Flinders University
Australian Industrial Transformation Institute

Naval Shipbuilding and Industry 4.0

Building the Value Chain and Industry Capability

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Australian Industrial Transformation Institute

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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. This is taking place in our joint Line Zero – Pilot Factory of the Future test and trial facility based at the Tonsley Innovation District.

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), 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

This report is about the present position and future role of digital technologies in the Australian naval shipbuilding industry. Its specific concerns are: why and how, and according to what paths, plans and trajectories the Australian naval shipbuilding industry should adopt and embed digital technologies? Its goal is industry and enterprise education to help accelerate and drive innovation and capability development along the value chain (Primes, tier 1 and higher tier suppliers, and small and medium-sized enterprises (SMEs)), systematically to address impediments, and identify key success factors and associated measurement and benchmarking tools for use by the industry.

The report surveys existing literature to define and analyse key issues pertaining to successful digital adoption in naval shipbuilding. This is done from the following specific vantage points, each vital to rigorous problem-definition and the identification of effective solutions:

- Analysis of the impediments and inhibitors of digital adoption in naval shipbuilding, as these apply to
    - large lead customers (Primes) and their tier one suppliers on one hand, and,
    - to SMEs facing an array of distinct and often pronounced structural impediments to participation in the exacting naval defence value chain
- Assessment of enablers and practical means with which to drive innovation and capability development through structured collaboration and reciprocity along the value chain (primes, tier-1 suppliers and SMEs, SMEs and other SMEs)
- Related key success factors and associated measurement and benchmarking tools, incorporating not only Key Enabling Technologies (KETs) but also 'key enabling competences' for businesses.

Certain general observations about the Industry 4.0 literature are in order given the report's character as a distillation of existing sources, and its concern with applications of Industry 4.0 to the specific circumstances of Australian manufacturing, the Australian naval shipbuilding sector, and the position of SMEs within it. Only a proportion of the literature focusses on manufacturing as distinct from digital behemoths; there is a strong manufacturing and SME focus in much of the UK and European sources, but there are major disparities between the scale and capabilities of their companies compared to Australian manufacturing SMEs; there is a limited number of Industry 4.0 studies focussed on shipbuilding. Sources on digital adoption in Australian manufacturing are limited, and there are fewer still specifically about shipbuilding.

To arrive at some specificity about Australian shipbuilding, therefore, this analysis moves progressively from the general to the particular. Overall definitions of Industry 4.0 are surveyed, together with descriptions of the principal (KETs). This is followed by a discussion of the broad benefits claimed for digital adoption in manufacturing under the four heads of: smart factory, smart products, smart operations, and digitally driven services.

These broad Industry 4.0 benefits are discussed in the context of modern naval shipbuilding and are found to be pertinent and positive to this sector, which requires bespoke production in batch sizes of one, iterative design and production, high complexity and interdependency along the value chain, and involves long-lived assets requiring ongoing technology upgrades and replacements, alongside constant provision of real time data on component condition and performance (Section 3).

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, requiring intense problem-solving activity and cross-functional collaboration. Shipbuilding often requires intensive experimentation and near-concurrent design, testing and production of some components. It combines construction with manufacturing, short run production with the most advanced technology. The life of a warship is measured in decades, with through-life sustainment and technology upgrades costs typically being triple the value of the initial build. These factors are assigning new roles of special importance to digital technologies, requiring concerted effort to overcome impediments and effect positive change.

From the array of Industry 4.0 technologies, those most relevant and powerful in shipbuilding are: robotics (especially cobots), additive manufacturing, augmented and virtual reality, and the digital shipyard (Section 4). These technologies deliver benefits specifically sought by shipbuilding from optimisation and rapidity during production, to single batch production, to ability to negotiate small spaces in production and maintenance, to smart components using sensors to provide real-time monitoring (in turn allowing for control and condition monitoring of equipment to enable predictive maintenance), to real-time data and analytics, to process automation, to non-destructive testing of equipment, to process simulation to model factory logistics or component behaviour and performance, and so on. These capabilities are also immensely valuable to the through-life support of a ship, as well as to the potential for industry participation by SMEs at small scale.

The position of SMEs at low digital maturity seeking to advance themselves for the naval shipbuilding value chain will be improved by prioritising the development of competences related to data-driven services and smart products. While Primes will set the agenda for the specific technologies to be used along the value chain, competences developed in these two domains will benefit an SME's overall readiness.

Digital technologies can work in favour of a highly competent naval shipbuilding industry, but structural impediments need to be addressed through comprehensive strategies. Effective proposals and actions for faster and better digital adoption depend on a clear identification and analysis of the nature and causes of the major impediments facing businesses, and clarity about their relative causative weight and significance. The report finds that firm size matters and that businesses of different sizes face qualitatively different barriers (Section 5).

For SMEs, limited absorptive capacity is at the apex of inhibiting factors, which conditions a range of other constraints discussed in the literature. It should be understood that tackling limited absorptive capability (i.e., the capacity of the business to interpret and use information and knowledge applicable to the concrete problems it faces) is critical to the many other factors identified as impediments. Strategic deficits of SMEs reported in the literature include: the absence of a digital strategy, uncertainty about the costs and benefits of digital adoption, scarcity of time and internal resources for consideration, low levels of preparedness and a lack of clarity about how an enterprise can start its 'digitalisation journey', lack of capability and commitment from leadership, and difficulties in implementing the transition to new business models.

These structural limitations require the business to develop dynamic capability (i.e., its ability to adapt and reshape resources to changes in the strategic and operating environment), in part through various internal and external structures and processes discussed below.

Other limitations and inhibitors of specific relevance nominated in the sources are: cybersecurity and overall lack of codified standards inhibiting investment, with security of information and platforms a key defence industry concern; the weight of legacy investments and issues, such as large resources sunk into antecedent IT systems and the challenges of moving to new business models; deficits in skills and competences; and disjointed systems of business support from public authorities. The issue of legacy investments, practices and business models is, in general, a larger problem for Primes and higher-tier businesses at the apex of the value chain, because they invest on a large scale. Nevertheless, Primes have the main role in leading the transformation of naval shipbuilding 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 report discusses key structures and processes for overcoming or mitigating the principal structural impediments. Successful digital adoption must be part of a staged digital strategy for the business. The first step is to appraise the business's current position including gaps and weaknesses using one of the available maturity models or digital readiness tools (Section 6).

Section 7 discusses practical approaches for SMEs that will address immediate issues in digital adoption and, in so doing, help build the business's absorptive and dynamic capabilities. Conscious attention must be given to research and development projects and attention to formal structures and processes for knowledge management, organisational development and learning, innovation, employee involvement, change management and supply chain collaboration. The approach must be stepped and strategic to trial innovations to see what works and to avoid disruption of existing products and revenues. To experiment, SMEs must become adept at pilot programs and use of high-performance cross-functional teams. Projects must be scaled.

Examples of key questions are given as prompts for a hypothetical digital novice SME to stimulate thinking about where the business is currently, and what could be the next most valuable steps. A best practice framework for team-based working-up of concrete project proposals is described. Success requires going from what may be a good idea to the structured governance and processes required for proper innovation- and knowledge-management. Cross-functional teams, the clear mandate and support of leadership for the change process, and an initial codification by the business of 'what it knows' (existing IP, background competences, formal accreditations, product and technology knowledge, tacit workforce skills and knowledge), are all critical.

SMEs (and indeed all firms) in the naval shipbuilding value chain need a digital strategy, ultimately covering all facets and operations of the business. However, commencing the process requires setting priorities alongside pragmatic acceptance that the full strategy can only be developed in stages.

Getting started involves consciously valuing and developing data as a business asset, using it to generate indicators initially, and progressively extending the business's strategic management of its data. This means starting from an evaluation of the business's current assets, mapping existing production, and taking stock of data currently produced by the enterprise, examining it for potential added value and future development and deployment. Getting started also involves prioritising data-driven services and smart products. Support for this broad approach comes from many expert sources, including a substantial contribution from research of the Spanish shipbuilding industry, which has distilled results from fieldwork to define five key success factors for digital adoption in the industry, as follows:

1. Focus on process rather than specific technologies
2. Apply technology to enhance the role of people, not replace them
3. Scale projects from smaller to larger

4. Support organisational change
5. Build strategic alliances.

These principles concur with the approaches distilled in this report from multiple sources and are here applied in additional ways. This includes early-stage benchmarks and activity measures based on these key success factors.

Primes are at the apex of a complex, knowledge-intensive and highly interdependent value chain. Primes and 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. Through a strong mission-orientation balancing hierarchical relationships with collaboration, the naval shipbuilding value chain can be a virtuous circle.

The Prime's role is foundational. Robust structures and processes, including clear communication to SMEs, can make the value chain a virtuous circle for innovation and problem-solving. The level, quality and intensity of collaboration in a project is key to its success (Section 8). Creating productive collaborations comprises:

1. Awareness building before project prequalification and ongoing in parallel with a project: supplier forums, information on emerging technologies in shipbuilding, problem-raising sessions, activities in association with test labs including digital shipyards), encouraging use of digital maturity assessments by SMEs, etc.
2. Prequalification: working with SMEs to build general and specific business capabilities
3. Intense collaboration in the project: working together to achieve key common standards and accreditations (including in cybersecurity), development of risk-sharing frameworks and protocols, strong arrangements for protection and sharing of intellectual property (IP), participation in joint research and development (R&D) and mission-oriented projects (including through test labs and digital shipyards), and working cooperatively on workforce skills and leveraging these to create momentum for digital transformation.

These are critical ways in which Primes can drive technological improvement and innovation along the value chain, often resulting in new products, processes, technologies and organisational innovations. Test labs, including digital shipyards, are powerful partners in driving these changes, because they shift personnel and resources away from standard university research into product and service development, including technical testing and proof of commercial viability (Section 9).

Section 10 applies the above five key success factors to a digital novice business to suggest some very basic, early-stage activity-based measures. Like the questions posed in Section 7, they are intended only to stimulate early strategic thinking and more focussed decision-making.

This report is about practical pathways to digital technologies in the Australian naval shipbuilding industry. It is directed at an industry audience and policy and program leaders involved in providing assistance to the industry. It aims to contribute to development of a 'virtuous learning circle' in which knowledge acquisition and application and industry capability development are reciprocal and continuous.

1 Introduction

1.1 The scope and purpose of this report

This report has been commissioned as part of a wider collaborative project focusing on the influence of human factors on the adoption and adaptation of Industry 4.0 to naval shipbuilding and its entire value chain, through 'Digital Shipyards' and a 'Shipyard 4.0' agenda. This is the third AITI report to be published on this agenda. Quicker Off the Blocks (O'Keeffe, Moretti, Hordacre, S, & & Spoehr, 2020) surveyed the principal digital technologies and the implications of human factors for their successful adoption, while The Digital Shipyard: Opportunities and Challenges (Spoehr, et al., 2021) surveyed a wider range of factors pertaining to digital adoption in naval shipbuilding.

This report is about the present position and future role of digital technologies in the Australian naval shipbuilding industry. Its specific concern is with why, and how, and according to what paths, plans and trajectories the Australian naval shipbuilding industry should adopt and embed digital technologies. Its goal is industry and enterprise education to help accelerate and drive innovation and capability development along the value chain (Primes, tier 1 and higher tier suppliers and SMEs), systematically to address impediments, and identify key success factors and associated measurement and benchmarking tools for use by the industry.

This report surveys existing literature to define and analyse key issues pertaining to successful digital adoption in naval shipbuilding. This is done from the following specific vantage points, each vital to rigorous problem-definition and the identification of effective solutions:

1. Analysis of the impediments and inhibitors of digital adoption in naval shipbuilding, as these apply to
    a. large lead customers (Primes) and their tier one suppliers on one hand, and,
    b. to SMEs[1] facing an array of distinct and often pronounced structural impediments to participation in the exacting naval defence value chain
2. Assessment of enablers and practical means with which to drive innovation and capability development through structured collaboration and reciprocity along the value chain (Primes, higher tier suppliers and SMEs, SMEs and other SMEs)
3. Related key success factors and associated measurement and benchmarking tools, incorporating not only Key Enabling Technologies but also Key Enabling Competences for businesses.

This report has limited goals and its conclusions are to be treated as preliminary. It is a review of existing literature only. Although the Industry 4.0 literature is extensive, much of it exists at a level somewhat removed from the specific conditions pertaining to manufacturing businesses (Primes and SMEs) in the Australian naval defence sector.

Commentaries and analyses are often created by large business advisory houses interested in selling advisory services to larger potential customers. Much of this literature originates from the US and discusses digitalisation and new business models across several sectors of the economy, rather than having a specific manufacturing focus. Frequently emphasis is placed on the experiences of businesses and digital behemoths such as Google, Uber and GE.

[1] In Australia, a manufacturing SME is usually defined as having fewer than 200 employees and an annual turnover below $50 million. For current purposes of analysis, it is not useful to apply a rigid definition such as this. The issues and impediments later described are common to businesses in the naval shipbuilding value chain far larger than this standard definition.

On the other hand, much of the European (and especially the German) output focuses on Industry 4.0 as the specific framework for digitalisation of manufacturing, whilst the UK Fourth Industrial Revolution is also dedicated to manufacturing. Both the European and UK portfolio give special attention to the requirements of SMEs, although the UK output more often links SMEs to vertical lead customer relationships, whilst the European (and particularly the German) output is more oriented to the independently specialist horizontally oriented Mittelstand SMEs. At the same time, for present purposes it should be recognised that Mittelstand SMEs are frequently much larger and more technologically complex than in other nations, and particularly more so than Australian manufacturing SMEs.

A small number of international sources specifically analyse naval shipbuilding from the viewpoint of digital adoption (Giallanza, Aiello, Marannano, & Nigrelli, 2020; Gourdon & Steidl, 2019; Ramirez-Pena, Abad Fraga, Sanchez Sotano, & Batista, 2019; Stanic, Hadjina, Fafandjel, & Matulja, 2018), but again, these tend to be at a high level of abstraction and focused on technical dimensions. The exception in the international literature is (Torres Saenz, 2018), which surveys Spanish shipbuilding companies as well as industry experts to arrive at a weighted schedule of the most important impediments to digital adoption in shipbuilding, and of key success factors, to which reference will be made later.

From this limited position, then, the objective is to extract insights, information and analysis germane to manufacturing primes and SMEs within Australia, operating in the Australian defence industry sector and especially the naval defence industry. This must also recognise the lower scale and state of maturity and capability of Australian manufacturing SMEs compared to those in other advanced economies. Australia today has a low overall manufacturing GDP share for an advanced economy, and with the demise of complex interdependent value chains such as automotive production, economic complexity has decreased, together with the associated technological, organisational and business capabilities of SMEs. Through strong lead customer relationships had come the transmission of requirements along the value chain, and the development of common high competences and standards. Today, Australian manufacturing SMEs are less likely to be part of such a complex, articulated vertically integrated value chain, or substantial positive ecosystem. However, Australian defence industry generally, and naval shipbuilding particularly, presently have more of the characteristics of vertical and horizontal integration than any other manufacturing sector.

The analysis proceeds by way of successive approximations and a discussion in progressive stages moving from the general toward the particular, to arrive closer to an analysis pinpointed to the situation of manufacturing SMEs and Primes in today's Australian naval defence sector.

Nevertheless, this remains a desktop literature review. Its value lies in consolidating sources and raising questions and hypotheses for future field work. Its conclusions should be regarded as provisional at this time, and the basis for future work as the project matures.

The report is directed at an industry audience primarily, together with policy and program leaders involved in providing assistance to the industry. Its goal is industry and enterprise education to help accelerate and drive innovation and capability development along the value chain (Primes, higher tier suppliers and SMEs), to address impediments more systematically, and identify key success factors and associated measurement and benchmarking tools. In line with the provisional conclusions and hypotheses reached, the aim is to broaden discussion within the industry (and between it and industry development specialists) to assist rapid capability development. The report aims over time to contribute to a 'virtuous learning circle' in which knowledge acquisition and application and capability development are reciprocal and continuous. An immediate output is expected to be the preparation of thematic fact sheets for use by SMEs and Primes.

1.2 Defence Procurement Program and naval shipbuilding

More than $200 billion has been committed by the Commonwealth to defence procurement and Australian industry development to 2027-28, under the national government's Defence White Paper and associated policy statements (Defence, Defence White Paper, 2016b; Defence, Integrated Investment Program, 2016c; Defence, Defence Industry Policy Statement, 2016a). This aims to modernise Australia's naval, land and airborne defence forces, whilst seeking to develop Australia's defence industries' size and capabilities. Australia's sovereign defence capabilities are seen to embrace not only operational and field capabilities of the forces, but also the industrial and technological capabilities of Australian industry and its supply chains.

At a total $140 billion, naval shipbuilding makes up the lion's share of this commitment, comprising the building and through-life support for 9 air warfare destroyers ($35 billion), 12 submarines ($90 billion) and 12 offshore patrol vessels ($4 billion).

The COVID-19 crisis underlined the low levels to which Australia's sovereign manufacturing capacity and capability have fallen. This has led to official acknowledgement of the need for certainty of some domestic manufacturing capability in priority areas to guard against possible future supply chain instability. However, the defence industry is the only segment of Australian industry thus far considered to warrant a strong vertical sectoral policy, comprising inter alia, largescale advanced procurement practices, domestic industry participation targets, and recognisably mission oriented and directional projects for new technology, product and process development.

The attempt to give this program a long-term, directional, developmental and mission-oriented substance beyond standard public procurement, means casting needs as challenges beyond discrete individual projects, drawing in powerful demand side forces and emphasising connections between the different facets of a problem[2].

This approach has been adopted by organisations charged with helping to find key solutions to broader defence and industrial challenges, such as: the Defence Science and Technology (DST) Strategy 2030, '*More, Together'* (Defence, 'More, Together', Defence Science and Technology Strategy 2030, 2020), focused on strategic research directed at high-impact outcomes over ten years, through eight priority research areas, or 'STaR Shots' (Science, Technology and Research Shot), recalling John F. Kennedy's Moon Shot of the 1960s; the Next Generation Technology Fund (NGTF) which supports research in emerging and future technologies and R&D in "emerging and future technologies for the 'future Defence force after next'", through a

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[2] For definitions and discussion of the significance and practice of mission-oriented projects in advanced economies see (Aiginger & and Rodrik, 2020) (Kattel & Mazzucato, 2018) (M., 2018a) (Mazzucato, Kattel, & and Ryan-Collins, 2020) (Mazzucato M. , A mission-oriented approach to building the entrepreneurial state, 2014) (Mazzucato M. , Building the entrepreneurial state: A new framework for envisioning and evaluating a mission-oriented public sector, 2015b) (Mazzucato M. , Mission-oriented research and innovation in the European Union, 2018a) (Mazzucato M. , Re-igniting public and private investments in innovation, 2015a) (Mazzucato M. , The Value of Everything: Making and Taking in the Global Economy, 2018b) (Mazzucato M. , The entrepreneurial state, 2011) (Rodrik, 2014). Whilst this literature typically discusses largescale national and multinational programs and projects, it is very much applicable to industries, value chains and individual companies, working with lead customers (Primes) and final customers (government), together with intermediate organisations. Even in Australia, the defence sector, together with pharma and MedTech, already exhibits key characteristics of highly directional mission-oriented projects, and uniquely is accorded its own comprehensive sectoral industrial policy. This explicit mission-orientation is a function of unique industry role and structure, which puts demand from powerful public and private sector customers at the apex, and involves the solving of problems at the very technological frontier.

mixture of ‘Grand Challenges’ and smaller scale ‘lean focussed technology acceleration’; and the Defence Innovation Hub (DIH) which focusses on five Defence innovation priorities or streams with an SME priority. The Centre for Defence Industry Capability (CDIC) operates as active industry outreach using a geographically distributed model of business advisers. The CDIC works with companies and research institutions to facilitate development of proposals which are then assessed and approved by NGTF and DIH (Australian Government. Department of Industry, 2021).

In sum, these factors mean that despite Australia’s overall poor position with respect to manufacturing, defence industry including naval shipbuilding, has greater potential than perhaps any other sector of the Australian economy to build complex and productive value chains that can drive high rates of innovation and capability development between Primes and SMEs. The unique characteristics of naval defence industry, which include the pronounced roles of government and national security, its position at the technological frontier and its scale and long-term horizons, also mean that through the identification of key success factors and associated measurement and benchmarking tools, defence industry could provide a stimulus to broader manufacturing development.

2 Definitions and perspectives on Industry 4.0

2.1 Overview

This report is concerned with the present position and future role of digital technologies in the Australian naval shipbuilding industry. It specifically concerns why and how, and according to what paths, plans and trajectories the Australian naval shipbuilding industry should adopt and embed digital technologies. Its goal is industry and enterprise education to help accelerate and drive innovation and capability development along the value chain (Primes and SMEs), systematically to address impediments, and identify key success factors and associated measurement and benchmarking tools for use by the industry.

Before arriving at that point, however, it is important to survey the broad meaning of Industry 4.0. It is today a commonplace that digital technologies are transforming enterprises, industries, sectors and the global economy. The application of digital technologies to manufacturing (Industry 4.0, the Fourth Industrial Revolution or the Industrial Internet) seeks the creation of high-performance production systems through end-to-end digitalisation of physical assets and integrated vertical and horizontal value chains. This end-to-end digitalisation of enterprises and of whole value chains is setting new terms of competition and, increasingly, the actual conditions of participation in complex knowledge intensive value chains such as naval shipbuilding. Digitalisation is promoting not only direct technological change, but also dramatic changes in business models and organisation, and is leading to the development of new products and new market niches. In addition to key enabling technologies, it is increasingly demanding a range of 'key enabling competences' (business, organisational, leadership, collaborative, etc.), arranged in new combinations, with an expanding suite of new technological ones.

Consequently, across all sectors of the economy, and manufacturing in particular, digitalisation is setting new terms of competition and norms, standards and governance in business models and Global Value Chains (GVCs) including process and product capability standards (such as product lifecycle management - PLM) that are minimum conditions for enterprise competitiveness and participation in GVCs. Although it is the revolution in the finished and consumer goods markets that informs most popular discussion of digital technologies, the transformation of B2B relationships and value chains is as, if not more, profound, requiring rapid adoption of new common standards across all aspects of the business.

The many and various ways in which digital technologies are reshaping and helping to set future directions for naval shipbuilding will be a later focus of analysis. The next subsection reviews definitions and descriptions of Industry 4.0 in the literature, while the one following summarises its potential benefits to manufacturing businesses.

2.2 Industry 4.0 digest/summary

The headline definition of Industry 4.0 here adopted is: the application of digital technologies to manufacturing to create high-performance production systems through end-to-end digitalisation of physical assets and integrated vertical and horizontal value chains.

It is valuable to survey and summarise definitions provided by key commentaries and sources to provide a broader perspective prior to a more concrete discussion pertaining to naval shipbuilding. What can be inferred from so high level and selective a survey is that there are consistent core characteristics of Industry 4.0 technologies, alongside different emphasises about likely and desirable future trajectories.

Table 2-1: Industry 4.0 definitions (selective survey)

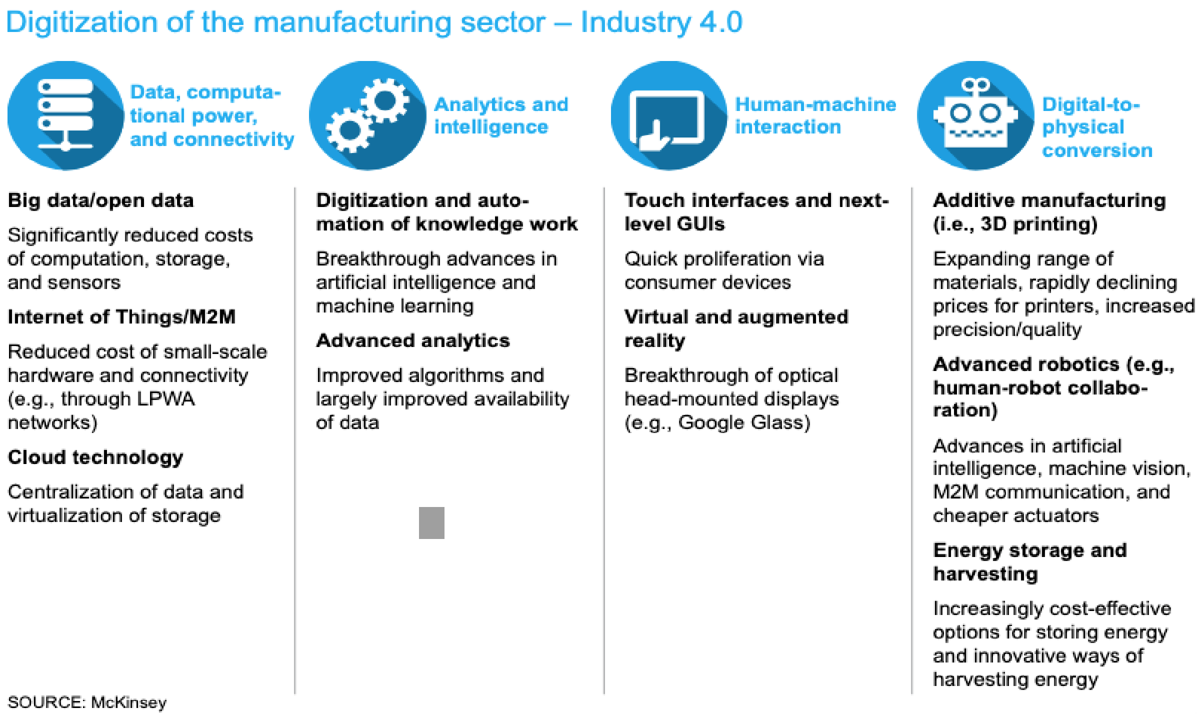
Source	Industry 4.0 is
(McKinsey, 2015a)	"..digitisation of the manufacturing sector, with embedded sensors in virtually all product components and manufacturing equipment, ubiquitous cyber physical systems, and analysis of all relevant data". These developments are driven by 1. The rise in computational power 2. Analytics and intelligence 3. Human-machine interaction 4. Digital to physical conversion.
(Stock & Seliger, 2016)	"(1) Horizontal integration across the entire value chain creation network, (2) end-to-end engineering across the entire product life cycle,..(3) vertical integration and networked manufacturing systems".
(Anderl, et al., 2015)	"Modern information and communications technologies are merging with production technologies to form a new stage of value creation….information in real time through networking of all partners involved in the entire value-adding process leads to dynamic, real-time optimizing….value-adding networks".
(Price Waterhouse Coopers , 2016)	"While Industry 3.0 focused on the automation of single machines and processes, Industry 4.0 focuses on the end-to-end digitisation of all physical assets and integration into digital ecosystems with value chain partners. Generating, analysing and communicating data seamlessly underpins the gains…".
Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies (Schuh, et al., 2017)	"The real-time networking of products, processes and infrastructure is ushering in the fourth industrial revolution where supply, manufacturing, maintenance, delivery and customer service are all connected by the internet. Rigid value chains are being transformed into highly flexible value networks".
Guideline Industrie 4.0 – Guiding principles for the implementation of Industrie 4.0 in small and medium sized businesses (Picard, Wang, Fleischer, & S. Dosch, 2015)	"…the next stage in the organisation and control of the entire value stream along the life cycle of a product…based on increasingly individualised customer wishes and ranges from the idea, the order, development, production, and delivery to the end customer through to recycling and related services. "The fundamental here is the availability of all relevant information in real-time through the networking of all instances …Connecting people, objects and systems leads to the creation of dynamic, self-organised, cross-organisational, real-time optimised value networks…"
(Deloitte, 2015)	"…a further developmental stage in the organisation and management of the entire value chain process involved in manufacturing industry".
(Boston Consulting Group, May 2016)	"…the convergence and application of nine technologies: advanced robotics; big data and analytics; cloud computing; the industrial internet; horizontal and vertical system integration; simulation; augmented reality; additive manufacturing; and cybersecurity".
Impuls: Industrie 4.0 Readiness (Lichtblau, et al., 2015)	"Our understanding of Industrie 4.0 encompasses the following four dimensions…: • Smart factory • Smart products • Smart operations

	• Data-driven services.”
UK Made Smarter (Her Majesty's Government, 2017a)	“…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”.

Sources add to these headline descriptions of Industry 4.0 the key enabling technologies that underly Industry 4.0. They do not all treat or enumerate these technologies identically. For example, the CSIRO (CSIRO Futures, 2016) gives special attention to new advanced materials, which are not included in all overviews. However the following is a distillation of the key technologies from a survey of several sources (CSIRO Futures, 2016) (Matt & Rauch, 2020) (Spoehr, et al., 2021) (McKinsey, 2015a) (McKinsey, 2015b) (European Commission , 2016) (Brambley, 2017) (Boston Consulting Group, May 2016) (Ash, 2018) (Price Waterhouse Coopers , 2016) (Price Waterhouse Coopers, 2014):

- The Internet of Things - the digital interconnection of physical devices exchanging information and data regarding the performance of components, products and tasks in the physical world
- Big data - the cloud-based multiplication of computational and algorithmic power of the past decade and a half
- Cyber-physical systems (CPS) - the platform for collaboration of ICTs to monitor and control physical processes and systems (e.g., sensors, cobots, or additive manufacturing)
- Cobotics – the advanced and safe interaction of humans and robots in production
- Artificial intelligence, being the simulation of intelligence by machines for decisions and actions
- Additive manufacturing - 3D printing technology to manufacture parts and components, potentially customised to batch sizes of one and on-demand production
- Augmented and virtual reality - devices that use virtual imaging to help guide work processes and production and decision making.

Figure 2-1: Digitisation of the manufacturing sector (McKinsey, 2015a)

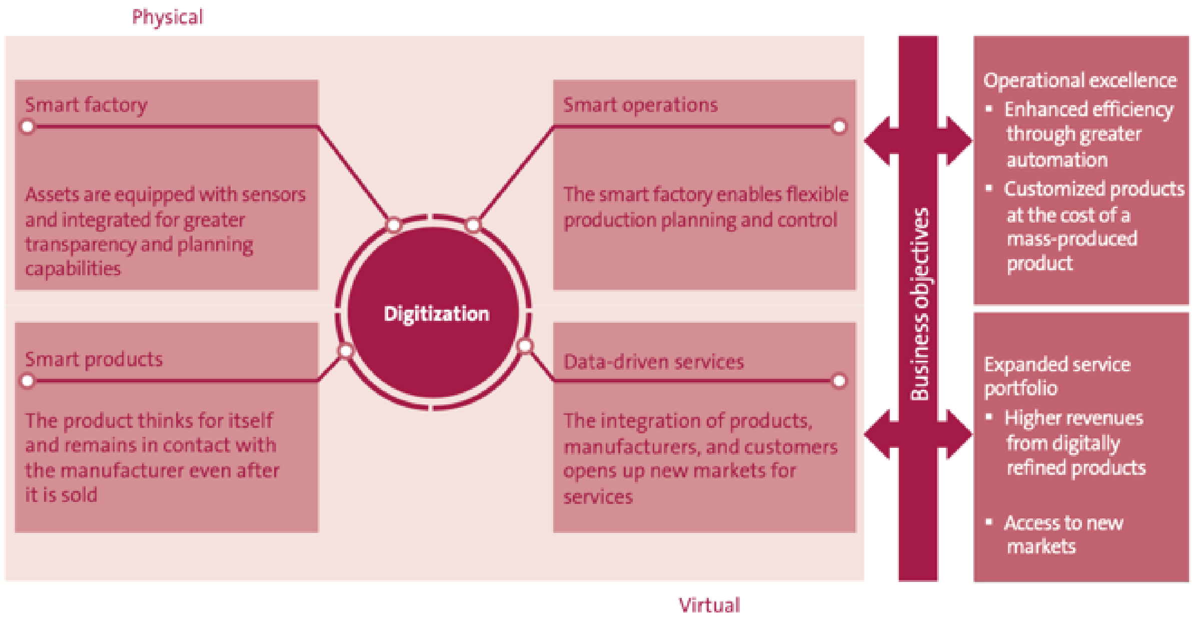


2.3 Benefits of Industry 4.0

This subsection scans the literature to provide a digest of the high-level potential benefits of Industry 4.0. How we understand these potential benefits, together with the likely or preferred developmental trajectories of digital technologies, influences subsequent consideration of the highest-priority targets for application to naval shipbuilding and methods for overcoming barriers to adoption, particularly by SMEs.

A useful frame for considering potential benefits of Industry 4.0 is through the categories of smart factory, smart products, smart operations and data-driven services, together with accompanying enhanced business outcomes (Lichtblau, et al., 2015).

Figure 2-2: Industry 4.0 as the fusion of the physical and virtual worlds (Lichtblau, et al., 2015)



These provide an organising template for consideration of the broad potential benefits of digital adoption, prior to specific analysis of naval shipbuilding[3]. These are summarised below:

2.3.1 Smart factory

- Lower capital expenditure requirements (Badri, Boudreau-Trude, & & Souissi, 2018) estimate 40% lower capital costs, while (McKinsey, 2015a) estimates that the fourth industrial revolution will result in replacement of 40-50% of installed capacity, compared to 90% for the third industrial revolution)
- Productivity improvement
- Higher revenues and lower costs (Price Waterhouse Coopers , 2016) estimates 2.9% revenue gain, 3.6% cost reduction, whilst (McKinsey, 2015a) sees larger revenue gains of up to 30% and higher input efficiency gains of 30-50%)
- Improved asset utilisation and reduced downtime
- Reduced waste
- Reduced inventory
- Real time supply chain optimization
- Batch size of one, at prices close to mass production
- Better planning, vertical integration across supply chains
- Reduced carbon footprint

[3] A vast array of sources informs the following summary. It would be impractical and repetitious to cite authors individually. The main sources include (Badri, Boudreau-Trude, & & Souissi, 2018) (Boston Consulting Group, May 2016) (Brambley, 2017) (Bruner & Kisgergely, 2019) (CSIRO Futures, 2016) (Matt, Modrak, & Zsifkovits, Industry 4.0 for SMEs. Challenges, Opportunities and Requirements, 2020) (EEF, 2016) (Government, 2017b) (Her Majesty's Government, 2017a) (Kagermann, Andrel, Gausemeier, Scuh, & Wahlster, 2016) (Matt & Rauch, 2020) (McKinsey, 2015a) (McKinsey, 2015b) (Mohamed, 2018; (Picard, Wang, Fleischer, & S. Dosch, 2015; Picard, Wang, Fleischer, & S. Dosch, 2015) (Price Waterhouse Coopers , 2016) (Price Waterhouse Coopers, 2014) (Schroder, 2017) (Stock & Seliger, 2016) (Deloitte, 2015).

2.3.2 Smart products

- Faster to market (Badri, Boudreau-Trude, & & Souissi, 2018) see a 30% reduction in time to market)
- Offerings tailored to customers
- Remote diagnostics
- Digitalisation of product and service offerings
- Data analytics for condition monitoring
- Predictive maintenance
- Mass customisation of products

2.3.3 Smart operations

- Reduced wastage and faults
- Improved optimisation of production and operations
- Ability to manage data across supply chain
- Ability to network all partners with real time information
- Data analytics for collaboration within the firm and across the supply chain
- Pooled data for supply chain collaboration
- Reconfigurability of production
- Reduced energy consumption
- Potential for better jobs
- Improved workforce safety
- Improved opportunities to use measures and benchmarks to guide decisions
- Decentralised, distributed production and decision making
- Better production lifecycle management

2.3.4 Data-driven services

- Tighter fit with desires of customers
- Production volumes aligned to changes in demand
- Remote problem resolution
- Ability to add services to product portfolio
- Improved capture and lock-in of customers, with improved revenues/margins
- Through life support services
- Predictive maintenance
- Enhances potential new product development
- Environmental monitoring
- New business models/service enhancement.

In summary, Industry 4.0 broadens the focus of enterprise decision making and strategy from antecedent models focused on production and optimisation within the firm, to better encompass whole product life cycles, collaboration across entire value chains, the development of common standards, near-concurrent design, and production of components, sharing of data and technology, new business models with high service content, and the acceptance of high levels of interdependency.

Digital technologies are transforming the terms of competition in global manufacturing, enabling competitive short-run flexible and customised production, promoting service enhancements of products (servitisation), and creating opportunities in complex niches in Global Value Chains (GVCs). Digital technologies also help reduce inventories, reduce resource use with favourable environmental impacts, and can radically reduce time to market for new products and services.

These Industry 4.0 features are pertinent and positive to naval shipbuilding, which requires bespoke production in batch sizes of one, iterative design and production, high complexity and interdependency along the value chain, and involves long-lived assets requiring ongoing technology upgrades and replacements, alongside constant provision of real time data on component condition and performance.

3 Naval shipbuilding today

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 spillovers. It requires intense problem-solving activity and cross-functional collaboration. 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, for participating enterprises along the value chain, and the economy generally. The latter is one of the reasons why, in addition to defence and security, nations develop sovereign industrial capabilities in these sectors, and is precisely why projects in defence and naval shipbuilding especially are competed for between subnational economic units.

In naval shipbuilding, lead customers (Primes) and their suppliers (larger tier 1 and higher tier suppliers together with SMEs) 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 spillovers are created by this constant process of iterative problem definition and problem solving.

This report concerns the ways in which innovation and higher capabilities, together with the capture of positive spillovers, can be maximised. Doing so requires structured processes and practices consciously aimed at such maximisation.

Shipbuilding combines construction with manufacturing, short run production with the most advanced technology. Modern shipbuilding came to Australia with the Collins Class submarine build of the 1990s. This pioneered an engineering approach of modular construction in various locations, with subsequent consolidation of the modules and systems integration occurring at a single site. This contrasted with the legacy practices of many shipyards, particularly in the UK, in which complex labour-intensive tasks were combined in ad hoc ways resembling handicraft production, lengthening build times, multiplying potential for production faults and associated non-operational periods, and costs of maintenance and upgrades (Yule & Woolner, 2008).

The character of naval shipbuilding as a hybrid of manufacturing and construction is reinforced by the low volume and bespoke nature of production. Ships can have up to 900,000 separate parts, and intermediate inputs comprise 70 to 80 percent of the total value of the build (Gourdon & Steidl, 2019) (Stanic, Hadjina, Fafandjel, & Matulja, 2018). This again underlines high levels of complexity and interdependency. The life of a warship is measured in decades, with through-life sustainment and technology upgrades costs typically being triple the value of the initial build. This unique feature of naval shipbuilding – the role of continuous technological innovation and investment over a single vessel's entire life – is assigning new roles of special importance to digital technologies, which will be explored later.

Today, 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, to be considered below. Whilst an array of impediments affects the capacity of SMEs to transform their business models, it is broad legacy issues that are the greater concern to lead customers, Primes and larger players. These must invest heavily in new plant and equipment, systems and business models, as well as value chain upskilling and reorganisation.

This too assigns high importance to digital applications to shipbuilding, including the Digital Shipyard. The past decade has seen a major turnaround in attitudes toward digital technologies of both naval shipbuilding industries and of their customers (national governments). An initial stance of caution has given way to a necessary acceptance and exploration. The initial stance stemmed from factors such as national security concerns and the credible belief that digital technologies would increase vulnerabilities; the weight of legacy investments, infrastructure and business models as a barrier to investment in new technologies and business models (to be examined below); and product standards and acceptability defined by strictly codified production processes (this was a factor initially weighing against the role of additive manufacturing in supply of replacement parts).

The present position recognises these factors as challenges to be considered against the fact that digital technologies are, and will increasingly be applied, not only to design, but to the production process in general (smart factory using sensors ubiquitously), to the development and production of components (smart products with condition-monitoring abilities providing real time information on performance), and to decades-long through-life support and technology upgrades and predictive maintenance. Digital technologies are aligned to modern shipbuilding requirements of advanced production in small batches, constant iteration of designs and standards across the value chain, and continuous technology upgrades over the long life of a vessel.

Digital technologies can work in favour of a highly competent naval shipbuilding industry by, inter alia, facilitating near-concurrent design and production of components, enabling economic short-run batch of one production, flexible reconfiguration of production, optimisation of production and workshop and supply chain logistics resulting in reduced costs and wastage, use of smart processes and smart products that supply real-time data to allow performance and condition monitoring and preventative maintenance for effective through-life support, and facilitating flexible opportunities for industry participation by SMEs at small scale.

4 Naval shipbuilding and Industry 4.0

The broad characteristics and potential benefits of Industry 4.0 have been surveyed, prior to now considering the changes in the nature of modern naval shipbuilding in part brought about by the introduction of digital technologies, and unquestionably accelerated and sharpened by those technologies. Here the discussion focusses on those Industry 4.0 technologies and applications most relevant to naval shipbuilding.

These technologies deliver benefits specific to modern shipbuilding along the standard four axes of:

- Smart factory
- Smart products
- Smart operations
- Data-driven services.

These apply differentially across all phases of the production and life of a warship:

- Design and engineering
- Production/manufacturing and construction
- Operation and deployment
- Through-life maintenance and support; technology upgrades
- Decommissioning.

They provide benefits from optimisation and rapidity during production, to ability to negotiate small spaces in production and maintenance, to smart components that monitor their own condition and performance, to real-time data and analytics, to process automation, to use of sensors to provide real-time monitoring (in turn allowing for control and condition monitoring of equipment to enable predictive maintenance), to non-destructive testing of equipment, to process simulation to model factory logistics or component behaviour and performance, and so on.

(Ramirez-Pena, Abad Fraga, Sanchez Sotano, & Batista, 2019) list 12 digital technologies important to modern shipbuilding: Advanced Manufacturing, Big Data, Cloud Computing, Augmented Reality, Autonomous Robots, Autonomously Guided Vehicles, Blockchain, Cybersecurity, Horizontal and Vertical Integration Systems, Artificial Intelligence, the Internet of Things, and Simulation.

The following more condensed discussion is a summary of shipbuilding-relevant digital technologies and systems identified in (O'Keeffe, Moretti, Hordacre, S, & & Spoehr, 2020) (Sullivan, et al., 2020) (Stanic, Hadjina, Fafandjel, & Matulja, 2018) (Spoehr, et al., 2021) (Ramirez-Pena, Abad Fraga, Sanchez Sotano, & Batista, 2019) (Price Waterhouse Coopers, 2014) (Picard, Wang, Fleischer, & S. Dosch, 2015) (McKinsey, 2015a) (Matt, Modrak, & Zsifkovits, Industry 4.0 for SMEs. Challenges, Opportunities and Requirements, 2020) (Lichtblau, et al., 2015) (Kagermann, Andrel, Gausemeier, Scuh, & Wahlster, 2016) (Her Majesty's Government, 2017a) (Gourdon & Steidl, 2019) (Giallanza, Aiello, Marannano, & Nigrelli, 2020) (EEF, 2016) (CSIRO Futures, 2016) (Badri, Boudreau-Trude, & & Souissi, 2018) (Anderl, et al., 2015) (Ash, 2018) (Torres Saenz, 2018).

4.1 Robotics

Industrial robots are generally used for tasks of processing (using tools on a workpiece), materials handling (moving items, transferring, and loading and unloading items) and inspection and quality control (Bruner & Kisgergely, 2019).

In shipbuilding we can see increased use of cobots (collaborative robots), being lightweight flexible robots capable of machine learning, and therefore able to be deployed to a range of nonrepetitive and highly variable tasks. This includes production tasks such as assembly and monitoring of other machines. They are capable of collaboration with humans on the shop floor and of eliminating or reducing hazardous tasks previously performed by humans. They can be deployed for inspection and quality testing of components in confined spaces, which are ubiquitous in shipbuilding.

Further robotic applications include Automated Guided Vehicles (AGVs), which are used for logistical tasks of transporting and processing goods, usually according to standard designated routes, and using various track and trace technologies such as barcodes, RFID and GPS to ensure real-time status and location information.

4.2 Additive manufacturing/3D printing

This means the production of forms and objects from progressive layering of sintered raw materials (sands, metals, plastics). In shipbuilding additive manufacturing is under increasing attention for prototyping and production of components. The advantage will often be production inhouse without reliance on potentially distant suppliers, and the ability to produce bespoke components at small batch size on demand for the support of the ship throughout its life.

Information management software uses big data and associated analytics to achieve continuous flow of data across the entire product lifecycle. It provides for monitoring and control of various elements in the production process and across the value chain. Data may be entered either manually or automatically, but either way provides real-time data to guide decision making. Systems include digital work management (DWM), product data management (PDM), and very importantly, product lifecycle management (PLM).

4.3 Virtual and augmented reality

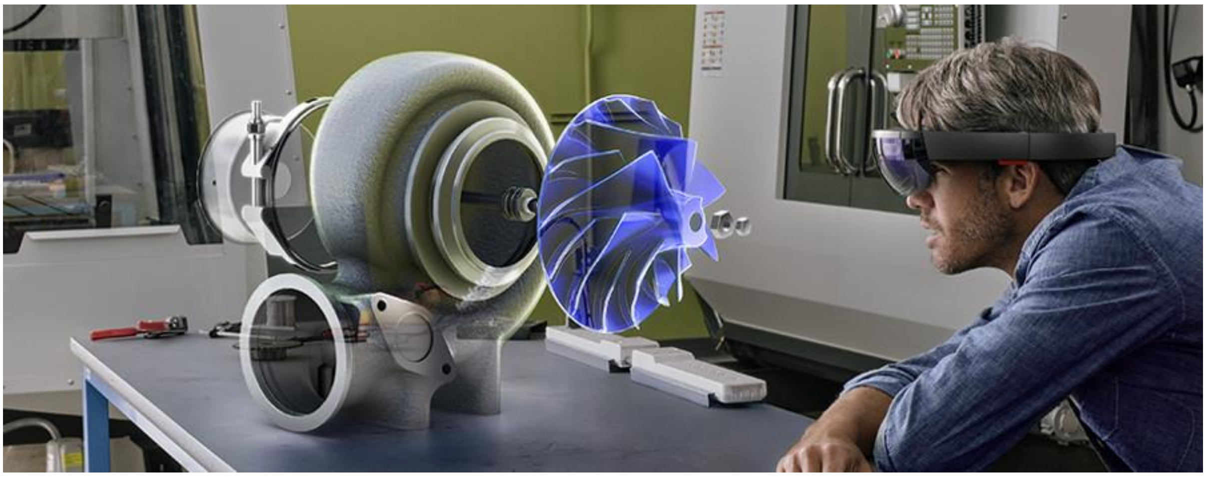
These use VR headsets or domes (spaces) to visualise a simulated process for an individual, while AR simulates processes in an area without worn devices. Applications include training, inspection in confined and complex spaces, and remote surveys of spaces and components for preventative maintenance.

4.4 Digital twin/Digital shipyard

This goes directly to the issue of the transition from legacy investments and issues, one of significance to naval shipbuilding and to Primes and larger businesses particularly (see below). A manufacturing and production environment can be simulated that supports understanding and modelling of production processes and logistics. A digital twin is created of a device in order to model and simulate its characteristics and performance over its lifecycle. In this manner, better-informed decisions can be made about design and specifications to improve through-life performance and reduce time to market (supporting the near-concurrent design and manufacture of components required increasingly by modern naval shipbuilding). The legacy shipyard interacts with the digital shipyard by transmitting digital information and images to the digital shipyard, monitoring and modelling actual processes and physical objects via its virtual twin. In addition, the digital twin can facilitate smoother, quicker and less costly change and development, reconfigurable production, non-destructive component testing, improve understanding and communication, anticipate changing customer requirements, and help guide production and maintenance decision making.

The Digital shipyard is also of critical importance to another feature of shipbuilding: the long life of the vessel requiring ongoing maintenance and major technology upgrades, with though-life costs typically exceeding build costs by three to one.

Figure 4-1: A digital twin (Ash, 2018)



4.5 Data-driven services and smart products – starting points for SMEs

The application of these technologies to shipbuilding will largely be driven by Primes, rather than independently initiated by SMEs. Primes have the responsibility to the customer for delivery of major defence projects to exacting specifications. They have the systems integration and technology capabilities required, together with the resources for investment.

SMEs are required also to meet exacting specifications including explicit ISO frameworks. These are also largely set by the Prime. SMEs occupy positions in a hierarchy in which they must respond to the demands and requirements of the Prime(s) and the final customer (government). Within such a hierarchy, as well as within SME resource constraints, they must actively pursue innovative contributions to the solving of common problems. They can and should pursue the development of proprietary technology and IP.

Although investment by SMEs in specific technologies will follow project requirements, from the viewpoint of positioning SMEs for overall readiness for digital adoption and participation in naval shipbuilding, the VDMA's analysis seems apposite to shipbuilding. It is that companies beginning to develop their digital strategies, from relatively low levels of readiness, need to prioritise the development of data-driven services using smart products (Anderl, et al., 2015). These offer SMEs a good point of departure for the development of their digital strategies and participation in the naval shipbuilding value chain. Smart products that provide data on their performance throughout their entire lifecycle offer potential to companies to expand their service offerings into areas such as predictive maintenance. These offerings have potential for further expansion over time, as SME capabilities and knowledge grow, and a Prime's requirements evolve. This is of particular importance in naval shipbuilding given:

- The need that is as great in defence industry as vital infrastructure sectors such as water, power and communications, for continuous and effective operations, including real time condition monitoring, and

- The fact that through-life support and technology upgrades are critically important, with through-life support typically accounting for three-times the value of the initial construction cost of a naval ship.

Functionalities may be added to products over time, tailoring the product and solution strategies to evolving customer requirements and through-life support. Data-driven services and smart products are a solid starting position.

4.6 Summing up: shipbuilding and Industry 4.0

(Torres Saenz, 2018, p. 95) summarises the specific meaning and significance of Industry 4.0 for shipbuilding as follows: "..Industry 4.0 technologies could be further transferred to a shipyard setting, giving birth to a Smart shipyard. In this type of production setting, the engineering processes and resources are entirely integrated, making the production process more efficient and more flexible by using real-time monitoring and control. During the production process, Industry 4.0 technologies will help to improve processes through self- optimization and automatic decision making in the design cycle.."

This summation is compelling as it relates to production, however subsequent discussion will show that this is the essential core, but not the totality, of the implications and applications of digital technologies to shipbuilding.

This report is about practical pathways to digital technologies in the Australian naval shipbuilding industry. It will later be asserted that an indispensable point of departure for any enterprise in commencing digital adoption involves:

- Starting to value data as a strategic asset of the business (McKinsey, 2015a), and
- In line with the principle of using current assets of the business as the starting point (McKinsey, 2015a), taking stock of data currently produced by the enterprise, and examining it for potential added value and future development and deployment.

In this context, it is worthwhile citing the assessment of (Torres Saenz, 2018, p. 17) regarding the state and recent practices of Spanish shipbuilding: "The massive amounts of stored and produced data are not being used during [the] manufacturing process..".

5 Barriers to innovation and digital adoption

A positive approach to enterprise and value chain capability development must be based in a comprehensive analysis and appreciation of the typical structural impediments to the acquisition of the required competences. There exists no automatic mechanism favouring acquisition of key competences by firms. That acquisition must be organised and intentional, involving a range of participants and stakeholders. The following discusses generic impediments before outlining a positive framework for improvement of enterprises' capacities for new capability acquisition and development. These impediments are structural. That is to say, they are inherent and are inscribed in unequal positions occupied by firms of different sizes and positions within an economy. This is contrary to versions of orthodox economics that assume all agents within the economy have equal access to perfect information about prices, technology choices, markets, etc. All agents share structurally equal positions. In reality, the information needed to make decisions is nearly always partial and often wrong. Agents to a transaction do not have equal, let alone perfect, information. Information is asymmetric. Vendors of complex financial products, for example, will usually know more about those products than the firms and households purchasing them (Stiglitz, 2010). A strategy for digital adoption and absorption is first and foremost a strategy to increase the quality and quantity of available information and knowledge.

Many of the impediments discussed below apply to issues beyond digital adoption but have especial relevance to uptake of Industry 4.0. Whilst many also apply to firms generally, they will have their most inhibitive effects on SMEs.

Therefore, a key overarching finding is that firm size matters. A German study finds "The degree to which Industry 4.0 applications are disseminated depends on the size of the enterprise" (Schroder, 2017, p. 11). This conclusion is supported widely (Lichtblau, et al., 2015) (Rauch, Vickery, Brown, & Matt, 2020) (Orzes, Poklemba, & Towner, 2020) (Matt, Modrak, & Zsifkovits, Industry 4.0 for SMEs. Challenges, Opportunities and Requirements, 2020) (Torres Saenz, 2018).

It will be seen that firm size influences the extent and nature of digital adoption in several dimensions. The most obvious of these relates to resources, with its concomitant effects on enterprise competence in key domains: technology, organisation, market and strategic awareness, and leadership. However, our central starting point needs to be an acknowledgement of the limited absorptive capabilities of SMEs. This is because it is the cause, sometimes direct and sometimes proximate, of many of the seemingly discrete impediments described below. These latter impediments can in turn and in combination reinforce a vicious circle of underperformance and slow digital adoption. This can even be true of very real resource constraints, which might however, be amenable to staged investment, and be made more tractable through, e.g., experimentation and pilot programs.

5.1 SME limited absorptive capabilities

The central impediment to digital adoption is lack of knowledge and awareness (Lichtblau, et al., 2015). Although this factor is intimately connected to resource matters, lack of knowledge and awareness is at the top of causal analysis of the impediments to digital adoption. As stated above, even resource constraints may be less of an inhibitor upon analysis of options for staging, controlled experimentation and pilot programs.

A key facet influencing this is the structural constraint of limited absorptive capabilities. This refers to the distinction between knowledge and information. To be useful to a business, information about digital applications needs to be recognised and understood, then assimilated, refined and processed into useable knowledge. It is through such a knowledge production process that the specific value and relevance of new information can be recognised and then applied by a particular firm. Lacking resources, SMEs frequently will lack the required absorptive capabilities.

These capabilities can be developed through research and development projects and attention to formal structures and processes for knowledge management, organisational development and learning, innovation, employee involvement, change management and supply chain collaboration. Such practices help build dynamic capability – the ability to adapt and reshape organisational resources and competences to changes in the strategic and operating environment. A number of consequential impediments either issue from, or are related to, limited absorptive capabilities[4].

5.2 Strategic deficits

The consequences of this structural limitation are pervasive. They condition many aspects of a business. They encompass overall lack of awareness, the absence of a digital strategy for the enterprise, uncertainty about the costs and benefits of digital adoption (including a frequent assumption that digitalisation is inherently expensive and is not able to be incrementally staged), scarcity of time and internal resources for consideration (further reinforcing low absorptive capability), low levels of preparedness and a lack of clarity about how an enterprise can start its 'digitalisation journey' (Her Majesty's Government, 2017a), lack of capability and commitment from leadership, and other organisational deficits that reinforce low awareness and capability, uncertainty about outcomes and a perception of high costs associated with adoption of digital technologies, and difficulties in implementing the transition to new business models (see the summaries in (Price Waterhouse Coopers, 2014) (Her Majesty's Government, 2017a) (Matt, Modrak, & Zsifkovits, Industry 4.0 for SMEs. Challenges, Opportunities and Requirements, 2020) (Torres Saenz, 2018) (Australian Industry Group , August 2019) (EEF, 2016) (Her Majesty's Government, 2017a) (Lichtblau, et al., 2015) (McKinsey, 2015a) (Mohamed, 2018) (Price Waterhouse Coopers, 2014)).

As can be seen, digital transformation involves overcoming impediments (endemic informational market failures and information asymmetries) and lifting the absorptive capabilities and strategic awareness of enterprises – their ability to recognise, sift and discriminate, understand, and then to act, - on key information. It involves building dynamic capability: the business's capacity to reorganise resources, effort and focus in response to, or anticipation of, new exigencies. The development of formal processes and structures for knowledge- and change-management are critical. The difficulties of small size can be mitigated, with some of the literature (Lichtblau, et al., 2015) even suggesting it can sometimes be turned to advantage through agility, compared to

[4] Again it would be impractical and repetitious to cite authors individually. The main sources on the impediments to digital adoption are (Mohamed, 2018), (Schroder, 2017), (Orzes, Poklemba, & Towner, 2020), (Matt, Modrak, & Zsifkovits, Industry 4.0 for SMEs. Challenges, Opportunities and Requirements, 2020), (Lichtblau, et al., 2015), (Anderl, et al., 2015) (Price Waterhouse Coopers, 2014) (Her Majesty's Government, 2017a) (Government, 2017b) (Matt & Rauch, 2020), (Australian Industry Group , August 2019) (Torres Saenz, 2018).

large companies affected by silos and compartmentalisation. (Torres Saenz, 2018) specifically focuses on the criticality of IT infrastructure and suggests that in shipbuilding SMEs might be able to incorporate new IT platforms more easily than larger firms and Primes, which will likely have higher sunk investments.

SMEs need to utilise opportunities for pilot programs and structured small-scale experimentation to open up new business opportunities (Lichtblau, et al., 2015) (Torres Saenz, 2018). However, Schroder's pithy statement of "Lack of a digital strategy alongside resource scarcity" (Schroder, 2017, p. 11) is to the point in characterising the actual position of most SMEs and how resource constraints and strategic deficits are mutually self-reinforcing and can form a vicious circle.

5.3 Security and standards

Cyber security heads this cluster of issues which also includes issues of ownership of data and IP, together with concerns about lack of codified standards and associated questions about adopting nonstandard solutions (Schroder, 2017) (Australian Industry Group , August 2019) (Boston Consulting Group, May 2016) (European Commission , 2016) (Her Majesty's Government, 2017a) (Kagermann, Andrel, Gausemeier, Scuh, & Wahlster, 2016) (Lichtblau, et al., 2015) (McKinsey, 2015b) (Mohamed, 2018) (Orzes, Poklemba, & Towner, 2020) (Price Waterhouse Coopers , 2016) (Rauch, Vickery, Brown, & Matt, 2020). Networking of production relies on business and customer confidence in the security, robustness and reliability of the network. Uncertainty and lack of knowledge and confidence inhibit investment.

Nowhere are security and standards more central than in defence industry, and nowhere do they represent a larger challenge to the participation of SMEs in the value chain. The challenges of digital collaboration are amplified in the defence industry, where national security concerns overlay normal commercial imperatives of value creation, capture and IP protection.

The lack of general standards inhibits SME participation in broader supply chains where a business may have different standards and norms to those required by potential value chain partners. There are related concerns about investing in interface technologies that may become sunk if the project or technology are not proceeded with. If interoperability and security cannot be guaranteed through standard interfaces, the project may stall. Cloud services carry still-greater security concerns for businesses (Schroder, 2017).

Cybersecurity countermeasures include increased investment in data encryption, methods for rapid decoupling of networks in the event of attack, enterprise education and understanding of data security standards (IEC/ISO 27001) and knowledge- and risk-sharing arrangements with trusted partners (Spoehr, et al., 2021). (Ash, 2018) points to potential gains in information security from digitalisation provided stability and management of security across the platform itself, as it eliminates the need for collaboration using email, web portals and other insecure platforms.

For defence industry, however, the issue for the SME will be whether they can adopt and adapt to the norms and standards required by the lead customer to which they supply. Defence industry was characterised by vertical integration prior to Industry 4.0. Systems integration is all-important and defines and encodes overall supply chain requirements. Digitalisation increases vertical integration. Those standards will be exacting for an SME but will be well codified. Expectations of the Prime will be clear. The issue will be the cost and the challenge of demonstrating to the Prime or lead customer, the SME's ability to meet the standards. Later this report examines the potential for Prime-SME collaboration and joint investment in gaining required standards accreditations (including cybersecurity) and infrastructure for secure digital collaboration. This includes potential risk sharing frameworks.

5.4 Legacy investments and issues

Legacy investments and issues are of greater significance in naval shipbuilding than perhaps any other sector. (Torres Saenz, 2018) emphasises the negative weight of legacy investments and issues in his survey of Spanish shipbuilding. For example, IT infrastructures are critical, but resources sunk into antecedent systems, general resistance to change, often worsened by segmentation of enterprises into different divisions and departments, affect adversely the potential for digital adoption, particularly for larger players.

Within shipbuilding, these impediments and issues affect Primes and larger players more than SMEs, given the size of investment typically required, and the often more segmented and siloed structure of larger enterprises. However, once the transition is decided upon, all businesses within the value chain, regardless of size, must respond through investment and effort. (Torres Saenz, 2018) suggests that in shipbuilding SMEs might be able to incorporate new IT platforms more easily than larger firms and Primes, which will likely have higher sunk investments. SMEs however face the array of other impediments issuing from lower absorptive capability and fewer resources.

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. (Chesbrough, 2010) and (Massa & Tucci, 2014), have discussed the impact of legacy investments, and legacy business organisation, practices and business models across the economy. They also refer to 'cognitive' or 'paradigmatic' impediments – organisational culture and leadership - as the other major barriers 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. 427-9). 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 spillovers. It also raises potential security risk.

Where the need for major technological, organisational and business model reconfiguration comes up against large sunk investment in existing systems, the scope of change is likely challenging. This applies to both Primes and lead customers and SMEs already invested in the value chain. However, granted the size of investment required of Primes and larger firms, legacy issues constitute a larger impediment the larger the firm, generally speaking.

The digital shipyard is a way of helping to reconfigure relationships, models, and practices to the new requirements. It is a vehicle for change management across enterprises and supply chains and can help accelerate, improve, and align processes. Investments in systems must be complementary, and on occasions, joint investments might be considered.

5.5 Competence and skills

Several sources report high deficits of workforce skills and capabilities as a major barrier to digital adoption (Mohamed, 2018) (Her Majesty's Government, 2017a) (Price Waterhouse Coopers, 2014) (Australian Industry Group , August 2019) (University of Warwick, (ND)).This refers not only to capabilities specifically pertaining to digital technologies, but also to broader problem-solving skills, the ability to deal with organisational change, ongoing problem iteration and task reconfiguration, and so on. This issue then refers to both an enterprise's capacity for organisational change – its dynamic capability - as well as specific skills sets. Later in this report we will examine opportunities for enterprises, and especially SMEs, to leverage the tacit digital skills of their workforces to create momentum for digital transformation. This might include joint projects to discover existing tacit skills of the workforces of several collaborating businesses, as well as joint programs for training and skills enhancement.

5.6 Business and investment support

Finally surveys often report businesses speaking of disjointed systems of technology and business advice, together with difficulty in raising loan capital for new technology acquisition. Again, asymmetric information markets play a role here. Acquisition can be inhibited by a lack of trust in advice on equipment purchase, particularly from equipment vendors. Conversely, expensive equipment may be purchased that never fulfills the business's need because its concomitant organisational and workforce requirements have not been addressed, or because the right investment for the company was in any case not new kit but an enhancement of existing assets. A lack of peers and shared case studies from which to learn can also be a factor inhibiting digital adoption. Later this report considers new forms of business support and peer learning, through intermediate and translational organisations, that provide better alignment to the challenges of digital adoption, including peer learning.

6 Maturity models: Digital readiness

There are many tools, often of European or UK origin and with an SME focus, available to enterprises as a means of assessing their current state of maturity with respect to digital adoption and application. ‘Maturity’ here refers to the level and nature of the business’s underlying capabilities, or its ‘readiness’ to deploy productively digital technologies in a thorough-going manner. This section broadly overviews the content of a cross-section of these. They provide a high degree of thematic commonality and, in so doing, help to define desirable characteristics of enterprises in digital value chains according to defined developmental stages of maturity.

The application of such maturity models therefore commences the process of addressing the impediments to digital adoption and new business models discussed generically above, but in the concrete context of a single enterprise.

They can be used to inform a business of its current state and priorities for improvement. They can assist partner businesses and Primes to pinpoint actions required to de-risk an SME’s participation in the value chain and can help to prequalify an SME for a project. They identify areas for improvement that will have the most beneficial impact. They help establish prime facie benchmarks of current performance and capability, thereby being a gateway to more intensive targeted capability development programs, and therefore also feeding into the development of more rigorous benchmarks over time. Desirably, they can be the entry-point to more intensive processes involving intermediate organisations and collaborations along the value chain, together with improved internal business processes discussed below.

6.1 Stylised digital maturity model

Digital maturity frameworks typically assess businesses across dimensions considered key to their capability and long-term performance. These dimensions are broken down into subdimensions or fields. The maturity of the enterprise with respect to these dimensions and subdimensions or fields is either self-assessed or externally assessed according to criteria usually, but not always, captured by levels of agreement with statements about the state of the enterprise.

6.1.1 Dimensions of a typical maturity model

- Products and services – including awareness of ‘manufacturing as a service’, use of data, digital features of products, how well value is created and captured for the business and customers, degree of customer lock in
- Manufacturing and operations – extent of awareness and use of various digital technologies, automation, machine to machine communications, decentralisation of processes, etc.
- Leadership - extent of awareness and commitment of leaders to innovation, digitalisation, new business models, sustainability, how well the leadership reaches all parts of the organisation, etc.
- Strategy - including I4.0 roadmap, resources, change management, culture (including flow of communications), alignment of divisions
- People and workforce development – extent of knowledge sharing, autonomy, digital competence of employees
- Supply chain – levels of integration and collaboration, application of digital, collaboration over the supply chain, strategic suppliers
- Industry 4.0 and digitalisation – including current use of digital tools, awareness of Industry 4.0, and utilization of Industry 4.0

- Governance – standards, cybersecurity, IP protection.

6.1.2 Measures of maturity level

For each of the dimensions and subdimensions or fields, the level of the business's maturity is determined and described in one or more of the following ways:

- Usually a five-point scale from strongly disagree to strongly agree, with a statement such as: "Our business has a well-articulated digital strategy that is an integral part of our overall strategic plan" (Innovative Manufacturing CRC, 2018).

- Assignment of readiness level (or stages) of business such as:
    - Level 0: Outsider (the company has very little in place/low readiness) through to Level 1: Beginner (the company has some pilot projects, but little is in place) through to Intermediate, Experienced, Expert, and Top Performer (full implementation of the Industry 4.0 vision and systems) (Lichtblau, et al., 2015), or
    - Beginner, Intermediate, Experienced or Expert (University of Warwick, (ND)), or
    - Digital Novice to Vertical Integrator, to Horizontal Collaborator to Digital Champion (Price Waterhouse Coopers, 2014)
    - Other description of appropriate developmental stages (Lichtblau, et al., 2015)

6.2 Selective list of Industry 4.0 maturity or readiness models and tools

Table 6-1: Key industry 4.0 models and tools

Name of model	Institution/source	Nationality
(Lichtblau, et al., 2015) Impuls – Industrie 4.0 Readiness	VDMA	Germany
(University of Warwick, (ND)) - An Industry 4 readiness assessment tool (ND)	Warwick University	UK
Numerous intensive diagnostic frameworks	Fraunhofer	Germany
(Innovation Value Institute, 2016) - Digital Business Readiness Index (2016)	Innovation Value Institute, Maynooth University	Ireland
Guideline Industrie 4.0: Guiding principles for the implementation of Industrie 4.0 in small and medium businesses (Anderl, et al., 2015)	VDMA	Germany
Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies (Schuh, et al., 2017)	Acatech	Germany
IoT Adoption Index Survey (IoT Alliance Australia, 2017)	IoT Alliance Australia	Australia

Industry 4.0 and Opportunities and Challenges of the industrial internet (Price Waterhouse Coopers, 2014)	Price Waterhouse Coopers	Germany
futuremap (Innovative Manufacturing CRC, 2018)	Innovative Manufacturing CRC	Australia

7 Approaches for SMEs

Digital adoption and participation in complex value chains by SMEs means overcoming or mitigating a range of structural difficulties and limitations outlined above. These limitations are multi-faceted but many of them issue from the structural limitations imposed by small size, limited absorptive capabilities, and structural deficits, of which lack of awareness, information and knowledge are central. The required approach involves increasing the absorptive capabilities of SMEs, together with their dynamic capability – their ability to shift and reorganise resources and effort to meet new challenges and opportunities.

The central inhibitor for SMEs is uncertainty about the perceived costs (organisational disruption, return on investment) and benefits of investment in digital technologies. Other impediments either relate to this or are of a more contingent discrete nature.

Effort must take account of immense variation in the practical circumstances of SMEs and address a range of structural and resource limitations, such as the lack of internal resources for research and development, for achieving ISO qualifications (especially for IT and cybersecurity), that leadership is often diluted by a business's never-ending operational requirements, the lack of a comprehensive IP policy, the lack of change management approaches, the challenges of developing new business models, etc.

These practical issues often prevent SMEs even from commencing the process of digital transformation. This section concerns how and from where SMEs may start the process. It concentrates on developing internal processes and capabilities.

Increasing the absorptive capacity, knowledge and maturity of an SME is the appropriate overriding goal of a strategy to embed digitalisation. This is true at the level of individual businesses and across the value chain and whole industries. This requires a structured and stepped maturity approach as illustrated in the summary of maturity frameworks in the previous section. The starting point for SMEs often will be a focus on production efficiencies and cost reductions as the motivator for digital adoption. This is an appropriate point of departure for successful digitalisation. But a properly structured process will add to the potential – indeed, the necessity - for digital adoption to take in changed business models and new modes of enterprise leadership and organisation.

Proficiency in pilot projects is an important skill for an SME in developing a digital strategy (Lichtblau, et al., 2015). A well-executed pilot program allows boundaries to be placed around an initiative. This in turn helps new ideas to be trialed and proved with minimal disruption to existing products and revenues. It allows appropriate experimentation. It limits the call on the business's resources and helps ensure that any failures are contained financially.

7.1 Some key questions

A key principle in considering digital adoption and entering new value chains is to begin by assessing and asking: where is the business, and what specific assets and capabilities does it have currently, upon which it can build? Existing capabilities can take on added value when appraised from the perspective of new business opportunities (Lichtblau, et al., 2015) (McKinsey, 2015a).

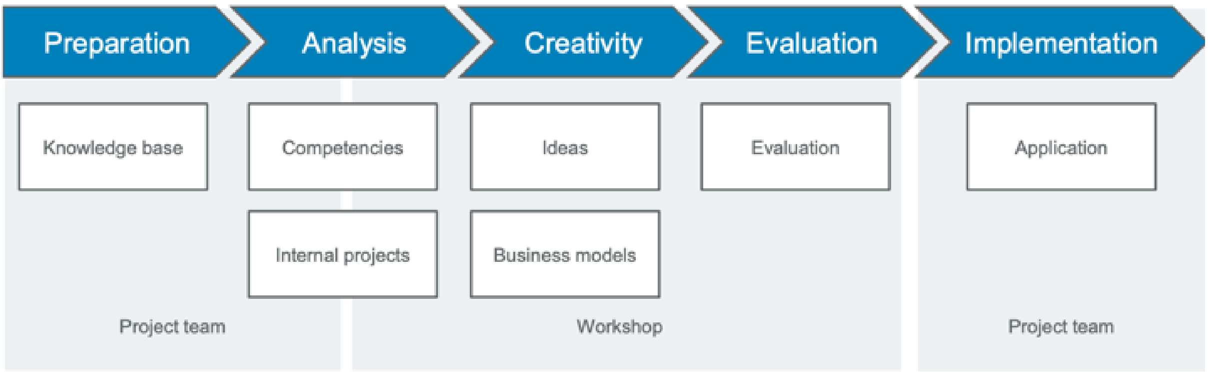
The following headline questions are representative of a business that would be designated a 'beginner' or 'digital novice' in the maturity frameworks previously described, for example having few or no digitally connected machines and collecting little or no data from their operation. The questions are designed to lead on to longer-term structured and sometimes formal processes of innovation and change management and development of IP. As (Lichtblau, et al., 2015) observes, a beginner or novice will be concerned primarily with a cluster of internal issues; the more advanced is a business, the more will its concerns straddle internal and external factors.

- What existing machines of the business could be connected digitally? Where could cheap sensors be fitted to our machines? How could this be done incrementally with low investment and risk? How could this benefit our production efficiency or help us develop a new product or service?
- What services does the business offer currently in association with its products? Could these be enhanced through digital technology to offer e.g., the security of predictive maintenance and real time data on the product? Are customers asking for new services from our business?
- What digital technologies does the business use currently? For example, CAD/CAM, various Cloud applications, any sensors?
- What data does the business collect currently? What does our business know about how customers use the products currently? Could this be enhanced to add revenue and provide lock-in with key customers? Are our customers already asking for more data-driven services?
- Could we do better in leveraging the existing digital skills of the workforce? What are those existing skills and is the business making good use of them? Apart from their formal qualifications, what additional practical and tacit skills do they have, and can we make better use of those on the shop floor?
- Can the business move to offerings with a higher service content, such as predictive maintenance of a product/component? How does the business change from a mindset of just production and unit cost, to lifespan, lifetime performance and use? How does the business go from thinking about just the cost components and margins at point of sale, to revenue based on all aspects of the product's performance over its life?
- How do we create awareness of Industry 4.0 across the business: the board, leadership, management, workforce? Given that digitalisation is about all aspects and sections of the business, do we have the leadership capable of driving the change throughout the organisation?
- Given the business's modest resources, who are the leaders ready to step up? How do we carve out the resources to work on proposals? How do we ensure all parts of the organisation are aligned to the change process? What structures, teams and processes are needed? What goals should be set? What timelines should be set?
- How can the project be scaled to allow experimentation, and to ensure that if something does go wrong, it does not have a major impact on the business?
- What are the developmental stages the business can identify to allow a manageable, phased transition to Industry 4.0?

7.2 Key structures and processes

These questions need to be answered through agreed structured approaches and processes that can define the procedures and developmental stages toward Industry 4.0 appropriate to the individual business. This means the process should be set up as project with dedicated responsibilities, resources, goals and timelines. Successful digital adoption requires the business to have a digital strategy. Germany's VDMA (Anderl, et al., 2015) has produced one of the most comprehensive guides to manufacturing SMEs for digital adoption, *Guideline Industrie 4.0: Guiding principles for the implementation of Industrie 4.0 in small and medium sized enterprises.* It is focused on identifying practical steps and identifiable stages towards digital adoption, as against 'all or nothing' preconceptions that work against staged exploration and implementation, and even against commencing the process at all. It is a useful illustration of the types of approach possible and appropriate, that can be modified to suit different circumstances and requirements.

Figure 7-1: Key stages (Anderl, et al., 2015)



The process is organised in five stages, with attention to the pre-implementation phases in the following summary.

7.2.1 Project team

Prior to commencement of preparation a project team needs to be composed to guide preparation and all subsequent steps. It must reflect the full support for the process by the business's leadership, and include personnel from production, IT and development.

7.2.2 Preparation

This phase involves the team consolidating as much information as possible about Industry 4.0, the business's current market and product portfolio, and organising the workshop, which is a critical ingredient in informing subsequent phases.

7.2.3 Analysis phase

This is a stock take of the Industry 4.0 expertise within the business with respect to both the products it makes and the production processes and technologies it employs, using the VDMA Industrie 4.0 toolbox (see below). This phase includes not only analysis of the business's internal capabilities but also an assessment of how the business is regarded by its main customers.

This phase yields a company-wide competence profile and provides a common starting point of facts for the workshop participants. It aggregates not only known formal competences but also aims to unearth latent or tacit capabilities.

The 'external competence analysis' focusses on the business's product profile to see how the business's customers evaluate its competence. Less developed aspects of the competence profile are examined for development opportunities.

The 'internal competence analysis' provides a more comprehensive picture by taking in both products and production. Again, it is about revealing not only formal but also tacit competences: "Experience has shown that the product portfolio as well as the technologies already used in the in-house production do not reflect the entire range of competencies that are existing in the company. Thus, the internal competence analysis pursues the objective of identifying Industrie 4.0 competencies which go beyond market-mature, saleable products and solutions already implemented in the in-house production" (Anderl, et al., 2015, p. 18)

7.2.3.1 VDMA Industrie 4.0 toolbox

Like the other maturity assessments discussed previously, the Industrie 4.0 toolbox is used to assess a business's level of development against key characteristics and enablers for digital adoption. This approach is applied to both the products and the production of the business.

7.2.3.1.1 Products

Sensors and actuators; communication and connectivity; data storage and exchange of information; monitoring; product-related IT services; business models.

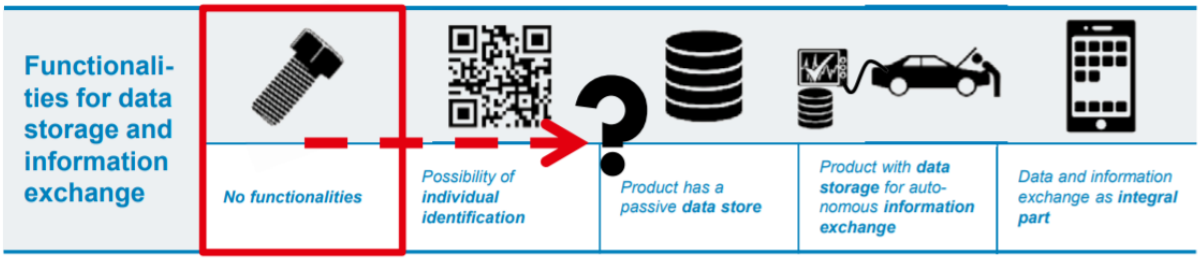
7.2.3.1.2 Production

Data processing in production; machine to machine communication; company-wide networking with the production; infrastructure of information and telecommunication technology in production; human-machine interfaces; efficiency for small batches.

7.2.3.1.3 Example: From vision to practical implementation

Here is an example of a workshop assessment of the business's current product offerings and capabilities with respect to a possible opportunity for a smarter product. The workshop takes perspectives from across the business to test and assess its current capabilities.

Figure 7-2: Example: from vision to practical implementation



7.2.4 Creativity phase

Using the hard information and assessment of current capability derived from analysis, the idea in this phase is to generate ideas for new business models and opportunities at the workshop, and to then develop them further into more solid models, concepts and propositions. This involves individual and group inputs in developing and testing ideas about Industry 4.0 opportunities focused on what can the business offer to the customer(s) and deepening the business's value proposition to the customer(s). This uses one of the available business model analysis frameworks.

7.2.5 Evaluation phase

Still within the workshop, worked-up concepts and propositions are ranked according to their value as either market potential (for products) or for production gains, as well as against an assessment of the resources required for implementation. "The aim is to identify business models with a high potential and a low resource input or a valuable utilization of the company's strengths" (Anderl, et al., 2015, p. 10). Hence the two key criteria relate to the market potential of the business model and the available resources and capabilities within the business required for its implementation.

7.2.6 Implementation phase

The project team prepares the proposals for further examination by the business's leadership. A leader is designated as the contact for follow-up and ensuring further development of approved proposals.

7.2.7 Results

The outcomes of the process outlined in 7.2 might involve project implementation in the initial form of a pilot program, so structured and designated to test propositions and opportunities on a manageable scale to deal with risk, allow experimentation, and avoid compromising existing products and revenues of the business. As a pilot, the project can develop an actionable roadmap for implementation at full scale.

The process will have generated additional data and information about the business. These data should help inform the development of new benchmarks and KPIs for the business. Given that this will be as a part of a naval shipbuilding value chain project, additional benchmarks will need to be agreed between the SME and Prime (see below). However, it is vital that the above structures and processes and the information generated start to be used to guide thinking and future decisions.

7.3 Internal change management and projects

As earlier stated, VDMA's (Lichtblau, et al., 2015) comprehensive analysis found that whilst the digital agendas of large firms straddled internal matters and external relationships, those of SMEs are much more focused on the internal. This is for reasons discussed above, but it is also desirable for organisations needing to build absorptive capability and dynamic capability.

This means improved structures and practices for communication of goals and objectives throughout all parts of the organisation. It also means a strong role, as required, for leadership-mandated project and action teams, sometimes with formal and at other times semi-formal roles. They may be given specific capability-building tasks, such as preparing the conditions for acquiring ISO certification for cybersecurity, devising a roadmap for the development of a new product, service or specific technology, overhauling the business's strategic plan, specific innovation projects, etc.

It means that more activities will have a structured if still flexible character. These will often be in the form of pilot projects that trial an idea or process in a part of the business, at low risk, prior to broader rollout. It will involve cross-functional governance, steering and action teams (McKinsey, 2015a) (Torres Saenz, 2018). These structures and processes help insulate the ongoing production, products and revenues of the business whilst allowing experimentation in new technologies, products and processes.

Structured governance and processes are needed for innovation- and knowledge-management see (Spoehr, et al., 2021). It is important for an SME to know and codify what it knows, and what its competences are. These relate to the making of products, background technical competences, formal standards accreditation, existing IP, together with latent or tacit workforce skills. These issues are of especial importance in supply chain collaboration with a Prime.

Issues relating to recognition and sharing of intellectual property, and adoption of standards (including cybersecurity) are finally determined within the context of value chain and lead customer relationships, to be considered in the next section. The clear advice from experts is for SMEs to be active in the establishment of standards for interoperability and cybersecurity and to embed such considerations into the core of their business, prioritising protection of key assets (McKinsey, 2015a), and actively build strategic alliances and partnerships with Primes and lead customers (McKinsey, 2015a) (Torres Saenz, 2018).

7.4 Digital strategy: getting started

The fundamental point is that SMEs will need a digital strategy, ultimately covering all facets and operations of the business. However, commencing the process requires setting priorities alongside pragmatic acceptance that the full strategy can only be developed in stages. This could be the role of a dedicated project group or team(s).

This means consciously valuing and developing data as a business asset, using it to generate indicators initially, and progressively extending the business's strategic management of its data. It is advisable to start by concentrating on a limited number of digital applications and be prepared to use workarounds pragmatically, in order to gain experience (McKinsey, 2015a) (Lichtblau, et al., 2015). (Price Waterhouse Coopers, 2014, p. 46) sets out three pragmatic "first steps on the path to digitization":

1. Give all things a name: all products and materials to have a clear ID as the basis for digitising and connecting products and generating data from them
2. Measure, measure, measure: install sensors to measure processes and sensor data along the entire value chain to improve processes, product quality and reduce costs
3. Connect and analyse: connect products to their digital specification, their production materials and data from their manufacturing process, and connect the different sources of data, to define efficiency measures and improve optimisation practices.

This starts from an evaluation of the business's current assets (McKinsey, 2015a) of the type earlier described. (Torres Saenz, 2018, p. 17) finds not only that in Spanish shipbuilding: "The massive amounts of stored and produced data are not being used during [the] manufacturing process..", but also that enterprise leadership frequently does not have a complete understanding of actual current production processes. Such an understanding is the basis for the incorporation and adoption of digital technologies. Hence, and as indicated by other sources, a map of existing production is the requisite starting point.

7.4.1 Prioritise data-driven services and smart products for SMEs

As earlier stated, from the viewpoint of positioning SMEs for overall readiness, for the VDMA's conclusion, which it applies to all manufacturing, seems apposite to digital adoption and participation by SMEs in naval shipbuilding. It is that companies beginning to develop their digital strategies, that may be at a relatively low level of readiness, need to prioritise the development of data-driven services using smart products (Lichtblau, et al., 2015). These offer SMEs a good point of departure for the development of their digital strategies and participation in the naval shipbuilding value chain. Smart products that provide data on their performance throughout their entire lifecycle offer potential to companies to expand their service offerings into areas such as predictive maintenance. These offerings have potential for further expansion over time, as SME capabilities and knowledge grow, and a Prime's requirements evolve.

This is of particular importance in naval shipbuilding given the criticality of continuous and effective operations, including real time condition monitoring, and that through-life support and technology upgrades are critically important, with through-life support typically accounting for three-times the value of the initial construction cost of a naval ship.

Functionalities may be added to products over time, tailoring the product and solution strategies to evolving customer requirements and through-life support.

7.4.2 Torres Saenz on Key Success Factors in digitalising shipbuilding: A basic roadmap

A recent fieldwork-based study of the Spanish shipbuilding industry by (Torres Saenz, 2018) confirms the key impediments to digital adoption summarised earlier. It is worth repeating that this study concluded that currently potentially valuable data are not being sufficiently fed back into the manufacturing process, and that enterprise leaders frequently lack awareness of actual current production processes. He distills key success factors in digital adoption from a larger array of factors volunteered in interviews with businesses and technical industry experts. He has analysed and cross-correlated this larger set of responses to arrive at a shortlist of those with greatest significance and weight. These apply to the whole value chain, not only to SMEs, and will inform further discussion. Hence his conclusions merit separate summary, as they reinforce the analysis so far, and will feed into subsequent analysis of the value chain.

7.4.2.1 Focus on process rather than specific technologies

As previously observed, businesses were found to lack a full understanding of their current processes. Yet such mapping of existing processes, and especially those that are priorities for improvement, is vital. Understanding current process is the basis for correctly identifying the problem to be solved and, therefore, the technologies and the technology roadmaps needed. The potential of any technology cannot be realised concretely without answering: “what is the problem we want to solve”? Research needs to start with that issue, then expanding into analysis of the business and strategic environment of the enterprise, and what its competitors are doing.

7.4.2.2 Apply technology to enhance the role of people, not to replace them

Shipbuilding businesses will succeed in maximising value creation when digital technologies are deployed to assist the workforce and enhance the role of people, rather than replace them. This is seen in the role of technologies such as Augmented Reality which enable teamwork, trialing of new ideas and approaches on a smaller experimental scale. The introduction of such technologies on the shop floor requires clear communication from leadership and management, ensuring all understand its purpose of enhancement not replacement. It therefore brings into play the importance of organisational change management.

7.4.2.3 Scale projects from smaller to larger

This approach allows trialing of minor changes that will not compromise existing production and revenues, because they are insulated from other parts of the business. It has potential to provide early demonstration of the technological success and potential return on investment of the proposal. In this way, they help build support and momentum for change. Such scaling of projects is a key role for dedicated designated cross-functional teams and can result in product and technology roadmaps for adoption by the business.

7.4.2.4 Support organisational change

Leadership and management of organisational change is critical. It cannot be successful through the simple addition of functions to existing structures, which leads to poor communication and failure. Change involving digital in one area will lead to change across the organisation. All parts of the enterprise need to change and adapt, and the flow and sharing of knowledge and information needs to reflect this. Structural change is required but, again, can be piloted and trialed using inter alia, cross-functional teams. Successful processes will see greater use of work teams, decentralisation of activity, sharing of knowledge, and a premium on positive communications sharing distilled experiences of change from research, the shop floor, etc.

7.4.2.5 Build strategic alliances

Strategic alliances can be critical to adopting digital technologies and solving common problems. The main forms will be collaborative R&D, splitting the risks and costs of investment, and spreading the benefits of such investment by building their scale, significance and ambition.

8 Primes, the value chain and SMEs

8.1 Overview: The value chain as virtuous circle

Several sources describe the shipbuilding value chain in largely technical and engineering terms (Sullivan, et al., 2020) (Stanic, Hadjina, Fafandjel, & Matulja, 2018) (Ramirez-Pena, Abad Fraga, Sanchez Sotano, & Batista, 2019) (Gourdon & Steidl, 2019) (Giallanza, Aiello, Marannano, & Nigrelli, 2020). Work by (Torres Saenz, 2018) (Spoehr, et al., 2021) and (O'Keeffe, Moretti, Hordacre, S, & & Spoehr, 2020) combine the engineering dimensions with those of firm and value chain strategy and organisation.

The previous sections have considered in some detail the requirements of and specific areas for capability and maturity development amongst SMEs. The section to follow considers the potential for various intermediate organisations to provide certain inputs and an important part of the framework and direction for intensive and long-term collaboration between Primes and SMEs in major naval shipbuilding projects. This includes the Digital Shipyard.

In the present section, the focus is on the entire shipbuilding value chain and, in particular, the critical, leading, structuring and shaping roles that Primes must play as lead customers within that value chain. In addition, the standard descriptions of the value chain in physical engineering and functional terms as cited above, are assumed[5], but are here supplemented by a more structural and qualitative view about value chain governance and organisation. The guiding thread of this embodies two ideas, that:

1. The naval shipbuilding value chain has as many, if not more, of the characteristics of a hierarchy than other industries. The lead customer is in a controlling structural position.
2. However, to be successful given the long-term, experimental, stochastic nature of shipbuilding, collaboration, iteration and continuous, instantaneous information and feedback loops between Primes and SMEs are essential.

By adopting mission-oriented structures and processes, the naval shipbuilding value chain can form a virtuous circle, in which innovations and beneficial spill overs can be maximised through intensive and structured exchange of knowledge and information, and constant iteration, between Primes and suppliers. Digitalisation increases the importance and density of B2B relationships. Industry 4.0 increases the velocity, frequency and overall importance of information and knowledge exchange within businesses and along the value chain entirely.

Project success depends upon all participating businesses contributing and developing their IP and specialisations through structured and intentional interactions. In modern shipbuilding, design and production are near-concurrent. Digital technologies further and accelerate this fusion of concept and execution. This essential interdependency needs not only to be recognised, but positively exploited as a long-term benefit.

This requirement for collaboration accompanies an ultimately greater requirement for hierarchy. Different parts of the value chain occupy different positions of power. An equilibrium of hierarchy and collaboration is required, one that can alter its form and function as required.

As lead customers Primes (prior to the final customer, Government) occupy the apex in major projects. Both government, as final customer, and Primes, as lead customers and systems integrators, can structure value chain relationships in a project on the model of mission-oriented projects. Mission-oriented projects leverage demand around a need defined as a mission, as

[5] (Sullivan, et al., 2020) (Stanic, Hadjina, Fafandjel, & Matulja, 2018) (Ramirez-Pena, Abad Fraga, Sanchez Sotano, & Batista, 2019) (Gourdon & Steidl, 2019) (Giallanza, Aiello, Marannano, & Nigrelli, 2020).

distinct from solely responding to and evaluating individual project proposals. Practically, this means:

- Setting the directions for the project and the desired direction for innovation
- Setting directions by defining a challenge and desired outcomes: goals are outcome-based
- Ensuring the challenge is clearly and accurately defined: this can often best be couched in a scientific or technological target, such as the weight of a component part
- Having cross functional teams to coordinate and lead all the relevant value chain partners
- Having clear agreed measures to know whether the mission is being achieved
- Ensuring that the demand-side – the Prime – is involved in the project design and throughout the delivery process.

As previously stated, naval shipbuilding value chains embody complexity, that is, knowledge intensity. Primes and 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.

Beneficial spillovers 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 being created and circulated on a larger scale and at a quicker pace as a result. It cannot be overemphasised that the nature of such knowledge and competence transfer, feedback and flow is not only technical, but also deeply rooted in an understanding of a wide range of human factors including management and organisational dynamics and leadership. Such projects feedback into the research system innovations in process, organisation and leadership through strong results and demonstration effects.

This is especially relevant in defence projects where not only initial product development, but through-life maintenance, adaptation, and enhancement costs, are so important. In the case of naval shipbuilding, through-life maintenance can be three-times the value of the initial ship build. Importantly the Industry 4.0 agenda brings these different factors of influence together, focusing heavily on the role of co-design in helping to respond more effectively to the needs of users and customers.

The role of the lead customer (the Prime) is foundational: “New products will never be better than the competence of customers to understand and to use them, and what they are willing to pay for” (Eliasson, 2010, pp. 2, 4-5). Robust structures and processes, including clear communication to SMEs, can make the value chain a virtuous circle for innovation and problem-solving.

8.2 Before prequalification and ongoing in parallel with the project

Prior to prequalification of SMEs to a project, and as an ongoing activity through the project’s life, Primes, and the final customer (government) can structure activities to create broad awareness about potential future project opportunities. These can take several forms, including supplier forums, information on directions in modern shipbuilding, and other thematic issues such as emerging trends in Industry 4.0 and shipbuilding, new technology information sessions, problem-raising sessions on specific issues, etc. They could signal possible upcoming joint research opportunities, including grant opportunities from the Australian Research Council, CRCs or others. Finally, powerful positive case studies can be disseminated to promote rapid peer learning.

Such activities could be in partnership with intermediary research translation bodies or test labs which, as will be discussed, can assist in recruitment of SMEs to the naval shipbuilding value chain.

Use should be made of maturity models and diagnostic tools as discussed previously. Intermediate translational organisations such as test labs can be trained and accredited to deliver such tools, perhaps with additional modules for issues most relevant to naval shipbuilding.

The core rationale for activity at this level is awareness-raising, including of mandated and expected benchmarks and KPIs, including those relating to quality, engineering and cybersecurity.

These are opportunities for Primes particularly to cast a net for SMEs and begin identification and development of candidate businesses. It is essential that the processes, timeframes and horizon be sufficient to give SMEs a real opportunity to develop the new capabilities required by the project and the Prime to deal with the following inhibitors to SME participation:

- Primes' reliance on their international supply chains, especially for systems integration, that can work against SME value chain participation, and
- SMEs sometimes being excluded as lacking required capabilities, without sufficient time to possibly acquire those required capabilities.

Processes of this nature can:

- Help SMEs to assess their capabilities, and identify which additional capabilities they would need to acquire, to compete for a new opportunity, and in a complementary manner,
- Help primes substantially de-risk their use of qualified SMEs through a process and framework focussed on prospective capability development.

8.3 Prequalification

Prequalification assesses potential suppliers against predetermined criteria to consider whether individual businesses will later be considered for project work. Prequalification typically assesses technical capabilities and experience, financial capacity, business and management systems and capability (quality management, OH&S, standards accreditations, environmental practices), management of people, and business and organisational factors. The exacting nature of defence procurement means that criteria relating to technical capability and business systems and continuity will be of a high order.

The point here is the general one that Primes can work with selected SMEs to help address identified deficits where the business has strengths that place it at the threshold of prequalification for a project.

8.4 In the project: Areas for intense collaboration

Once the project is cast as a mission-oriented project, giving it extra directionality and focus, a range of possible collaborations can be considered. Once qualified to tender for work within a project, SMEs can be assisted by a Prime in several likely ways. No business, SME or Prime, comes to a complex naval defence project with the fully developed complement of required capabilities. Prequalification only establishes the presence of generic capabilities.

The level, quality and intensity of collaboration in the project is key to its success. High quality collaboration is both cause and consequence of a successful project. It cannot be left to chance, but must be purposeful, organised, led and orchestrated. 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 ex ante outcomes cannot be prescribed (Massa & Tucci, 2014). However, these must also ensure the necessities and hierarchies inscribed in lead customer relationships are recognised.

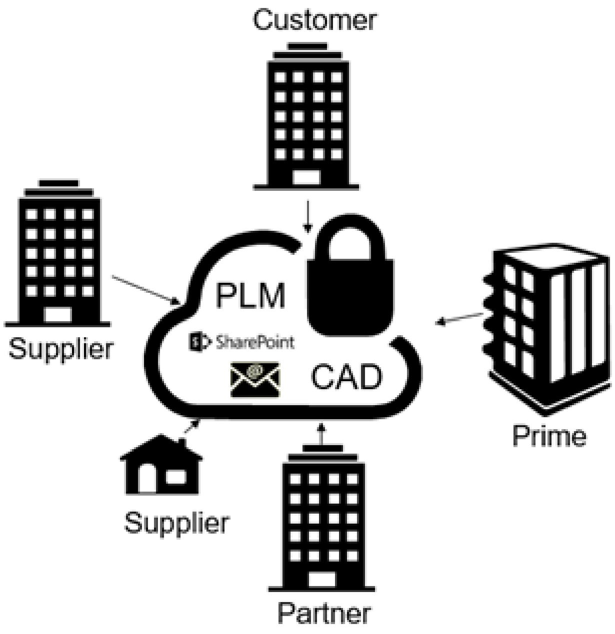
The ideal sought is a governed "network of exchange partners" (Massa & Tucci, 2014, p. 423), allowing collaboration, experimentation and iteration along the value chain, whilst being organised around hierarchical lead customer relationships and vertical integration. This is a framework of "co-creation and lead-user innovation" (Paasi, Luoma, Valkokari, & & Lee, 2010, p. 631).

8.4.1 Working together to achieve key standards and accreditations

Primes' requirements set the approaches to be taken by SMEs. These will be exacting, but they lessen the sources of uncertainty pertaining to SMEs generally, such as differences of standards and norms and concerns about interoperability and investment in interface technologies that could become redundant.

A central issue for digital applications in defence clearly is cybersecurity. ISO 27001 is the international standard for information security management. It is a risk-based framework with the planning, implementation, operation, monitoring and improvement of an Information Security Management System (ISMS) at its centre. As a risk-based framework, it does not mandate a set of security controls but focuses on continuous improvement. It depends to a high degree on stakeholder engagement and management to identify gaps and areas for improvement and ongoing attention. It is well-suited to collaborative joint projects and work involving Primes and SMEs together. Primes can help SMEs identify their most important gaps and work with them to address these.

Figure 8-1: Secure collaboration (Ash, 2018)



8.4.2 Risk-sharing framework

Collaboration on the scale and intensity required by naval shipbuilding projects depend on applying risk-sharing frameworks and protocols without which, there will likely be underinvestment in new technologies and processes. Risk-sharing underpins effective strategic alliances and lowers the barrier to new investment by both resource-challenged SMEs and Primes in new research and equipment and technologies. Risk-sharing frameworks and protocols have a role in the success of long-term research and development projects. Reference has been made previously to SMEs' resource limitations which restrict capacity to conduct internal R&D projects. The digital shipyard provides common infrastructure and resources for collaborative inquiry and projects. The splitting of costs and risks of investment lowers the barriers to such investment and helps build over time the scale, significance and ambition of mission-oriented projects.

8.4.3 Protection and sharing of Intellectual Property (IP)

This is critical for effective value chain collaboration. IP will not be shared unless its owner can be assured of retaining the benefits of ownership. Standard IP protection contractual approaches retain relevance and are not inherently opposed to more fluid longer-term collaborations required by long-term defence industry projects. But 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, power imbalances between primes and SMEs condition disputes on provenance and ownership.

The issues concerning IP, knowledge-management and collaborative long-term projects are canvassed in (Spoehr, et al., 2021). Such projects include two key and distinct 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 (Paasi, Luoma, Valkokari, & & Lee, 2010).

As largescale and long-term defence projects have strong mission-orientation, they straddle both stages and exhibit higher levels of translation from exploration to exploitation (see for example (Mazzucato, Kattel, & and Ryan-Collins, 2020) than is usually seen in other sectors.

As described in (Spoehr, et al., 2021) the process of sharing IP should commence with codification of each participants' existing knowledge. Over-reliance on standard IP law, such as joint ownership of patents, is suboptimal because of the open-ended and stochastic nature of the process, and the importance of tacit versus codified knowledge, making difficult the clear attribution of outcomes to individual partners (Paasi, Luoma, Valkokari, & & Lee, 2010). The customer can own the results, whilst extending certain rights of use to partners, as these can often improve and build upon the results and improve the long-term value chain relationships (Paasi, Luoma, Valkokari, & & Lee, 2010).

A collaborative project between a Prime and SMEs should commence with a "brief but adequate formal agreement" (Paasi, Luoma, Valkokari, & & Lee, 2010, p. 647) 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 innovation outcomes, and their lifecycles (Paasi, Luoma, Valkokari, & & Lee, 2010).

8.4.4 Joint Research and Development/Mission-oriented projects

Collaborative programs to solve problems, deepen joint applications of digital technologies for the project, and create common technology roadmaps are critical manifestations of a strong strategic alliance between enterprises in the value chain (Torres Saenz, 2018). They lower the costs of R&D to all participants (and make R&D possible for many SMEs which would otherwise be unable to resource such a project internally). They also allow partners to build scale and capability over time, so that the scope, significance, and ambition of such collaborations can also grow over time.

8.4.5 Industry 4.0 workforce

High deficits of workforce skills and capabilities are cited as major impediments by several sources (Mohamed, 2018) (Her Majesty's Government, 2017a) (Price Waterhouse Coopers, 2014). However, this was found to relate not only to specific workforce skills but also to broader issues of enterprises' capacities for organisational change. There exist digital skills in a business in tacit and uncodified forms. There is opportunity to find out what these are and leverage them to create momentum for digital transformation. This might include joint projects to discover existing tacit skills of the workforces of several collaborating businesses, as well as joint programs for training and skills enhancement between Primes and SMEs. Although there is no denying that such arrangements can be inhibited by concern about loss of key skills by an individual firm, cooperative arrangements to work on common challenges, together with appropriate agreements, can reduce these inhibitors.

9 Value chain participation and Intermediate organisations

There is a growing body of evidence on the positive role that intermediary organisations, at the intersection between universities and industry can play as drivers of research translation and innovation. The most compelling evidence comes from evaluations of the UK Catapult Network, jointly funded by the UK Government, industry and universities. These have been a source of inspiration for the establishment of the Flinders University Line Zero – Factory of the Future at the Tonsley Innovation District. To test the concept under Australian conditions, BAE Systems Maritime Australia co-invested with Flinders University in the establishment of a pilot factory of the future facility on the site of the former Mitsubishi automotive manufacturing plant.

Intermediate organisations, or test labs or factories of the future work at multiple levels - the individual enterprise, the industry cluster, sector, and the value chain level – to diffuse and embed digital technologies. They act as industry multipliers focusing on diffusion of Key Enabling Technologies with emphasis on digital technologies and associated new business models. They often focus on value chain issues and improving the connections between lead customers and SMEs.

They perform mission-oriented research to solve problems shared by a Prime and SMEs (a key function too of the digital shipyard), as well as carrying out educative functions for SMEs particularly, to increase their maturity. They sometimes blur in positive and desirable ways, the lines between research and enterprise education and business extension. They work to overcome impediments to digital transformation through enterprise education, helping to address the multi-faceted impediments to digital adoption and adaptation surveyed above. As argued, the most pervasive impediments relate to issues of information, awareness, uncertainty, and risk.

This includes uncertainty as to the costs and benefits of digital adoption (the possible misconception that digital technologies are expensive and cannot be adopted affordably and incrementally), the difficulty in arriving at a clear return on investment in certain digital technologies, and lack of clarity about how an enterprise can start its 'digitalisation journey' (Her Majesty's Government, 2017a). These issues can start to be addressed by having new more integrated systems of business support, through intermediate organisations that bring together Prime and SMEs on common problems and can importantly offer technical advice different from that of a commercially motivated equipment vendor.

Moreover, such organisations can be important in positively increasing and shaping the directionality and mission-orientation of defence industry projects, in building the relationships between Primes and SMEs, and in the capture of useful knowledge and spill overs, particularly through research translation. They can help Primes and lead customers and their suppliers transmit information and their issues, challenges, and requirements along the value chain. As previously claimed, 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.

In short, such organisations, including a digital shipyard, can help realise the value chain as a virtuous circle and be the ‘technical university’ described by (Eliasson, 2010). They can be vehicles for bringing all the Industry 4.0 agenda items together, focusing heavily on the role of co-design in helping to respond more effectively to the needs of users and customers.

Recall Eliasson's judgement on the foundational role of the Prime: "New products will never be better than the competence of customers to understand and to use them, and what they are willing to pay for" (Eliasson, pp 2, 4-5).

Effectively, this takes the personnel of the test lab away from standard university research into product and service development, including technical testing and proof of commercial viability. For this reason, test labs and the digital shipyard differ from the norms of a standard university department or faculty. Projects are typified by team-based leadership of the research project with participants from the lead firm, collaborating suppliers, as well as researchers. Hence, as Eliasson (2010,13) states, in relation to Sweden's Gripen fighter aircraft project, these projects and these institutions take us much closer to a functioning product than a standard university research project can: "The [Gripen] development project not only takes R&D much closer to a functioning project than university research will ever be capable of achieving. It has also to some extent been commercially tested, which academic research rarely is".

Successful intermediate organisation recognise and accentuate these key features and practices: recognition of the foundational role and importance of lead customers and of the power of demand-side forces to shape products and services; going beyond standard research projects to include product development, including technical testing and proof of commercial viability; being organisations that stand in relationships to universities different from those of a standard university department or faculty; and team-based leadership of the research project with participants from the lead firm, collaborating suppliers, researchers, and others.

The UK Catapult Technology and Innovation Centres Program, which commenced in 2013, is an exemplar of these approaches. There are presently nine centres focussing on Cell and Gene Therapy, Compound Semiconductor Applications, Connected Places, Digital, Energy Systems, High Value Manufacturing, Medicines Discovery, Offshore Renewable Energy, Satellite Applications (Catapult Network, 2020).

By linking high-end research with businesses large and small in the nine focus areas the centres aim to close the 'gap between concept and commercialisation', and gaps in the national innovation system itself.

The innovation centres perform the following activities:

- Enhance business access to leading-edge technology and expertise,
- Reach into the research base for world-leading science and engineering,
- Undertake collaborative applied research projects with business,
- Undertake contract research for business,
- Be strongly business-focussed with a highly professional delivery ethos,
- Create a critical mass of activity between business and research institutions,
- Provide skills development at all levels.

Funding for research projects is a mixture of public and private, with core public funding for long-term investment in infrastructure, expertise and skills development, (expected public funding support of at least ten years), combined with variously configured business funded, and joint publicly and privately funded, applied research and development projects. Over the period 2013-20 the Catapult network claims to have supported more than 8000 SMEs and nearly 15000 industry collaborations, more than 5000 academic collaborations and over 1200 international projects (Catapult Network, 2020).

The Advanced Manufacturing Research Centre (AMRC), Sheffield, has become a world-leading institute and is now central to the High-Value Manufacturing Catapult, a network of seven manufacturing centres across the UK. The AMRC is the model for the Flinders Line Zero factory of the future. The AMRC has attracted major investment from the private sector (Boeing, Rolls-Royce, BAE Systems and Airbus) and the public sector (UK government, University of Sheffield and European agencies), including the 2015 establishment of ‘Factory 2050’. This is the UK’s first fully reconfigurable factory, focussed on collaborative research on flexible reconfigurable production of high-value components, using digital and other technologies. The AMRC workforce has grown to more than 650 FTEs, including around 500 researchers and engineers.

Such organisations can play a role in defining and sharpening individual business benchmarks and measures relevant to key success factors, and those shared between SMEs and Primes. This is the subject of the next section.

10 Key success factors and developing benchmarks

This section considers high level and qualitative approaches to the future development of certain benchmarks and measures. This is not comprehensive, but indicative. It is concerned with what the benchmarks should be about, with precise content to be determined by the specific business or businesses. They should be read in conjunction with the key questions posed in section 7. Completing a maturity assessment is vital, providing a range of current performance and future aspirational benchmarks to a business. The following considerations and actions are indicative of what a business might undertake after completing a maturity assessment.

The following are not metric or quantitative. They are activity- rather than outcome-based. They pertain to process and to the very early stages of consideration of digital adoption by companies beginning to develop their digital strategies from relatively low levels of readiness. They refer to the abbreviated five-item schedule of key success factors provided by (Torres Saenz, 2018).

10.1 Focus on process rather than specific technologies

- Current production has been mapped and key weaknesses are understood
- On this basis potential areas of greatest opportunity for improvement have been identified and being considered
- The business has defined the problem to be solved, or is in the process of so doing with key customers and partners
- The business is compiling affordable options for digitalising selected existing assets, thinking about service enhancements of its products, documenting existing and desired new digital technologies and competences, together with its current data production and use, and has started to consider and how this could be augmented to provide competitive advantage
- The business is committed to a staged digital strategy and currently considering what it should entail.

10.2 Apply technology to enhance the role of people, not to replace them

- The business is looking at the workforce’s current digital skills, both formal and tacit, including use of devices and tablets at work and at home
- The business is considering these from the viewpoint of better utilisation, but also towards filling gaps under the developing digital strategy
- The business is using open processes to understand current attitudes to new technologies on the shop floor, and to increase receptivity to them
- The business is communicating clearly with the shop floor about the future trialing of several new technologies that will enhance work life, such as Virtual and Augmented Reality and cobotics.

10.3 Scale projects from smaller to larger

- The business is identifying actions and a small number of potential projects for piloting, that could address identified weaknesses and capture new opportunities
- The business is identifying the key technologies and products for consideration and has clear idea of the benefits being sought from the technologies (product and technology roadmaps)
- The business is considering the developmental stages for each project with clear evaluation and decision points for further action, modification of approach, or cessation

- The business is working on objectives, timelines, and potential resources for each project
- The business will structure and stagger the small number of projects as a rolling program to ensure focus and manageability
- The business has identified personnel for each dedicated designated cross-functional team, aligned to designated responsible leaders at the top of the organisation.

10.4 Support organisational change

- The business's leadership is committed to the staged development of a comprehensive digital strategy, involving a manageable, phased transition to Industry 4.0
- The business is working to ensure clear two-way communication across the organisation
- The business is committed to change across and throughout the organisation, which will be reflected in good flow and sharing of knowledge and information
- The business is working on institutionalising greater use of work teams, decentralisation of activity, better sharing of knowledge, and more positive communications
- The business is committed to use of cross-functional teams and pilot projects to discover what works and assist wide involvement, and to ensure stability of existing production and revenues
- The business has awareness and plans to identify and use early successes to demonstrate the potential of the technology or product, show positive return on investment, and help build support and momentum for change across the organization.

10.5 Build strategic alliances

- The business is identifying its most important existing, and potential future, strategic value chain partners
- The business is identifying problems common to it and one or more of its strategic value chain partners for potential joint investment in technology and research, together with risk-sharing.

11 Bibliography

Acatech. (2013). *Securing the future of German manufacturing industry. Recommendations for implementing the strategic initiative Industry 4.0. Final report of the Industrie 4.0 Working Group.*

Advanced Manufacturing Growth Centre. (n.d.). *AMGC and BAE Systems Australia to fund Industry 4.0 initiative for worlds biggest defence program.* Retrieved April 21, 2021

Aiginger, K., & and Rodrik, D. (2020). Rebirth of Industrial Policy and an Agenda for the Twenty-First Century. *Journal of Industry, Competition and Trade , 20* (2), 189-207.

Anderl, R., Picard, A., Wang, Y., Fleischer, J., Dosch, S., Klee, B., & Bauer., J. (2015). *Guideline Industrie 4.0 – Guiding principles for the implementation of Industrie 4.0 in small and medium sized businesses.* Frankfurt: VDMA Forum Industrie 4.0.

Ash, B. (2018). *Digital shipyard sounds great but what is it?* Retrieved 2021, from Retrieved from Australia: https://www.dxc.technology/au/insights/145714-digital_shipyard_sounds_great_but_what_is_it

Australian Government. Department of Industry, S. E. (2021). *Innovate in defence.* Retrieved April 24, 2021, from https://business.gov.au/cdic/innovate-in-defence

Australian Industry Group . (August 2019). *The Fourth Industrial Revolution Australian businesses in transition .* Australian Industry Group .

Badri, A., Boudreau-Trude, B. l., & & Souissi, A. S. (2018). Occupational health and safety in the industry 4.0 era: A cause for major concern? *Safety Science*(109), 403-411.

Bitcom; VDMA; ZVEI. (January 2016). *Implementation Strategy Industrie 4.0. Report on the results of the Industrie 4.0 Platform.* Bitcom VDMA ZVEI.

Boston Consulting Group. (May 2016). *Time to Accelerate in the Race Toward Industry 4.0.* Boston Consulting Group.

Brambley, S. (2017). Industry 4.0: Taking factories to the next level. *E&T Magazine*.

Bruner, J., & Kisgergely, B. (2019). *The Digital Factory Report. Digital Transformation in Manufacturing.*

Catapult Network. (2020). *Creating the Future Through Innovation: Recovery and Resilience.* Catapult Network.

Chesbrough, H. (2010). Business model innovation: opportunities and barriers. *Long range planning, , 43*(2-3), 354-363.

CSIRO Futures. (2016). *Advanced Manufacturing: A Roadmap for unlocking future growth opportunities for Australia.* CSIRO.

Defence, D. o. (2016a). *Defence Industry Policy Statement.* Australian Government.

Defence, D. o. (2016b). *Defence White Paper.* Australian Government.

Defence, D. o. (2016c). *Integrated Investment Program.* Australian Government.

Defence, D. o. (2020). *'More, Together', Defence Science and Technology Strategy 2030.* Australian Government.

Deloitte. (2015). *Industry 4.0. Challenges and solutions for the digital transformation and use of exponential technologies.* Zurich: Deloitte.

Department for Business, Energy and Industrial Strategy. (2017). *Industrial strategy: building a Britain fit for the future.* London: Her Majesty's Government.

EEF. (2016). *The 4th Industrial Revolution: A Primer for Manufacturers.* EEF.

Eliasson, G. (2010). *Advanced public procurement as industrial policy: The aircraft industry as a technical university.* Springer Science & Business Media.

European Commission . (2016). *sCorPiuS. European Roadmap for Cyber-Physical Systems in Manufacturing.* European Commission .

Giallanza, A., Aiello, G., Marannano, G., & Nigrelli, V. (2020). Industry 4.0: smart test bench for shipbuilding industry. *International Journal on Interactive Design and Manufacturing, 14*, 1525-1533.

Gourdon, K., & Steidl, C. (2019). *Global value chains and the shipbuilding industry. Retrieved from https://www.oecd-ilibrary.org/science-and-technology/global-value-chains-and-the-shipbuilding-industry_7e94709a-en.* OECD.

Government, H. (2017b). *Industrial strategy: building a Britain fit for the future .* Department for Business Energy & Industrial Strategy.

Her Majesty's Government. (2017a). *Made Smarter Review.* Energy & Industrial Strategy Department for Business.

Innovation Value Institute. (2016). Digital Business Readiness Index. Maynooth University Ireland.

Innovative Manufacturing CRC. (2018). futuremap. Innovative Manufacturing CRC.

IoT Alliance Australia. (2017). IoT Adoption Index Survey. IoT Alliance Australia.

Kagermann, H., Andrel, R., Gausemeier, J., Scuh, G., & Wahlster, W. (. (2016). *Industrie 4.0 in a Global Context: Strategies for Cooperatiing with International Partners (acatech STUDY).* Munich: Herbert Utz Verlag: acatech.

Kattel, R., & Mazzucato, M. (2018). Mission-oriented innovation policy and dynamic capabilities in the public sector. *Industrial and Corporate Change, 27*(5), 787-801.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., . . . Schroter, M. (2015). *Impuls: Industrie 4.0 Readiness.* Cologne: VDMA.

M., M. (2018a). *Mission-oriented research & innovation in the European Union .* Publications Office of the EU.

Massa, L., & Tucci, C. L. (2014). *The Oxford handbook of innovation management. .* Oxford: Oxford University Press.

Matt, D., & Rauch, E. (2020). SME 4.0: The Role of Small- and Medium-Sized Enterprises in the Digital Transformation. In D. Matt, V. Modrak, & H. Zsifkovits, *Industry 4.0 for SMEs. Challenges, Opportunties and Requirements.* Palgrave Macmillan.

Matt, D., Modrak, V., & Zsifkovits, H. (2020). *Industry 4.0 for SMEs. Challenges, Opportunities and Requirements.* Palgrave Macmillan.

Mazzucato, M. (2011). *The entrepreneurial state.* London: Demos.

Mazzucato, M. (2014). *A mission-oriented approach to building the entrepreneurial state.* Innovate UK.

Mazzucato, M. (2015a). Re-igniting public and private investments in innovation. Middle Class Prosperity Forum July 2015.

Mazzucato, M. (2015b). *Building the entrepreneurial state: A new framework for envisioning and evaluating a mission-oriented public sector.* Levy Economics Institute of Bard College Working Paper, (824).

Mazzucato, M. (2018a). *Mission-oriented research and innovation in the European Union.* Publications Office of the EU.

Mazzucato, M. (2018b). *The Value of Everything: Making and Taking in the Global Economy.* London: Penguin Books.

Mazzucato, M., Kattel, R., & and Ryan-Collins, J. (2020). Challenge-driven innovation policy: towards a new policy toolkit . *Journal of Industry, Competition and Trade, 20*(2), 421-37.

McKinsey. (2015a). *Industry 4.0. How to navigate digitization of the manufacturing sector.* McKinsey.

McKinsey. (2015b). *Raising your Digital Quotient.* McKinsey.

Mohamed, M. (2018). Challenges and Benefits of Industry 4.0: An overview . *International Journal of Supply and Operations Management , 5*(3), 256-265.

O'Keeffe, V., Moretti, C., Hordacre, A., S, H., & & Spoehr, J. (2020). *Quicker off the blocks: The role of human factors in the uptake and diffusion of advanced technologies in shipbuilding. .* Adelaide: Australian Industrial Transformation Institute, Flinders University.

Orzes, G., Poklemba, R., & Towner, W. (2020). Implementing Industry 4.0 in SMEs: A Focus Group Study on Organisational Requirements. In D. Matt, & e. a. (eds) (Eds.), *Industry 4.0 for SMEs. Challenges, Opportunties and Requirements.* Palgrave Macmillan.

Paasi, J., Luoma, T., Valkokari, K., & & Lee, N. (2010). Knowledge and intellectual property management in customer–supplier relationships. . *International Journal of Innovation Management, 14*(4), 629-654.

Picard, R. A., Wang, Y., Fleischer, J., & S. Dosch, B. K. (2015). *Guideline Industrie 4.0 –Guiding principles for the implementation of Industrie 4.0 in small and medium sized businesses.* Frankfurt: VDMA Forum Industrie 4.0.

Price Waterhouse Coopers . (2016). *Industry 4.0: Building the digital enterprise.*

Price Waterhouse Coopers. (2014). *Industry 4.0. Opportunities and challenges of the industrial internet.*

Ramirez-Pena, M., Abad Fraga, F., Sanchez Sotano, A., & Batista, M. (2019). Shipbuilding 4.0 Index Approaching Supply Chain. *Materials, 12*(4129).

Rauch, E., Vickery, A., Brown, C., & Matt, D. (2020). SME Requirements and Guidelines for the Design of Smart and Highly Adapatable Manufcaturing Systems. In D. M. (eds), *Industry 4.0 for SMEs. Challenges, opportunties and requirements.* Palgrave Macmillan.

Rodrik, D. (2014). Green industrial policy. *Oxford Review of Economic Policy, 30*(3), 469-491.

Schroder, C. (2017). *The Challenges of Industry 4.0 for Small and Medium-sized Enterprises.* Friedrich Ebert Stiftung.

Schuh, G., Anderl, R., J., G., ten, H., M., & Wahlster, W. (2017). *Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies.* Munich: Herbert Utz Verlag: acatech STUDY.

Schumacher, A., Erol, S., & Sihn, W. (2016). A maturity model for assessing Industrey 4.0 readiness and maturity of manufacturing enterprises. *Elsevier*.

Spoehr, J., Jang, R., Manning, K., Rajagopalan, A., Moretti, C., Hordacre, A., . . . & Worrall, L. (2021). *The Digital Shipyard: Opportunities and Challenges.* Adelaide: Australian Industrial Transformation Institute, Flinders University of South Australia.

Stanic, V., Hadjina, M., Fafandjel, N., & Matulja, T. (2018). *Toward Shipbuilding 4.0 - an Indsutry 4.0 changing the face of the shipbuilding industry* (Vol 69, No 3, September ed.). Brodogradnja.

Stiglitz, J. (2010). *Freefall: Free Markets and the Sinking of the Global Economy.* London: Allen Lane.

Stock, T., & Seliger, G. (. (2016). Opportunities of Sustainable Manufacturing in Industry 4.0. *Elsevier*.

Sullivan, B., Desai, S., Sole, J., Rossi, M., Ramundo, L., & Terzi, S. (2020). Maritime 4.0 - Opportunities in Digitalization and Advanced Manufacturing for Vessel Development. *Procedia Manufacturing*(42), 246-253.

Teece, D. J. (2010). Business models, business strategy and innovation. . *Long range planning,, 43*(2- 3), 172-194.

Torres Saenz, A. (2018). *Identifying Challenges and Success Factors Towards Implementing Industry 4.0 Technologies in the Shipbuilding Industry.*

University of Warwick. ((ND)). An Industry 4 readiness assessment tool. Warwick: Warwick University.

Yule, P., & Woolner, D. (2008). *The Collins Class Submarine Story. Steel, Spies and Spin.* CUP.

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