced from: Paasi et al. (2010)

The focus of discussion has been on value chain relationships, these help define the capability requirements of processes internal to the individual firm. They vary from case to case, but include technology capability and deployment, product development, a defined business model, and top-down and bottom-up leadership aligned to a strategic plan, which includes knowledge- and information-management. Evidence of a strategic plan encompassing the codification and application of knowledge within an organisation is critical. Effective leadership and strategy delivery depend on good communication and change management to ensure alignment. In assessing an individual firm, one looks for evidence of structured processes that aim at providing such focus and organisational alignment, together with digital competences and a culture with an emphasis on building digital competences from every available corner of the business.

3.4 Employment and skills

Enterprise-based digital transformation changes the technology landscape, processes, tasks and ultimately jobs. It alters the mix of technical (e.g. IT and software knowledge) and non-technical competencies (e.g. communication and collaboration, adaptability, continuous improvement mindset) that are required for employees to function (Kane et al., 2015; Muller et al., 2018; Schroder, 2016). The development of Industry 4.0 capabilities through the application of advanced technologies and management competencies will change task allocations and employee responsibilities, in other words change *what* people do for work (Moktadir et al., 2018). They will also change *how* and *where* work is done. Human-machine interactions will be more central to the workday, signalling demand for easy to use and useful machine interfaces to gain employee acceptance, enhance learning, and maintain engagement and satisfaction (Muller et al., 2018).

There are concerns that digital transformation may decrease job opportunities as production systems become increasingly automated (Moktadir et al., 2018). However, local (Hordacre, Spoehr, & Barnett, 2017) and international research suggests that, “jobs growth (jobs gained) could more than offset the jobs lost to automation” (Manyika et al., 2017: 4), indicating a transformation rather than elimination of jobs. This offset is based on certain assumptions, namely that the introduction of technologies enables productivity growth in its own right, and that businesses and governments will invest in infrastructure, construction and energy to address growing consumer demands. Hence it appears that the future of work is secure, assuming the labour force is able and willing to switch occupational categories. By 2030, up to 14% of the global workforce (375 million workers) may need to switch occupations in order to remain employed (Manyika et al., 2017).

People in occupations involving predictable physical work will most likely need to switch careers in the future. Occupations in demand will be those requiring the application of creative or cognitive expertise, interaction with stakeholders and managing people (e.g. executives and professionals, and care providers) (Hordacre et al., 2017). Consequently, both individual workers and organisations will need to place greater emphasis on skill development and retraining (especially mid-career), seek better person-job fit and allow for transition periods and support programs (Manyika et al., 2017).

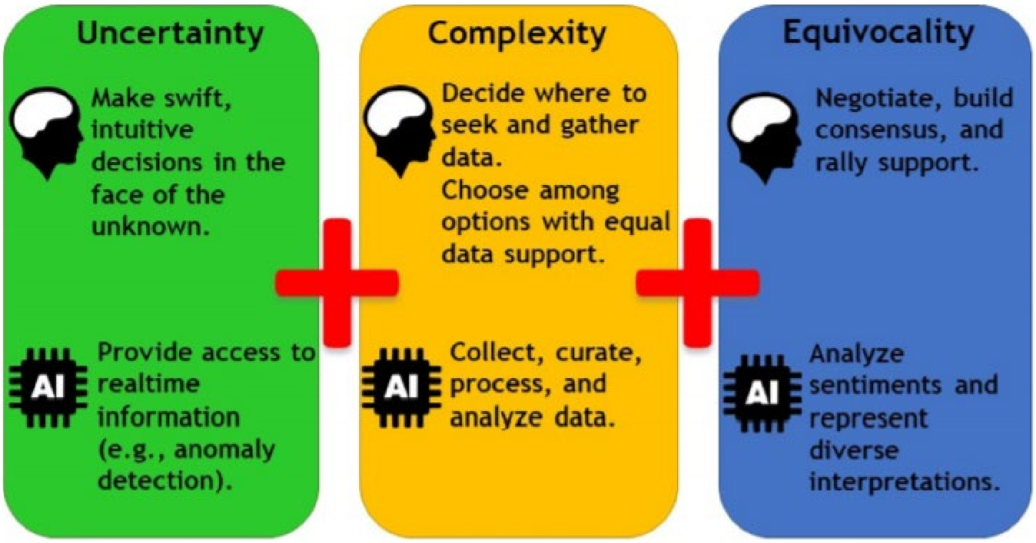
A sophisticated training and skills management regime is required to deliver the vision of Industry 4.0, together with necessary structural and cultural changes to support these key capabilities (Seet, Jones, Spoehr, & Hordacre, 2018). This may include organisational change programs incorporating flexible, non-hierarchical structures designed to stimulate collaboration across roles and disciplines, and increase creativity in problem solving (Kane et al., 2015; Schroder, 2016). Further, promotion of a risk-taking culture requires alignment of recognition and reward policies and leadership behaviours that incentivise failure as well as adopting a trial and error approach (Kane et al., 2015). With increased connectivity (and hence capacity to work remotely), policies and procedures supporting aspects such as data privacy and protection, and flexible work arrangements will need to be reviewed in consultation with employees and approved by relevant governing bodies.

Sourcing skills presents a challenge for the shipbuilding industry, and the digital shipyard represents an opportunity for individuals as it provides impetus and tools for enhanced skills acquisition. The skills demand generated by prime shipyards also creates resources for skills development in the industry.

Uptake of Industry 4.0 technologies in business operations will have a profound impact on work design and business processes. Technologies such as AGVs, RFID and cobots require novel capabilities and introduce new skills requirements even among highly technical employees (King, 2019). In the absence of focused skill development, Australian businesses risk being at a crippling disadvantage in the rapidly evolving landscape of technology (Gekara, Snell, Molla, Karanasios, & Thomas, 2019). In Australia, the National Centre for Vocational Education Research (NCVER) identified a significant need for upskilling the Australian workforce, including trade-based work learning and greater integration of education across apprenticeship and higher education pathways (Loveder, 2017) (Seet et al., 2018).

By design, the digital shipyard incorporates Industry 4.0 technologies and frameworks into the workplace. Robotics, automation and artificial intelligence perform industrial tasks ranging across physical operations and data and information processing. An inherent challenge is to develop and align human skills to optimise outputs, ranging from fabricated products to production processes and decisions. For fabricated products, the emphasis is on optimal collaboration with robots and automation; in the production of processes (e.g. procurement and logistics) and decision-making, the emphasis is on effective human-AI collaboration. The powerful complementarity of human and AI competencies, collaboratively executed in decision-making contexts that are characterised by uncertainty, complexity and equivocality is shown in Figure 14.

Figure 14: Strategy for collaboration of Human with Artificial Intelligence for supporting decision making



Source: Jarrahi (2018)

Industry 4.0 also offers the capability to introduce augmented reality (AR) and virtual reality (VR) enabled by cheaper high performance computing (HPC). These technologies can be leveraged to support workplace skills development across a wide range of industrial tasks other types of roles in the shipyard. For example virtual reality can be harnessed to train the next generation of welders (Knoke & Thoben, 2017) extending to human-robot welding collaboration (Matsas & Vosniakos, 2017).

3.5 Supply chain and manufacturing ecosystems

The manufacturing supply chain involves the full set of organisations which perform specialised functions, linked together as a whole to enable the production of a product from raw materials through to its final form utilised by consumers. For shipyards, the condensed manufacturing supply chain is shown in Figure 15.

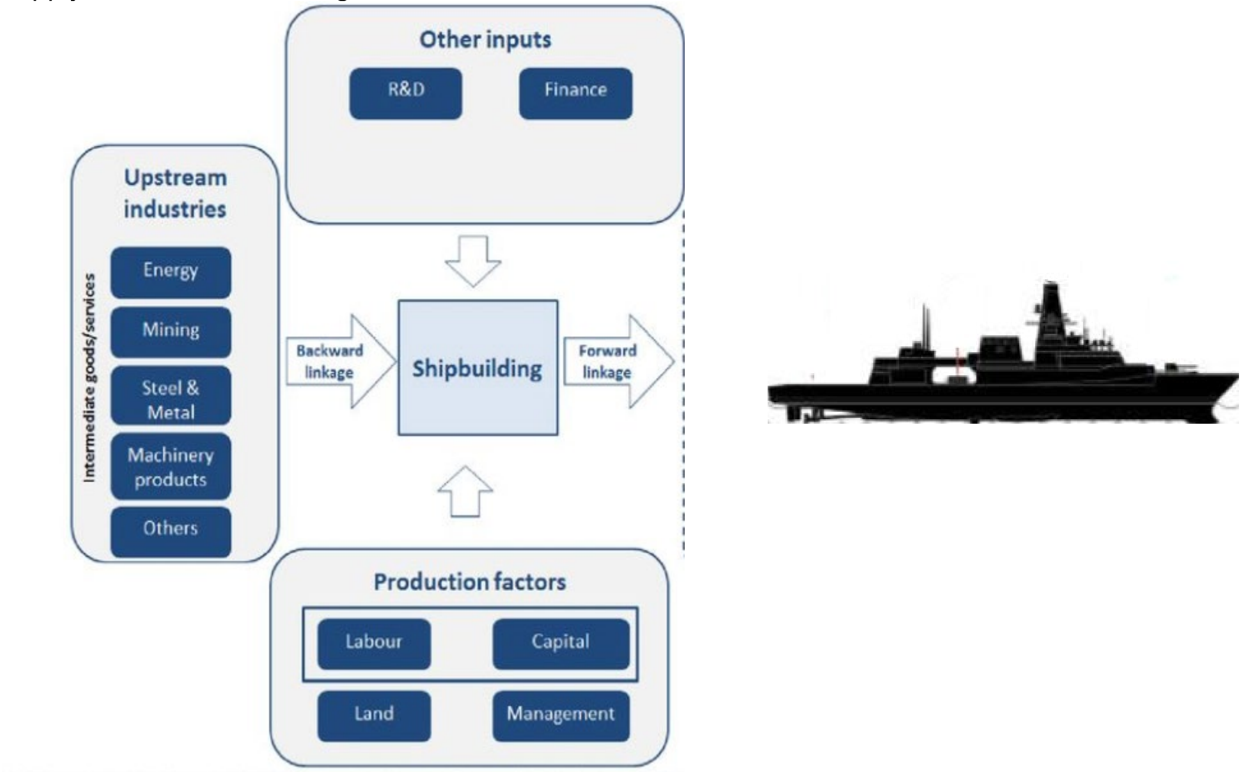
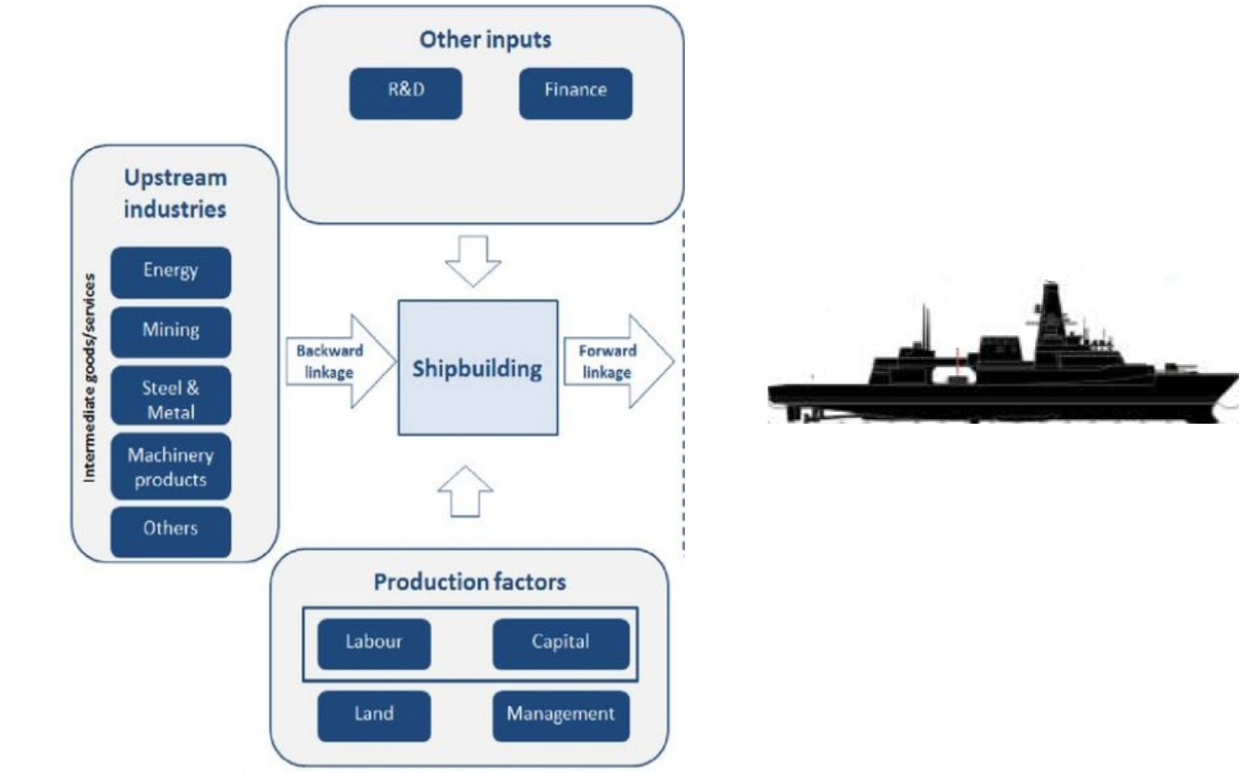


Figure 15: Condensed view of the shipbuilding supply chain



Source: Gourdon and Steidl (2019)

A major challenge for shipbuilding is the fabrication of low-volume/high-value customised components for the ship across the supply chain. As with any manufacturing, aligned frameworks for quality, compliance, cost, efficiency and flexibility are needed across all organisations involved in the manufacturing process, as well as the various sub-components and interim products.

To support low-volume/high-value customised components, SMEs need machinery, tools and equipment that make up the bulk of 'backward linkage' in the supply chain. With affordability constraints potentially posing limitations on the sophistication of products produced, shipbuilding primes and manufacturing SMEs in the supply chain need to develop internal and external collaboration strategies to support the production of sufficiently complex components and integrated interim products.

Industry 4.0 technologies and frameworks can help to address these challenges. Applications include cloud computing, industrial internet of things, portable 3D-scanning, light-weight and low-cost but powerful computer-aided manufacturing (CAM) systems, efficient and flexible additive manufacturing, lower overhead and easily reprogrammable robotics such as cobots, digital frameworks such as the supply chain tower (SCT), smart manufacturing workstations/ work cells that can be networked together in different configurations with relative ease, open-standards to facilitate interoperability and secured supply-chain-networking solutions. The aerospace industry, which is similarly complex and has established advanced manufacturing supply chain networks, provides an example of how risks can be reduced using these technologies (Sinha, Whitman, & Malzahn, 2004).

Other challenges posed by big digital transformation projects for SMEs in manufacturing supply chains include changes to product design, production, procurement processes and distribution methods. A case study by McKinsey & Company (2015) showed that the main concerns across 122 supply chains centred on data security and capacity of network capability. The creation of transparent online business ecosystems where data are generated and shared has potential to create an operating environment subject to cyber-attacks and industrial spying and to generate conflict about data rights and access (Moktadir et al., 2018; Muller et al., 2018; Schroder, 2016). Data security, reliable infrastructure and sophisticated service agreements are essential for wider engagement in digital transformation.

A further problem is a lack of standards and norms around integrating interfaces/IT systems between organisations (horizontal integration). Without consistency in requirements, organisations may be limited in the value networks they can join (Schroder, 2016) which may impede their competitiveness and future viability (Muller et al., 2018).

3.6 Leveraging data

'Data is the new oil' is one of the mantras of Industry 4.0, pointing to the commercial value of data in the Industry 4.0 context. Data drives important smart functionalities such as system autonomy and powers creation of new business models based on commercial exploitation of analytics. These developments are integral to the evolution of the digital shipyard.

Harmon, Corno, and Castro-Leon (2015) identify interconnection, instrumentation and intelligence as key properties of smart systems. The three properties represent functionalities for acquisition, transmission, processing and utilisation of data. Müller, Buliga, and Voigt (2018) and Gu, Jin, Ni, and Koren (2015) identified business model transformation based on data capabilities as a defining feature of Industry 4.0.

In the digital shipyard, the internet of things provides key instrumentation and interconnection functionalities using data collection capabilities. The mass deployment of these devices in the shipyard creates the platform for big data capabilities which in turn feeds analytics, and further down the system chain, autonomy, flexibility and value chain integration. Big data will enable track-and-trace applications for equipment and people, thereby facilitating optimised inventory management, operational agility and safety. Additionally, big data from cyber-physical systems will facilitate the development of predictive capabilities supporting maintenance, system optimisation, asset management and supply chain efficiency. Enhanced data capabilities will also underpin the autonomy and flexibility of the smart factory and the smart supply chain.

4 Conclusion

The digital shipyard is the Industry 4.0 blueprint for the modern shipyard. It is characterised by the integration of people, processes, tasks, and technologies used in shipbuilding. The vision promises enormous benefits in work quality, cost efficiency, safety, and product design capabilities.

The need for integration necessitates the digitisation of processes, using the internet of things and connected autonomous agents. Robotics are an effective means for digitising logistical tasks in the shipyard, with multiple applications for industrial robots, cobots and AGVs in undertaking structural tasks, piping, cabling tasks, quality assurance and administrative tasks. Robots are autonomous agents with a capacity for speed and accuracy, functioning in environments that may be impossible or hazardous for humans.

Design change management is known to be the biggest driver of cost in the shipbuilding process with even a minor design change having a potentially significant impact on ongoing or completed structural, cabling or piping works. The use of digital twins has the potential to reduce design changes to an acceptable minimum, while providing optimal procedures for implementing changes with the least possible impact on completed or ongoing works.

Safety is another area that is subject to high level impact from digitisation of shipbuilding. Autonomous agents have capabilities to reduce factory floor collisions and the amount of physical strain that workers are subjected to. Wearables have sensors that monitor workers' vital signals and can notify the worker and health officials of impending problems such as cardiac episodes.

There are challenges as well as benefits, such as potential invasion of privacy, drastic changes to corporate culture, exposure to cyber security risks and workforce disruption, for example rapidly changing skills requirements brought about by digital transformation. These issues need to be given detailed attention in transformation plans to guarantee maximum benefit from the digital transformation project.

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