Flinders University
Australian Industrial
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Quicker off the blocks

The role of human factors and ergonomics in the uptake and diffusion of advanced technologies in shipbuilding

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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, ASC Shipbuilding 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 Innovative Manufacturing Collaborative research Centre (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 and ASC Shipbuilding 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 and ASC Shipbuilding. It’s aim is a specific one - to help develop among key stakeholders a deeper understanding of the significance of human factors as determinants of the uptake and diffusion of advanced manufacturing and digital technologies. This work is the foundation for development, trialling and evaluation of appropriate HFE technology assessment and adoption processes in shipbuilding.

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

Professor John Spoehr,
Director,
Australian Industrial Transformation Institute

Executive Summary

Advanced manufacturing and digital technologies are transforming work and work design, creating challenges and opportunities for business and society. They have the capacity to disrupt existing business models, processes and patterns of work, ushering in significant improvements in quality, reliability, productivity and efficiency. Such gains from technological innovation cannot be taken for granted however. They are the product of deliberate attention to the interaction between human, organisational and technological factors in the making of things. A commitment to adoption of advanced technologies, while important, is insufficient for the successful uptake and diffusion of those technologies. Critically important is systematic attention to the role that human and organisational factors play in this process.

The discipline of human factors and ergonomics (HFE) has evolved to support this endeavour. It focuses on technology adoption through the application of systems thinking and techniques to real-world problems involving human interaction with the environments they find themselves in. HFE draws from a range of disciplines including psychology, engineering, health sciences, industrial design and social sciences knowledge and techniques. The goal is to better understand the contributions people make to their work, the impact of changes to work requirements and processes on personal and organisational performance and well-being, and the opportunities to harness this knowledge to improve systems. HFE views work performance as a system of interactions between people, technology, work processes and environments that produce successful outcomes. By analysing data about humans and performance, and applying it to design system improvements, human-centred principles can be integrated into organisational thinking and practices.

HFE is good for business but organisations' willingness to adopt it is determined by the perceived value proposition. HFE has long been recognised as beneficial for worker health, safety and wellbeing. It not only improves worker job satisfaction but has demonstrated reduced numbers and costs of injuries and absenteeism. Despite this, the value of HFE for improving productivity, product and service quality, performance reliability and sustainability of production is less well understood. Although these benefits are tangible, comparatively few interventions are evaluated for cost benefit and effectiveness. Research shows that musculoskeletal disorders interventions have resulted in a median reduction of 50 percent in numbers of injuries, with lost workdays and costs per claim reducing by 65 percent and 56 percent respectively. Cost benefit analysis of participatory ergonomics programs in textile manufacturing has shown a benefit to cost ratio of 5.5 to 1 at 20 months follow up.

While important, injury reduction is not the only goal of HFE – it can lead to a competitive advantage if the direct and indirect costs of inefficiencies in production processes and design of work are considered. Modelling has shown the total costs of production can be reduced by applying HFE techniques as an operations management strategy, for example by identifying waste and idle time. Modelling assembly with and without HFE interventions showed total production costs increased between 0.26 and 32 percent respectively. Operational systems performance is critical for business success, with product quality a main driver. Quality defects are most associated with workload factors such as fatigue and injury risk and where these are addressed effect sizes for quality improvement of up to 86 percent have been achieved.

Not only does HFE contribute directly to the bottom line through operational improvements, it also has the potential to add value to the customer and end-user experience of a product or service. User experience extends beyond a utilitarian concept of a design being fit for purpose, to include feelings of safety, satisfaction and even pleasure from using a product. Extending this concept to shipbuilding, the value of incorporating

HFE in ship design comes from reduced injury and accident risks and increased operational performance in safety and reliability, creating benefits for ship owners, as customers, and seafarers as end users.

The Industry 4.0 agenda is transforming the industrial landscape, across the spectrum of design, manufacture, operation and service of products and production systems. Among the key principles and practices embodied in this agenda are the decentralisation of information and decision-making; responsiveness, autonomy and flexibility of manufacturing facilities; and the emergence of new generations of interconnected and autonomous equipment. These technologies include collaborative robots or cobots, track and trace technologies, autonomous vehicles, cloud computing and data analytics with visualisation (big data) amongst others to innovate business practice.

Since humans are ultimately the users of technological systems, the design process should be participative and human centred. Adopting a competency-based approach, organisations should aim to identify the competencies critical to job performance and educate and train people accordingly. Critical competencies applicable in the Industry 4.0 context include:

- Technical competencies comprising all job-related knowledge and skills;
- Methodological competencies including all skills and abilities for general problem solving and decision-making;
- Social competencies encompassing all skills and abilities as well as the attitude to cooperate and communicate with others; and
- Personal competencies including individual social values, motivations and attitudes.

Human-technology interaction will become more prevalent and increasingly collaborative. Light-weight collaborative robots can work together in a shared workspace, performing tasks simultaneously. The benefits of co-locating humans and robots in a manufacturing work cell include the ability to customise production flexibly, cheaply and easily, and to adapt to production demands in the real time of production without interrupting production operations (agile manufacturing). Key considerations related to introducing advanced technologies into the workplace include how it affects people's relationships with technology, human wellbeing and employment into the future; and what this means for knowledge and skill requirements in the workplace (competence profile, technical and non-technical skills). Safety is a primary motivator for implementing technological solutions, however the user experience approach (UX) emphasises that acceptance of and trust shown in robot co-workers is a prerequisite for successful collaboration.

As with all other forms of manufacturing, Industry 4.0 is transforming the shipbuilding industry into Shipbuilding 4.0. 'Smart Ships' constructed using smart shipbuilding processes are predicted to improve production efficiency, ship safety, cost efficiency, energy conservation and environmental sustainability. In terms of shipyard design principles and strategy, digitisation is the key to success, involving the availability, exchange and processing of big data in the shipbuilding process. Major changes to human work in shipbuilding are implied in both new job definitions and working processes. To optimise shipbuilding transformation, we need further simplification of production processes, continuous improvement of production quality, innovative solutions and closer cooperation with and between shipbuilders, ship owners and bridge-connected suppliers. Often the focus is on technological solutions, with limited attention given to integrating human factors in order to accelerate the uptake and diffusion of technology in workplaces. Shipbuilding could benefit greatly from bridging this divide, supported by building the digital capability of the workforce.

Advanced design and production technologies and digitalisation processes are leading transformation in shipbuilding. This digital shipyard ambition also includes consideration of the potential application of a range of so-called key enabling technologies. These include robotics, autonomous vehicles, the Internet of Things, big data and analytics, cloud computing, cybersecurity, new materials, 3D printing, modelling and simulation, and virtual and augmented reality. New systems include advanced outfitting, merging of design and construction operation, and artificial intelligence stimulating new production systems and business models.

The foundation for successful adoption of technology is sufficient attention to addressing the human factors that enable and impede the uptake and diffusion of technology. This requires consideration of three key areas of human endeavour that impact and influence technology adoption. The first of these involves the *structural and organisational factors* that define divisions of labour, resources, competencies, and feedback processes. Second are *human factors* issues that focus on how individual users are organisationally supported to accept and utilise technologies. Finally, *technology factors,* including previous experience with technology, the mandatory use of technology and perceptions that technology is easy to understand and use, are highly influential. To achieve successful outcomes, involving key stakeholders on an ongoing basis and trialling prototypes with end users will encourage ‘buy in’ and enhance the likelihood of successful technology adoption.

This review concludes by outlining a draft HFE framework designed to support the uptake and diffusion of advanced technologies in shipbuilding and the manufacturing supply chain. This framework acknowledges the interactions between technologies, human actors and the design of work within organisations. Organisations are not islands – they consist of individuals, teams and functional divisions but also exist within ecosystems of supply chains influenced by political, economic and regulatory factors. There are complex interactions within and between each of these entities that have distal effects on productivity, quality, safety and costs. A business driver for technology adoption is increased competitiveness. Benefits are derived by optimising human performance through integration with technology and work redesign.

Human factors research adopts a holistic approach to identifying the human performance variables underpinning the design of quality jobs to promote safety, wellbeing and productivity. Achieving integration involves fitting jobs to the characteristics, capabilities and limitations of humans to enhance their performance, while creating safe, satisfying and sustainable work. Human factors as a design science brings together data, evidence and design principles to fulfil the goal of successful human-technology and system integration, supporting transformation along the supply chain. If emerging technologies can be implemented at scale this has the capacity to transform the future of industry and work and in doing so reinvigorate the Australian manufacturing industry.

1 The changing nature of work and workplaces

Shipbuilding is a complex, interdependent process that some have said has more in common with construction than with manufacturing. The fabrication process involves the division of ships into several blocks, each with its own unique characteristics and requirements. Construction of these blocks occurs in parallel, with the component parts that are assembled later. Typically, this block-building stage comprises more than half of the total building process (Torres, 2018). Tasks involved in shipbuilding are often dirty, dull and/or dangerous, including steel/pipe cutting, bending and welding, cabling and painting. Moreover, a great deal of planning and scheduling is required before and during construction so that activities can be coordinated safely and effectively. Accurate and reliable work management methods are sought to ensure the impact of any delays or changes in the construction process are minimised given ship construction is time consuming, labour intensive and expensive. Shipbuilding also demands a very high-quality end product that has been sufficiently inspected and tested (e.g. using non-destructive methods such as ultrasonic, magnetic and radiographic tests).

Shipbuilding is a low volume, high complexity undertaking. It is highly customised and characterised by low levels of repeatability. It often takes place in harsh working environments that are noisy and dangerous. Meanwhile design modifications can be ongoing throughout the build cycle. This process has been identified as a key barrier to the adoption of new technologies which must be subject to very stringent risk assessment given the function of maritime ships (ibid.). However, Industry 4.0 enabling technologies (e.g. Internet of Things, big data, cobotics, virtual reality) have considerable potential to improve safety, quality, efficiency and productivity in both the highly bespoke shipyard context and in low volume/high mix manufacturing more broadly due to their inherent adaptability.

In order to achieve *successful* adoption of such new technologies - where hardware/software functionalities and/or output are used to their full extent, where deliberate disuse or damage of technology is avoided and performance is optimised - consideration of the relationship between technical features, environmental constraints and end user experiences by organisations is essential. A human factors and ergonomics approach integrates these multiple perspectives to promote individual, team and organisational efficiencies and goal attainment and may serve as a pivotal mechanism to transform more traditional industries that have previously found change difficult to achieve.

The proliferation of advanced technologies synonymous with Industry 4.0[1] has the potential to transform human work and work design, creating challenges and opportunities for business and society (Kadir, Broberg, & da Conceição, 2019). In maritime shipbuilding the benefits of this resonate with the ‘Digital Shipyard’ agenda of the Australian and South Australian governments. Industry 4.0 technology adoption and the resulting transformation of work have inevitable individual and organisational dimensions, making attention to human factors critical to achieving business success. Emerging technologies have the capacity to disrupt existing business models, processes and patterns of work, requiring the engagement of the workforce and job redesign to ensure effective implementation (Healy, Nicholson, & Parker, 2017). This of course represents a major challenge to prevailing approaches to naval shipbuilding which remain heavily reliant on

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[1] Industry 4.0 is used to refer to the fourth industrial revolution whereby digital innovation and technologies are connecting and communicating in real-time. The uptake of these technologies is disrupting traditional business operations and processes.

analogue processes and methods. Understanding this history and its influence today is vitally important in charting a new digital voyage for naval shipbuilding.

In seeking to chart a new course we must be alert to potential obstacles and enablers. Technological change requires reinforcing organisational change, underpinned by capability development delivered through on the job as well as off the job education and training. Organisational change involves the transformation of the organisation from its current state to a desired future state. Internal and external factors drive the need for, and pace and nature of change. Key external factors include the emergence of technologies that create new product opportunities, dynamic socio-political landscapes and the competitive environment. Internal factors include performance pressures, current financial resources and social capital, or simply managers with new ideas (Agostini & Nosella, 2019).

Change management is the process of planning and executing the program of change in an efficient and effective manner. Change management evokes differing responses in individuals, affecting behaviours which in turn collectively influence the success of change programs. Negative experiences of change management may reduce workers' psychological attachment to, and trust in their organisation and even elicit counterproductive work behaviours that undermine planned change (Searle & Rice, 2018).

Change has the ultimate goal of better positioning the organisation to achieve its objectives of meeting customer needs, financial performance and socio-economic aspirations. Industry 4.0 allows the transformation of the production enterprise into a 'smart' state, where technologies, systems and people become autonomous, flexible and integrated, facilitating sharing of volumes of information in real time to support effective decision making. A key feature of smart systems is the integration of cyber-physical systems (CPS) which provide intelligence, inter-system communication and self-controlled (autonomous) system operations functions (Anderl, 2014). Smart technologies perform two key roles in organisational change:

1. powering technological developments, market shifts and socio-political factors that drive change, and
2. enabling transformational capabilities within the organisation.

Change is unavoidable, but by responding to external drivers, Industry 4.0 creates new opportunities. It enables an accelerated rate of change by creating transformational capabilities within the firm, positioning it to respond at an appropriate scope and pace. The potential for rapid transformation has significant consequences for the design of work and the people interacting with technology to perform that work, highlighting the value of human factors in understanding and proactively responding to the impacts for workforces experiencing transition.

2 Human factors – a systems approach and user-centred perspective

Naval shipbuilding can benefit greatly from the application of a holistic human factors and ergonomics approach to technology assessment, integration and diffusion. The discipline of human factors and ergonomics (HFE) applies systems thinking and techniques to real-world problems involving how humans interact successfully with the environments they find themselves in. A system is a set of inter-related activities or entities (hardware, software, buildings, spaces, communities and people) existing within a boundary, that aims to achieve a shared purpose (Wilson, 2014).

HFE has its origins in sociotechnical systems theory (Appelbaum, 1997) which views an organisation or a work unit as a combination of social and technical components that operate together to accomplish activities. Sociotechnical systems theory considers that social and technical elements must be integrated at the development stage of any product or activity to produce positive outcomes. It is not effective to establish the technical elements first, then try to adapt people to fit.

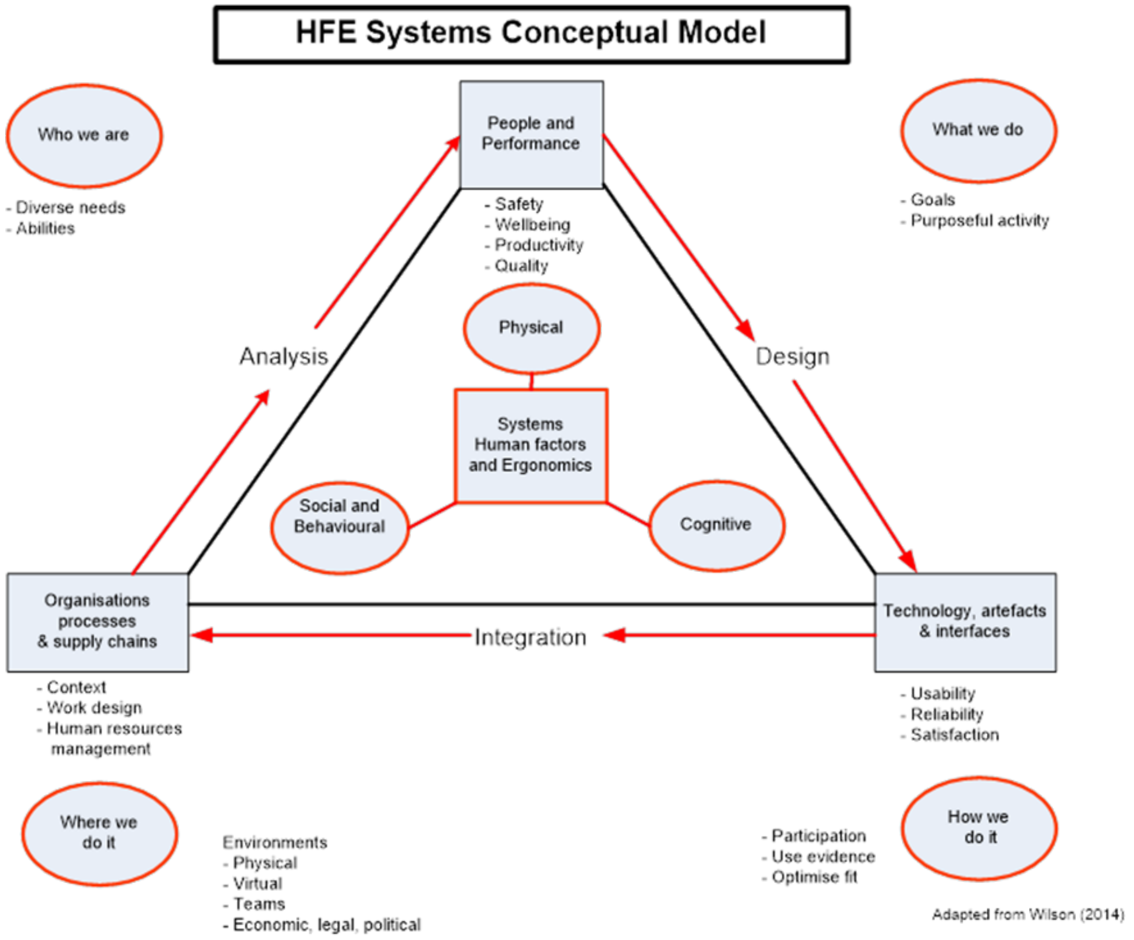
The International Ergonomics Association (2020: para 1) defines human factors and ergonomics as:

> *The scientific discipline concerned with the understanding of interactions among humans and other elements. It is the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance.*

HFE draws on a multi-disciplinary base using psychology, engineering, health sciences, industrial design and social sciences knowledge and techniques to better understand the contributions of people to their work, how changes to work requirements and processes affect personal and organisational performance and well-being, and the opportunities to harness this knowledge to make systems improvements.

Systems thinking is at the heart of HFE and recognises the importance of the connection between people, their local and broader environments. The technology, tools and resources; work processes, and organisational environments with which people work, all directly influence the performance outcomes they can achieve. Fundamentally, HFE takes a systems approach to optimise performance, is design driven and focuses on achieving the dual outcomes of performance and well-being, as shown in Figure 1.

Figure 1 Human Factors and Ergonomics Conceptual Framework



Adapted from Wilson (2014)

2.1 People and performance

HFE views people as located at the centre of the system and assumes people are goal-directed in their behaviours. People in the system have capacities and limitations that guide their understandings and behaviours. Capacities include their abilities to interpret information, make decisions, act and learn; while limitations are characteristics which restrain these abilities, including physical size, strength, information processing capacities and fatigue. To interact with, and make sense of their environment, people use their cognitive (thinking) and physical abilities, along with the social skills they develop by interacting in groups (e.g. culture), to behave in ways that achieve their goals. HFE aims to optimise work performance outcomes and ensure tasks are performed safely and efficiently by minimising errors and risks, designing productive workflows, achieving quality standards and promoting wellbeing. These outcomes are achieved by looking at the team and organisational level first. However, no team or organisation is an island – they all consist of individuals interacting together, while at the same time existing as parts of larger systems. Supply chains represent part of the larger system of interactions that occur between people and processes, within and between different organisations, as each works to contribute to a shared broader goal.

2.2 HFE as a process – analyse, design and integrate

HFE is a process that views work performance as a system of interactions between people, technology, work processes and environments. The aim is to optimise the working relationships to produce successful performance outcomes by analysing data about humans and performance, using these to design system improvements (technologies and work processes) and integrate these improvements into organisational thinking and practices.

Linking these factors together begins with analysis of work relationships to understand the reciprocal effects of people and processes, where each influences the other to produce both expected and unexpected outcomes (e.g. creating errors, fatigue, stress, and workarounds, where the actual work practice varies from the defined procedure and is adapted to fit the specific work context). Work analysis involves the collection of data to inform process improvement and technology development.

HFE is an iterative design-driven process, it continually reviews and refines previous decisions as new elements and decisions are implemented (Dul et al., 2012). A hallmark of HFE is that it is participative in nature and draws on evidence and the 'expert' knowledge of people involved in the work to identify the problems and opportunities. Pheasant (2003) described design in ergonomics as having two elements: the investigative methods of the empirical sciences combined with the creative problem-solving methods of the designer. These approaches are underpinned by the recognition that humans are highly diverse. From these principles, Pheasant developed his five fundamental fallacies of design (see Table 1). These fundamental fallacies highlight deeply held assumptions that inhibit effective human-centred design and motivate designers to consider human characteristics. To promote usability, safety and wellbeing, work processes and technology must be designed through participation, a backwards and forwards process between end users and designers to ensure the technologies and processes are fit for purpose. Participation should occur early, continue throughout the design process, be based on evidence and aim to optimise fit between people, technology and processes. Design in this context refers to the process of designing (i.e. shaping and organising information and decisions) rather than the design outcome itself (Hollnagel, 2014).

Table 1: Five fundamental fallacies of design

No. 1	This design is satisfactory for me – therefore it will be satisfactory for everybody else
No. 2	This design is satisfactory for the average person – therefore it will be satisfactory for everybody else
No. 3	The variability of human beings is so great that it cannot possibly be catered for in any design – since people are wonderfully adaptable it does not matter anyway
No. 4	Ergonomics is expensive and since products are purchased on appearance and styling, ergonomics can be conveniently ignored
No. 5	Ergonomics is an excellent idea. I always design things with ergonomics in mind but I do it intuitively and rely on my common sense, so I don't need tables of data or empirical studies

Source Pheasant (2003, p.10)

The final part of the HFE process is integrating system improvements into organisational thinking, planning and practice. This step involves the design of work processes, including policies and procedures. This stage also requires participation and involvement of people from along the (internal) supply chain, particularly those who perform the work and their supervisors. This focus should be integrated into broader operational requirements including strategic and production planning, procurement, human resources, work health and safety and quality management policies and processes (which are of relevance to the broader supply chain). Review processes within these domains should consider ongoing evaluation of the implementation and effectiveness of HFE systems within the organisation and between organisations along its supply chain.

The focus of HFE is to view the human as a central element of a successful working system. By adapting the environment to suit the human (rather than the reverse), the related system outcomes of performance (e.g. productivity, efficiency, effectiveness, quality, innovation, flexibility, systems safety and security, reliability and sustainability) and well-being (e.g. physical and psychological health and safety, satisfaction, pleasure, learning and personal development) can be more successfully achieved (Dul et al., 2012). The successful adoption of advanced manufacturing and digital technologies in naval shipbuilding will be determined to a large extent by the level of organisational and individual commitment to HFE processes and practices and the perceived value they contribute to business success. The pursuit of an ambitious agenda like Industry 4.0 in shipbuilding can be a vehicle for promoting the benefits of HFE.

2.3 The value proposition of human factors in Industry 4.0

The commitment that organisations make to investing in HFE is determined by its perceived value. HFE has long been recognised as beneficial for worker health, safety and wellbeing. It not only improves worker job satisfaction but has demonstrated its effectiveness in reducing numbers and costs of injuries and absenteeism. Despite this, the value of HFE for improving productivity, product and service quality, performance reliability and sustainability of production are less well understood. Although these benefits are tangible, comparatively few interventions are evaluated for cost benefit and effectiveness, and even fewer case studies are published. This is a perplexing paradox given that for many organisations the most common driver for undertaking HFE interventions is to reduce the financial burden of work-related injury and ill-health (Tompa, Dolinschi, & Natale, 2013). Some of the challenges contributing to lack of evaluation include difficulty in obtaining relevant data, understanding the methodology of economic evaluation within the organisation, and the time investment to undertake a robust study. Often these tasks fall within the domain of an organisation’s occupational health and safety personnel, rather than being viewed as a broader business investment and evaluated accordingly.

Most available economic literature focuses on cost effectiveness of interventions to reduce work-related musculoskeletal disorders. In a study examining 250 ergonomics case studies, benefits included reductions in injury rates, related lost workdays and workers’ compensation costs. Additional benefits included increased productivity and quality, and reduced staff turnover and absenteeism. Payback periods for these interventions were typically less than one year (Goggins, Spielholz, & Nothstein, 2008). An analysis of 91 HFE case studies to support introduction of the Washington State Ergonomics Rule in 2000 reported interventions produced a median reduction of 50 percent in numbers of work-related musculoskeletal disorders, with lost workdays and costs per claim reducing by 65 percent and 56 percent respectively (Goggins et al., 2008). A cost benefit analysis of a participatory ergonomics program in a textile manufacturing company showed a benefit to cost ratio of 5.5 to 1 at 20 months follow up. Statistically significant improvements in productivity measures of efficiency and re-work rates (reduced by 9 hours per week) were also achieved. Most interventions were low cost and able to be implemented by plant maintenance personnel.

The value proposition of HFE to promote a culture of health in organisations has been demonstrated by comparing US companies who have been awarded corporate health achievement awards with similar companies against their performance on the stock market. Findings revealed that the companies recognised as award winning for their culture of health outperformed the market in financial returns. Results suggest a competitive advantage for high performance on health and safety which also indicates the ability of health-focused companies to manage other aspects of their businesses equally well. Investing in human factors to improve health is associated with a participative approach, more effective communication, problem solving and collaboration, yielding benefits for workers, companies and their investors (Fabius et al., 2016).

While important, injury reduction is not the only goal of HFE – it can lead to a competitive advantage if considering both the direct and indirect costs of inefficient systems. Direct costs relate to product loss, and time lost due to faults and breakdowns, while indirect costs include, but are not limited to, time lost waiting for repairs, rework, worker replacement, administrative activity and damage to equipment. Indirect costs are conservatively estimated at four times the value of direct costs (Douphrate & Rosecrance, 2004). To realise the full potential of HFE, it is necessary to look holistically at the production process and design of work. Characteristics of work, including physical demands, task variety, level of autonomy and quality of communication and support, can induce different health states in workers, leading to variable levels of productivity and errors. HFE interventions are rarely introduced to optimise operations management and improve system performance, though modelling the financial benefits of HFE has shown the total costs of production can be reduced through applying HFE techniques as an operations management strategy, for example by identifying waste and idle time. Modelling assembly with and without HFE interventions has shown total production costs increased up to 32 percent for a range of different postural hazards that remained unmanaged (Sobhani, Wahab, & Neumann, 2017). Health and safety-related risk factors are associated with productivity and work quality losses, reducing output and increasing corrective work.

Operational systems performance is critical for business success, and product quality is a main driver. A systematic review of 73 empirical studies assessing the impact of HFE on quality performance revealed that quality defects are most associated with workload factors such as fatigue and injury risk. Forty-six percent of studies focused on HFE improvements to operations management, showing effect sizes for quality improvement up to 86 percent (Kolus, Wells, & Neumann, 2018). This review highlighted two types of HFE impacts on manufacturing: first, human impacts, including workload and fatigue; and second, system impacts, including errors and quality defects. Seventy percent of errors were associated with complexity, poor instructions, task difficulty, and inadequate training, and tools, with workload and management factors contributing a further 14 percent.

Not only does HFE contribute directly to the bottom line through operational improvements, it also has the potential to add value to the customer and end-user experience of a product or service. User experience extends beyond a utilitarian concept of a design being fit for purpose to include feelings of safety, satisfaction and even pleasure from using a product (Väätäjä, Seppänen, & Paananen, 2014). Extending this concept to shipbuilding, Osterman (2013) emphasised the value of incorporating HFE in ship design for reducing risks and increasing performance, creating benefits for ship owners, as customers, and seafarers as end users. Operational reliability and efficiency can be enhanced through reducing machinery damage and engine room failures, estimated at 35 percent of current losses. Reductions in workload, errors, fatigue, and inspection and maintenance due to HFE innovations may potentially reduce crewing costs and increase reliability (Costa & Lützhöft, 2014).

Due to its scale and complexity, shipbuilding has been slow to change its traditional intensively manual manufacturing methods. HFE has demonstrated value not only for transforming the health and safety aspects of work performance but also operational management, design and production processes, and can be a valuable strategy for business improvement. Integrating HFE into the adoption of technology in shipbuilding presents an ideal opportunity to capitalise on the benefits technology can bring to transforming manufacturing and achieving sustainable business performance.

3 Industry 4.0 – the transformation of manufacturing

On our way to the so-called Industry 4.0 era, we have transitioned through a number of industrial revolutions which have fundamentally reshaped the world in which we live and work. The first of these was the age of mechanisation (driven by the invention of the steam engine), followed by mass production (with electrical energy replacing the steam engine) and then computerisation and automation (driven by information technology and electronics). The fourth industrial revolution, sometimes characterised as Industry 4.0, is being propelled by advances in information and communications technologies (ICT) and is characterised by the evolving Internet of Things (IoT), cloud computing, advanced algorithms, artificial intelligence, hyper-connectivity, self-learning systems, automation, and big data and analytics (Imran & Kantola, 2019). Industry 4.0 is also characterised by a range of key enabling technologies summarised in Table 2.

Table 2: Industry 4.0 technologies

Category	***Definition***
Internet of Things (IoT)	A digitally interconnected network of physical devices exchanging information and data about the performance of real tasks in the physical world.
Big data	Large complex datasets usually derived from cloud-based applications. The data typically exceeds human intuitive and analytical capacities and those of conventional computing tools for database and information management.
Cyber-physical system (CPS)	A system in which computerised elements collaborate to monitor and control physical entities.
Cobotics	An advanced form of collaborative robotics enabling safe interactions of humans and robots. Cobotic design draws on a combination of information sciences, human factors (behaviour, decision, robustness and error monitoring), biomechanics (modelling of behaviour and of movement dynamics) and robotics.
Artificial intelligence (AI)	The multidisciplinary theories, techniques, concepts and technologies implemented in order to develop machines capable of simulating intelligence.
Digital twin	A digital equivalent of a physical asset in the virtual world facilitating real-time simulation or mirroring of an industrial process across the lifecycle (design-execution-change-decommission) by means of a computer model in which the parameters and variables are reflections of those in the process being studied.
Additive Manufacturing	Uses three dimensional models and 3D printing technology to create parts. Facilitates mass customisation and on-demand production.
Augmented and virtual reality (AR/VR)	AR enabled devices can superimpose a virtual image onto a physical object facilitating work processes and decision-making while minimising risks.

Adapted from (Badri, Boudreau-Trude, & Souissi, 2018: 406)

Industry 4.0 is transforming the industrial landscape, across the spectrum of design, manufacture, operation, and service of products and production systems. It involves new forms of engagement and interaction between humans and machines, and digital and physical worlds (Romero et al., 2016). New industrial concepts include the decentralisation of information and decision-making; responsiveness, autonomy and flexibility of manufacturing facilities; and the emergence of new generations of interconnected and autonomous equipment such as cobots (collaborative robots) (Badri et al., 2018).

Manufacturing system changes include shorter development and innovation periods, a shift from a 'seller's' to a 'buyer's' market, higher flexibility in product development, decentralisation to cope with the specified conditions, faster decision-making processes, reduced organisational hierarchies and resource efficiency (Imran & Kantola, 2019).

There are many benefits connected with Industry 4.0. As an alternative to conventional forecast-based production planning, Industry 4.0 allows real-time planning of production and dynamic self-optimisation, leading to improved efficiency, quality, safety, sustainability and company reputation (Brocal, González, Komljenovic, Katina & Sebastián, 2019). Badri et al. (2018) identify improved productivity and reduced costs, with industry data showing smart production contributes to reductions of 30% in time to market, decreased expenditure on planning, reductions of 40% in equipment costs and production increases of 15%. Imran & Kantola (2019) argue that Industry 4.0 technologies provide a new level of functionality, higher reliability, greater efficiency and optimisation possibilities that pose both opportunities and challenges for people and organisations.

While there is little uniformity in the pursuit of the Industry 4.0 agenda and great variability observable at the sectoral level, there is considerable momentum globally. This is giving rise to a rich body of industry case studies and use-cases that the maritime shipbuilding sector can learn from and be inspired by. This material is, however, often silent on HFE.

3.1 Human factors in Industry 4.0

It is early days in the evolution of Industry 4.0 and there is limited understanding at this point about the implications for work and humans of this new industrial agenda (Kadir et al., 2019). Fantini, Pinzone and Taisch (2020) highlight current uncertainty about how Industry 4.0 will interact with economic, geo-political and social trends to shape future work and jobs, and concerns about the number and quality of jobs in increasingly technological and digitised production systems. Current thinking about how new technologies and the organisation of work will evolve in this new world of manufacturing presents tensions between the techno-centric view and the human-centred view. The techno-centric perspective perceives cyber-physical systems (CPS) as dominant, with human work determined by technology. Alternatively, the human-centred view presents CPS as supportive, with workers controlling the process and decision-making.

Ghisleri, Molino and Cortese (2018, p. 3) argue that technological transformation needs to be managed in a way that energises and advances, rather than sidelines, human contribution:

> *The key lies in how the technological transformation will take place… and how this transitional phase is managed so that it can lead to a future where technology itself will create new jobs, characterised by less hard and repetitive work but more intellectual activities, jobs for which the necessary skills need to be developed through investments in retraining.*

Imran and Kantola (2019) note that the major research focus in Industry 4.0 has been on technical rather than social and managerial challenges. In the context of technical innovation, Fantini et al. (2020: 3) observe that engineers and designers have a heightened focus on the production phase and standard operating conditions, to the exclusion of sociotechnical implications of human-CPS interactions in complex systems:

> *There is general consensus that humans have a central and crucial role in production systems, as they are the only ones who can govern the systems, address anomalous situations and that can provide flexible solutions in case of need. However, when innovative technical solutions are considered, the attention of the engineers and designers is mainly directed towards the production*

> *phase and standard operating conditions, which do not allow comprehending all the facets of human contribution.*

Increasing recognition is being given to the centrality of human work and different facets of human contribution (i.e. human factors in Industry 4.0 systems). Peruzzini et al. (2017, p. 807) highlight that manufacturing in Industry 4.0 has become smart and adaptive due to collaborative and flexible systems that work to identify problems and execute solutions, enabled by communication and cooperation between cyber physical entities and humans in real time. Humans perform a range of vital functions in tandem with machines (for example, machine control, process monitoring, verification of product strategies):

> *…factories are not only made up of machines but also of human beings (i.e., workers) cooperating with the machines and each other in various ways: executing tasks, controlling the process, loading or unloading the machines, and interacting [with] the machine interfaces.*

Humans offer unique capabilities in strategic decision-making and flexible problem-solving, and human performance is central to product quality and factory productivity. Valdeza et al. (2015) point out that humans are the key flexible component in cyber-physical systems, as interpreters of simulation data and decision-makers for self-optimising processes. According to Sadik and Urban (2017, p. 3), in the context of human-robot cooperation, there is obvious synergy in the relationship:

> *On the one hand, the worker is a very important component of the manufacturing system, as (s)he does not only add the high flexibility of taking the proper actions and decisions based on the current production situation, but also (s)he is able during manufacturing to use his/her natural senses intuitively to form complex solutions which are very hard to be programmed and executed by a cobot. On the other hand, the cobot is a very reliable component in terms of speed, accuracy, and weightlifting… Cobots are able to provide the physical safety for the worker during cooperative manufacturing.*

3.2 Risks and challenges posed by Industry 4.0

Brocal et al. (2019, p. 2) argue that the increased complexity and dynamism of Industry 4.0 production processes have introduced significant uncertainty into the workplace. This complexity is a function of:

> *'Many components interacting in a network structure [where] components can be physical and cyber-physical, functioning heterogeneously, organised in a hierarchy of subsystems, and contributing to [the] system as a whole'.*

Risks associated with Industry 4.0 extend from:

- **Structural complexity**: heterogeneity of system components across different technological domains.
- **Dynamic complexity**: emergent (usually unanticipated) system behaviour in reaction to environmental stimuli. Systems become less transparent.
- **Human-machine and human-robot interactions**: uncertainty generated by heightened instances of interaction; increasing sophistication of tasks carried out by cobots.
- **Emerging factors**: risks of accident; psychosocial and musculoskeletal risks; over-reliance on automated safety systems; reduced physical activity and static postures; high mental workload (e.g. during the monitoring and control of processes); reduced privacy at work (new technologies allowing closer and more intrusive supervision); and increased multivariate decision-making (ibid.).

Within complex systems of this nature, industrial and human risks can arise from human error and organisational weaknesses, manifesting as accidents or other disruptions to complex systems. In this context there is a need for a rigorous, sophisticated approach to risk management encompassing both traditional and emerging risk management strategies.

In examining occupational health and safety (OHS) issues specific to Industry 4.0 businesses, Badri et al. (2018) identified a range of psychosocial hazards connected with the complexity of Industry 4.0 production systems. These relate to increasing interaction between *work content* (e.g. task variety, cycle times, skills, uncertainties, exposures), *organisation factors* (e.g. team scheduling, overtime, rush orders), *management factors* (e.g. responsibilities, communication, roles, relations, problem solving) and *other organisational factors* (such as promotion and pay raises, job security and social value of the work). Engineers and designers of advanced manufacturing systems often have poor comprehension of, and therefore overlook how these non-technical risks potentially intersect with the introduction of new technologies into the workplace, often undermining the effectiveness of technologies for business growth.

Valdeza et al. (2015) examined specific dimensions of complexity in human-computer interactions, in terms of visual and perceptual complexity, task complexity and cognitive complexity. At a superficial level, manual interaction, touch, voice, gesture, gaze and sometimes brain interfaces are the primary means for communication between humans and machines. The visual complexity category refers to the detection of sensory data, the ease with which information is processed and interpreted, and reaction time in recognition tasks. Task complexity relates to the increasing requirement for ‘multivariate decision-making’ which can contribute to higher mental workload and risk, potentially compromising performance. Cognitive complexity refers to people’s ability to understand and effectively deal with relationships (including with systems and objects) that bear the hallmarks of social relationships. Cognitive limitations associated with more complex, higher-order relationships include:

> *‘limitations in attention span, differences in bottom-up/top-down understanding of processes, time taken to interrogate data, and the limitations of the visual sketchpad to 3D space dimension (at best)’ (ibid.: 3).*

Valdeza et al. (2015, p. 4) highlighted the need for insightful interface design to address perceptual and cognitive limitations invoked by task complexity, contending that many engineers lack sufficient usability training: ‘*Often engineers design systems that present problems only understandable by themselves. They assume what is easy for them, is easy for others’.* The answer is to understand and integrate user requirements when designing systems that support decision-making and address complexity. Moreover, this process needs to account for individual characteristics because diversity factors such as age intersect with how users manage complexity:

> *Changes in requirements caused by Industry 4.0 (e.g. increased flexibility, more diverse tasks, higher order decision making) will stress the importance of good usability and ergonomics in scientific and industrial settings. This is specifically true in face of a change in demography, changing values and a globally connected world (ibid.: 6).*

3.3 Human factors from a technology acceptance perspective

People’s acceptance and use of technology are influenced by multiple factors including their previous experience, knowledge and expectations. Understanding such factors will guide how technology is developed (e.g. system requirements), promoted (e.g. communication strategy) and implemented (e.g. tailoring of support and training) (Taherdoost, 2018). When implementing new technology, Venkatesh and Bala (2008) encourage organisations to actively manage employee perceptions and intervene to ensure expectations of the technology (and its consequences on their work design and performance outcomes) are accurate. Preparing the workforce for change will minimise the risk of resistance to a new technology and facilitate successful adoption. Assessing workforce readiness and expectations ahead of implementing a new technology will identify potential barriers and allow pre-implementation strategies to be tailored to the nature of and timelines for planned adoption.

The Technology Acceptance Model (TAM) proposed by Davis (1986) is a highly influential and widely used model for studying the role of human factors in the adoption of new technologies. Adapted from the Theory of Reasoned Action (Ajzen & Fishbein, 1980), the model examines causal relationships between external variables and user acceptance and actual use of technology. The model is predicated on the core concepts of perceived usefulness, ease of use and behavioural intention (Svendsen, Johnsen, Almås-Sørensen, & Vittersø, 2013).

Perceived usefulness and ease of use have been found to strongly mediate the effects of external variables such as characteristics of the system development process, training and intention to use technology. Moreover, ease of use is more influential than perceived usefulness such that if the technology is highly complicated, this will offset perceived usefulness and lessen technology acceptance and use (Patrícia, 2015). Patricia makes the point that technologies cannot be effective unless they are used. Acceptance is a critical factor in determining use, hence it is essential to identify in advance anything that is likely to limit the acceptance of new technology, so that necessary corrective steps can be taken to facilitate its entry into the workplace.

TAM has been applied in various Industry 4.0 settings, for example big data analytics (Brock & Khan, 2017), augmented reality tools (Jetter, Eimecke, & Rese, 2018) and unmanned aerial vehicles (Yang, 2019). The model has also been applied in the context of human-robot cooperation involving sharing physical space and working in direct contact (Bröhl, Nelles, Brandl, Mertens, & Schlick, 2016). Results confirmed that a key factor of robot acceptance by humans is their ability to meet human needs and expectations. Perceived usefulness, perceived ease of use, behavioural intention and use behaviour were all related indicating the TAM model was useful when considering human-robot interaction. *Perceived usefulness* of cooperative robots was most strongly related to job relevance, organisational support for the robots and the quality of the robot's output. Strongest predictors of *perceived ease of use* included perceived usefulness and occupational safety.

TAM's simplicity facilitates the integration of other frameworks including the technology-organisation-environment (TOE) framework, which was applied by Arnold, Veile and Voigt (2018) to investigate the determinants of Industry 4.0 adoption in German manufacturing companies. Spanning characteristics specific to technology, the organisations and their external environments, the study found that the benefits and relative advantage conveyed by Industry 4.0 were the most influential drivers of uptake, backed by top management support and high levels of industry competition. Environmental uncertainty had a negative effect and no effect was found for perceived challenges (e.g. training staff, IT security, adjusting business models), firm size, absorptive capacity (ability to recognise, assimilate and apply new information) and perceived outside support.

TAM primarily focuses on the micro or individual perception, motivation and decision-making level. Some researchers have extended its scope to reflect group, cultural or social influences on technology acceptance (Brock & Khan, 2017; Peñarroja, Sanchez, Gamero, Orengo, & Abad, 2019). Similarly, it has been argued that TAM does not account for variation in human capabilities specifically relating to the acquisition, transfer and integration of individual and collective knowledge (Brock & Khan, 2017).

Venkatesh, Morris, Davis, and Davis (2003) note that existing TAM models can predict intention and usage however they struggle to provide definitive guidance to designers. Therefore, the Unified Theory of Acceptance and Use of Technology (UTAUT) model incorporates three direct determinants of intention to use (performance expectancy, effort expectancy and social influence) and two determinants of usage behaviour (intention to use and facilitating conditions). An advantage of the UTAUT model is that it highlights the importance of contextual analysis in developing strategies for technological introduction into organisations, recognising a complex range of moderating factors.

The Usability, Social Acceptance, User Experience and Societal Impact (USUS) model extends the TAM and UTAUT models and was developed from a human-centred human-robot interaction (HRI) perspective (Weiss, Bernhaupt, & Tscheligi, 2011, p. 3). It is a multi-level indicator model that selects factors to:

> *'identify socially acceptable collaborative work scenarios where humanoid robots can be deployed beneficially to convince society to positively support the integration of humanoid robots in a human's working environment'.*

Factors and indicators include:

- **Usability (ease of using an object)**: effectiveness, efficiency, learnability, flexibility, robustness and utility;
- **Social acceptance (willingness to integrate a robot into the everyday social environment)**: performance expectancy, effort expectancy (degree of ease of use), attitude toward using technology, self-efficacy (perception of ability to achieve a goal), forms of grouping (can people share identity with robots), attachment (emotional episodes of user experience with robots) and reciprocity (mutual exchange of performance and counter-performance);
- **User experience (how people interact with the technology, how it feels, how they understand it, how well it serves their purpose)**: embodiment (humanoid, intuitive interface), emotion (e.g. satisfaction in achieving product that fulfills user expectations; surprise, pride, attraction), human-oriented perception (simulate human perception e.g. interpreting human speech, recognising/communicating facial expressions etc), feeling of security, co-experience (focusing on personality of robot, communication paradigm and how robot mediates within group of people); and
- **Societal impact (effect of activity on the social life of a community in general and more specific for the proposed framework)**: quality of life, health and security, working conditions and employment, education and cultural context.

In a literature review of UTAUT models (Williams, Rana, & Dwivedi, 2015), self-efficacy (akin to technology affinity and personal innovativeness) was the most frequently employed external variable, closely followed by attitude and trust. In a recent study by Jacobs et al. (2019) both personal innovativeness and trust were included in evaluating employee acceptance of wearable technology in the workplace. In work environments where use of technology is (or at some point will be) mandatory, the attitude construct takes on heightened significance (Brown, Massey, Montoya-Weiss, & Burkman, 2002; Yousafzai, Foxall, & Pallister, 2007). These models of user acceptance of technology help system developers to understand end-user tasks, their work environment and use contexts since these are essential in making interactive technologies and systems more usable. These characteristics form the fundamental principles of human-centred design (Horberry, Burgess-Limerick, Cooke, & Steiner, 2017).

3.4 Establishing a sociotechnical systems-HFE approach within Industry 4.0

A systematic review to investigate the extent to which human factors and ergonomics (HFE) has been integrated into Industry 4.0-focused research has been recently completed (Kadir et al., 2019). Limited reference to HFE in Industry 4.0-related research was identified, although Industry 4.0-led research was more likely to cover aspects of HFE than research generated from within the HFE discipline itself. Notably, Industry 4.0 researchers had a different orientation to HFE compared with HFE specialist researchers, for example they tended to use the word 'ergonomics' purely when referring to physical activity and physical strain, rather than its broader, holistic systems-focused definition.

The review showed that research addressing HFE aspects was often theoretical and hypothetical in nature, and not based on empirical research methods. As such, the research tended to focus on future scenarios, challenges and opportunities rather than presenting evidence-based findings related to the current state of industry. Qualitative research revealed a preoccupation with analysing 'lower-level' operational matters of significance to Industry 4.0, at the expense of 'higher-level' tactical and strategic approaches geared to the success of HFE applications (Kadir et al., 2019: 10):

> *'while the strategic level of a company makes decisions related to the investment of new digital technologies and implementation of CPS, the tactical level focuses on the (re)design of work systems and implementation of new solutions'.*

Existing research reflects general agreement regarding predictions and estimations of how Industry 4.0 and new digital technologies might affect humans and work in industry. However, in the absence of empirical evidence the authors concluded that the research base was insufficient for building traction for the prescriptive actions needed to address the demands of HFE in Industry 4.0. Hence, there is need for:

- Greater understanding of HFE challenges and opportunities that are emerging with the implementation of new digital technologies;
- Industrial case studies with rich data presentation to validate or reject hypotheses on changes in human work in Industry 4.0;
- More testing of conceptual tools, methods, and designs outside of controlled laboratories, and inside real-life industrial scenarios;
- Closer collaboration between academia and industry, and
- A holistic research view (e.g. the Work System Method, Alter, 2006) with greater balance between operational concerns and high level tactical and strategic implications. Future research should focus on the three main domains of HFE (physical, cognitive, and organisational), including the relationships between them; and also widen the scope of research into new domains as necessary, as signalled by novel Industry 4.0 research findings.

The sociotechnical transformations involved in smart factory working environments, where 'human-centric' and 'cyber-physical' production systems come together have been examined by Romero et al. (2016). Automation, robotics and other advanced manufacturing technologies are viewed in terms of inherent possibilities for '*the augmentation of the human's physical, sensorial and cognitive capabilities rather than for unmanned, autonomous factories' (ibid.; p.2)*. The authors draw an Industry 4.0 analogy with the design of working environments for pilots, process industry operators and military personnel, which involve human supervisory control and human situational awareness. Approaching sociotechnical implications of Industry 4.0 from a social sustainability perspective, the focus is on how human-machine interactions, supported by workforce training and development, can improve the knowledge and capabilities of workers and through that maximise industry performance and opportunities:

> *The vision of the Operator 4.0 aims to create trusting and interaction-based relationships between humans and machines, making possible for those smart factories to capitalise not only on smart machines' strengths and capabilities, but also empower their 'smart operators' with new skills and gadgets to fully capitalise on the opportunities being created by Industry (ibid., p. 2).*

Romero et al. (2016) define a *human-centric production system* as one that unifies planning and implementation processes, considers operators as in control of the work process and supporting technologies, and fosters the development and utilisation of human competencies. A further core tenet is the *human cyber-physical production system* involves dynamic interaction between humans and machines in the cyber and physical worlds, facilitated by 'intelligent' human-machine interfaces, leading to enhanced operator capabilities. Human-computer interaction techniques are designed to accommodate operators' cognitive and physical needs; and improve human physical, sensing and cognitive capabilities through enhanced technologies. Ultimately, the aim of human cyber-physical production systems is to achieve optimal operator inclusiveness without compromising production objectives.

Consistent with the goal of enhancing human performance, Romero et al. (2016, p. 10) developed an Operator 4.0 typology to guide future factory workplaces in navigating sociotechnical challenges in Industry 4.0 transformation:

> *Operator 4.0 typology is useful in order to increase the understanding of the future roles of humans and machines in the factories of Human Cyber-Physical Systems. By creating a typology and a transcript of available assets and skills, traditional manufacturing companies can easily adopt the future contributions of humans in Industry 4.0. Future work will identify and address the specific challenges of the Operator 4.0 typology types.*

A summary of Industry 4.0 technologies identified by Romero et al. (2016) that are designed to enhance human capabilities and augment their work roles through human-machine interaction is presented in Table 3.

Table 3: Industry 4.0 technologies supporting human-machine interactions

Category	***Definition***
Powered exoskeleton (physical interaction)	*Super-strength operator*: mobile, representing a type of biomechanical system where the human-robotic exoskeleton powered by a system of motors, pneumatics, levers or hydraulics works cooperatively with the operator to allow for limb movement, increased strength and endurance.
Collaborative robots (CoBots) (physical interaction)	*Collaborative operator*: industrial robots capable of performing a variety of repetitive and physically hazardous tasks and that have been specially designed to work in direct cooperation with the smart operator by means of safety (e.g. force sensing and collision avoidance) and intuitive interaction technologies, including easy shop-floor programming.
Augmented reality (AR) (cognitive interaction)	*Augmented operator*: environment of the smart operator with digital information and media (sound, video, graphics, GPS data) that is overlaid in real-time in his/her field of view (e.g. head-gear, smart-phones, tablets or spatial AR projectors). Hence, AR can be considered a key enabling technology for improving the transfer of information from the digital to the physical world of the smart operator in a non-intrusive way.
Virtual reality (cognitive interaction)	*Virtual operator*: multimedia and computer-simulated reality that can digitally replicate a design, assembly or manufacturing environment and allow the smart operator to interact with any presence within (e.g. a blueprint, a hand-tool, a product, a machine tool, a robot, a production line, a factory), with reduced risk and real-time feedback.
Wearable trackers (physical and cognitive interaction)	*Healthy operator*: designed to measure exercise activity, stress, heart rate and other health-related metrics as well as GPS location and other personal data (e.g. biometrics). Aggregated personal and workforce analytics can prevent threats to operator safety and production quality, reduce human errors,

Category	*Definition*
	increase/decrease production targets, and locate and allocate closest operators to urgent function.
Intelligent Personal Assistant (cognitive interaction	*Smarter operator*: software agent or artificial intelligence developed to help the smart operator in interfacing with machines, computers, databases and other information systems as well as managing time commitments and performing tasks or services in a human-like interaction. Voice interaction technology (voice request), hands free, induces productivity and operational efficiency.
Enterprise social networking services (E-SNS) (cognitive interaction)	*Social operator*: social collaborative methods to connect the smart operators at the shop-floor with the smart factory resources. Such relations among the workforce (social network services) and between operators and smart things (social Internet of Industrial Things) to interact, share and create information for decision-making support. Can empower the workforce to contribute their expertise across the production line and to the shop-floor, can accelerate idea generation for product and processes innovation and can facilitate problem-solving by bringing together the right people with the right information and especially knowledge management and knowledge creation within the enterprise.
Big Data Analytics (cognitive interaction)	*Analytical operator*: process of collecting, organising and analysing large sets of data (big data) to discover useful information and predict relevant events. Its application to the smart factory has given birth to manufacturing real-time analytics at the shop-floor, also known as 'smart manufacturing'. Achieves better forecasts, understands smart factory performance, continuous improvement, visibility of key performance indicators, real time alerts based on predictive analysis, identifies problems, decision-support, operational efficiency.

Adapted from Romero et al (2016)

Industry 4.0 is expected to '*make firms much more efficient and productive with new technological capabilities and on the other hand, it will pose new challenges for organisations and people*' (Imran & Kantola, 2019, p. 118). Digitisation and automation of the manufacturing environment will demand new skills, knowledge and competencies from workers, and more flexible working environments from employers such as decoupling of work and place, of work and environment and of work and time. Key features of the implementation of Industry 4.0 manufacturing systems include highly complex horizontal and vertical processes:

> *Integration of IT systems, processes and data flows between different stakeholders like customers, suppliers and external partners (also known as horizontal integration), end-to-end digital integration of engineering through the entire value chain to enable highly customised products and integration of IT systems, processes and data flows within the company from product development to manufacturing, logistics and sales for cross functional collaboration (also known as vertical integration) (ibid., p.121).*

Implications for human work in the Industry 4.0 system are examined from the viewpoint of sociotechnical system theory, the purpose of which is to *'describe systems that involve a multifarious interaction between humans, machines and the environmental characteristics of organisational systems'* (Ibid., p. 121). Sociotechnical systems theory recognises the interconnected nature of social and technological aspects of the workplace where organisations are complex systems with many interdependent factors. This calls for holistic approaches to designing and managing changes in work practices resulting from the introduction of new technology into the workplace. The authors point to early experiences with workplace-based technological transformation where organisational objectives (about how technology would support performance) and outcomes (what the technology aided in practice) were disconnected. Critically they concluded that systems should be user-led and co-designed, they '*cannot be designed without the commitment of people, who will be users of it*' (ibid., p.121-122).

Imran and Kantola (2019, p. 123) also argue for a competency-based approach in which

> *'organisations aim to identify the competencies that are critical to job performance, and allocate tasks to employees based on the competencies they have, rather than on the position they hold in the organisation (as is the case for traditional Human Resources Management (HRM) systems)'*.

Critical competencies identified in the Industry 4.0 context include

- Technical competencies comprising all job-related knowledge and skills;
- Methodological competencies including all skills and abilities for general problem solving and decision-making;
- Social competencies encompassing all skills and abilities as well as the attitude to cooperate and communicate with others; and
- Personal competencies including an individual's social values, motivations, and attitudes.

Likewise it is important to identify new Industry 4.0 *job profiles* (e.g. data scientists and electro-mechanical engineers) and *work roles* (e.g. system designers who are designing new industry 4.0 systems for organisations, and Human Resources managers who are required to deal with big data and analytics for different HR practices, and so forth). Imran and Kantola (2019) propose a co-creation approach in the Industry 4.0 context to develop/analyse different processes within organisations, identify required competencies and develop new work roles and job profiles.

Competent and skilful people will be essential to capitalise on the benefits of Industry 4.0. There is a need to theoretically define and empirically validate models of adequate skills and competencies within the Industry 4.0 workforce (Ghislieri et al., 2018). The human role in Industry 4.0 is implicated in developing production strategy, monitoring strategy implementation, and intervening in the CPS if necessary, all of which require specific knowledge, qualifications, and skills. The authors predict increasing demand for higher standards of IT competency, knowledge about digital devices, virtual, augmented and mixed reality, and 3D printing and smart production. Soft or non-technical skills (as they are referred to in HFE) are critical to success and require continual development post university graduation. Such skills include openness to continuous learning, flexibility, working in multi-functional teams and dealing with complex situations.

To optimise the effectiveness of technology-human interaction, there is need to deepen the understanding of the interconnection between workers, organisations and technology and the effects of technology on people's performance, wellbeing and motivation. These impacts may be either positive or negative. There is a requirement for policies '*aimed at maximising the positive effects for workers and organisations and minimising the negative consequences'* (ibid.: 4) and adequate measures to cope with ongoing transformation. On a practical level, organisations should engage in detailed work analysis, team-working, targeted selection processes, training and development, talent programs and performance management (Ghislieri et al., 2018). Leaders and supervisors should be trained and supported through leading extensive transformation processes. Furthermore, applied research should be undertaken in the field of technology-induced work-related stress, and education and training outputs should be monitored to ensure that the required technical and non-technical skills are being taught to industry entrants.

While the roles played by humans in the Industry 4.0 manufacturing landscape are generally recognised as relevant, *'there is poor knowledge about how to design or adapt production systems taking into account the technological and the human-centric perspectives, aiming at maximising performance'* (Fantini et al., 2020, p. 9). Human factors have been examined in the context of CPS, developing a methodology to support the analysis and design of human work integrated with CPS that could be applied in any given context. The approach developed by

Fantini and colleagues (2020) highlights the need to develop and upskill workers to manage the transformation to Industry 4.0; apply a more concentrated focus on sociotechnical systems; and to enhance performance through the application of smarter technologies.

The framework for analysis and design of human work in the context of Industry 4.0 is based on the inclusion of two components - the human component (worker skills and characteristics relevant to performance) and the CPS component (different purposes of technology in relationship with humans). Four contributing perspectives are identified: abstraction (the need to contextualise human activity within CPS); decision-making (focusing on value added activities, identifying/selecting options to improve performance); and innovativeness and social interaction perspectives, both of which are a uniquely human contribution.

Charting facets of human-CPS interaction adheres to the following methodology:

1. **Problem-setting**: defining the context, purpose and orientation of integrated human-technology systems; identifying context-specific options and objectives for human-CPS interaction;
2. **Scoping**: defining benchmarks and criteria for measuring human-CPS interaction-related performance; identifying critical roles for achieving objectives (who does what to achieve set objectives);
3. **Analysis and design**: modelling the workflow and summarising activities across the workflow, extracting a comprehensive set of skills needed by the technician, using data (where feasible), and communicating and negotiating with other participants; and
4. **Assessment**: comparing synthetic information about the ‘new process’ (human-CPS interaction) outcome against the ‘usual’ outcome (non-human-CPS interaction); identifying emerging skill requirements, refining performance criteria, (e.g. more streamlined workflow, reduction in negotiated activities between responsible parties, maximisation of high value activities (e.g. decision-making), execution and alignment with existing skills); forming recommendations for human-CPS interaction (what do ‘responsible humans’ need to know, learn and experience to maximise the interaction/performance, e.g. predicting time before operational failures).

The aim of the methodology developed by Fantini et al. (2020) is to support Industry 4.0 enterprises to consider and entrench human dimensions in their design of CPS work roles. Enterprises are required to define specific objectives and key performance indicators relating to CPS human-machine interactions within their work systems. Indicators might include percentage of physical activities, non-value-added activities, activities with high or medium social interaction, activities with high or medium innovativeness and number of skills required per role. Objectives may involve increases or decreases in any of these indicators, whereby the performance of specific CPS work design options used by the enterprise can be assessed.

The methodology was applied in two industrial case studies to: *‘*

> *illustrate how industrial enterprises may address work organisation, while considering technological changes, at design time, when different options can be considered and early feedback to the technical projects can still be collected, evaluated and whenever feasible incorporated in the final plans’ (ibid.: 8).*

The results indicated potential for CPS functionalities to support and enhance human work and performance in Industry 4.0 settings, across the following domains:

- **Abstraction**: supporting or augmenting the sensory or motor abilities of workers (Stadler et al., 2017);
- **Decision-making:** cues that alert the worker whenever certain situations occur e.g. detecting a change in system state supports prediction of future states;

- **Innovativeness**: ability to deliver examples from workers' practices that support routine-based activities. These may involve developing task or context-specific procedures or tools that support work methods;
- **Social interaction**: facilitating multi-stakeholder engagement through simulations or optimisations that support negotiation and mediation activities; and
- **Human component:** customisable workplaces and human-computer-interfaces to adjust to the physical and sensory characteristics of the workers. These can support ageing workers or those with disabilities. Finally, personalisation features can enhance all the other support provisions to adapt to different conditions of the workers, such as stress, fatigue, and limitations from inexperience.

The challenge remains to apply lessons learned from this and other work to Industry 4.0 and CPS use cases in the Australian context. Just how we approach this from an HFE perspective is the subject of the next few sections.

4 Industry 4.0 human-machine interactions from the HFE perspective

The adoption of Industry 4.0 technologies is expected to fundamentally transform work by shifting toward technology-mediated interactions that are less physically demanding, more abstract, loosely coupled and cognitively challenging (Adriaensen, Decré, & Pintelon, 2019). Greater task complexity may increase potential for human errors as system operation becomes less transparent, requiring new understanding of system performance. As a human-centric, system science, HFE provides tools and techniques for analysing and predicting impacts and designing and integrating solutions to enhance user satisfaction and system outcomes. The following section explores two examples of human-machine interactions where Industry 4.0 technologies are transforming the current state of work. In the first, human-robot collaboration enables lightweight robotic technology to safely interact with humans in graduated levels of co-operation, altering the organisation of work and its physical, cognitive, and social dynamics. The second example explores the application of Industry 4.0 technologies to shipbuilding through a vision for Shipbuilding 4.0, focused on digitalisation, simplifying labour-intensive production processes and skilling the workforce. Collectively, these Industry 4.0 technologies can enhance the experience of work by reducing physical labour and providing opportunities to develop new skills, while modernising shipbuilding.

4.1 Human-robot collaboration

One technology that has great potential for human-technology interaction is cobotics. Industrial robots (IR) have been evolving since the early 1950s, progressing from simple mechanical manipulators (first generation IR) to clever-IR utilising developments in sensory technologies and computing power (second generation IR). Today 'intelligent' cobots (third generation IR) are supported by developments in safety technology and artificial intelligence. Cobots are light-weight robots that can operate safely with human workers in a shared work environment. They are viewed as 'cooperative' when humans and robots do not perform tasks simultaneously or 'collaborative' when they do perform tasks simultaneously. The benefits of co-locating humans and robots in a manufacturing work cell include the ability to customise production flexibly, cheaply and easily, and to adapt to production demands in the real time of production without interrupting production operations (agile manufacturing) (Sadik & Urban, 2017).

Ghislieri et al. (2018) approached the workplace implications of human-robot collaboration from a work and organisational psychology perspective, directing attention to the effect of advancements in Industry 4.0 automation in the workplace on the work, life and health of humans. Key questions related to the context of introducing advanced technologies into the workplace include how it is affecting people’s relationships with technology, human wellbeing and employment into the future; and what this means for knowledge and skill requirements in the workplace (competence profile, technical and non-technical skills). This study identifies a range of potential human-robot interaction (and other automation and advanced technology) issues in the workplace, including:

- Decreased situational awareness, distrust of automation, misuse, abuse, disuse of the technology, complacency and reduced vigilance;
- Loss or reduction of human relationships in the workplace, negative consequences relating to informal learning, organisational commitment, motivation and well-being;
- Introduction of innovative systems leading to lack of perceived autonomy and skills, stress, demotivation, and counterproductive work behaviours;
- Worker feelings of being controlled or oppressed; overwhelming transparency and visibility of individuals’ performance, increased data about work activities with results collected through digitised processes, surveillance and concerns about personal data protection, and
- Potential compromising of the instrumental needs satisfied by work (e.g. income, security, identity, psychological health).

Nordqvist & Lindblom’s (2018) examination of human-robot collaboration (HRC) identified the challenges involved in humans working with robots in dynamic, changing, fenceless and somewhat unpredictable settings (features of the anticipated factories of the future). The predominant focus of HRC research is on safety and performance, however human factors – namely issues of human cognition in a technology-mediated, socio-material context – require more attention: *‘safety is a necessary but not sufficient condition for avoiding accidents between humans and robots’* (ibid.: 341). Research drawing on the user experience approach (UX) explored worker trust in the context of human-robot collaboration in a manual assembly task with a voice-controlled collaborative robot prototype:

> *The findings indicate that the participants had confidence in the robot itself, but were insecure of their own ability to collaborate with the robot, because they could not smoothly predict the robot's intentions during the cooperation as well as the instructions provided via the robot's various modes of interaction’ (ibid., p. 342).*

The study highlighted the importance of intuitive interfaces, ensuring that robot actions and intentions are immediately clear to operators, and that interactions are based on strong understandings of interdisciplinary work. Success in achieving productive human-robot collaboration rests on user involvement at all stages of technology development:

> *UX evaluations should be carried out systematically throughout the whole design and developmental process so the final version of the collaborative robot fits the intended users’ and the defined UX goals (ibid., p. 342).*

Sauppé and Mutlu (2015) examined social dimensions of human-robot interactions (how people relate to collaborative robots) in the workplace. The study identified that collaborative manufacturing robots represent a radical change to how work is done in small and medium sized manufacturing businesses and that understanding how robots affect people’s perceptions of work in work settings is important for informing context-appropriate robot design. This is particularly relevant in the context of cobots that fulfil co-worker roles traditionally played by humans. Undertaken in three manufacturing sites, this ethnographic study (involving interviews and observations of staff), identified four key themes:

- **Operator-robot relationship**: owing to the different modes and intensity of interaction with robots, operators tended to view them as ‘human-like’ while maintenance and management viewed them primarily as ‘equipment’;
- **Attribution of human characteristics**: operators attributed robots with personality and intent; robots inspired a range of emotional responses in operators;
- **Social interactions with robots**: operators engaged in numerous social interactions with robots, and desired a speech channel for social and troubleshooting purposes; and
- **Responses to robot design**: robots’ physical appearance helped nearby workers feel safe, however operators expressed a preference for robot eye design that provided insights into robots’ status and next actions. The findings supported previous research indicating that workers rely on cues to understand robot actions and this is critical for feelings of safety.

The authors were surprised by the importance of the sociality of robots (ibid., p.3620):

> *‘We did not expect the social elements of the robot’s design or social relationships people established with it to be important factors in its integration into a manufacturing environment, due to our naïve presumption that there is little need for sociality in completing manufacturing tasks’.*

The researchers’ interpretation was that a human-like form provided a positive experience for workers and elicited feelings of safety and comfort. This style of cobot also provided communication cues necessary for the successful coordination of manufacturing tasks. However, there is a potential risk in sympathetic design creating a perception of safety that does not align with actual safety.

The study findings signalled two goals for successful robot design for human-robot interaction:

- Cobots that support and enrich the social environment, and support expectations for basic conversational skills and communicative functions that facilitate the coordination of actions (e.g. facility to ask the robot to identify what is wrong and a way to fix it); and
- Cobots that provide familiar interpretive cues for workers to interpret meaning (e.g. direction of gaze to support implicit communication).

Sadik and Urban (2017) explored the concept of human-robot cooperative manufacturing. In the manufacturing shared environment, successful human-robot interaction relies on the ability to communicate and cooperate on a shared platform of meaning. The key challenge is constructing an understanding of the manufacturing environment that is shared by worker and robot and is based on a natural language and reasoning that can be decoded by both human and cobot.

To facilitate shared meaning, a distributed control solution combining a Multi-Agent System and a Business Rule Management System was tested to solve the challenges of integration in cooperative manufacturing. It was designed to represent manufacturing knowledge, sharing, and reasoning, involving three steps:

- Step 1: agreeing a common language which can represent the shared environment between worker and cobot;
- Step 2: exchanging knowledge in a form that is understandable by the human worker and industrial cobot; and
- Step 3: understanding this shared language to adapt the overall status of the cooperative work cell to production demands (Sadik & Urban, 2017).

The study used a distributed control and communication structure to divide the manufacturing process tasks and responsibilities over different autonomous and cooperative categories that transform, transport, store and validate information and visual signals. The Business Rule Management System was used to create a set of rules necessary to process and comprehend the exchanged information and production requirements (establishing shared reasoning). In combination, these steps enabled the cooperative human-robot system to make collective decisions and to continuously adapt to customisation processes within the cooperative manufacturing system.

4.2 Human factors and Shipbuilding 4.0

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.

'Smart Ships' constructed using smart shipbuilding processes are promoted as the solution to industry challenges related to production efficiency, ship safety, cost efficiency, energy conservation and environmental protection. Stanic, Hadjina, Fafandjel and Matulja (2018) reviewed the concerted efforts of many major countries to adapt to the changes inherent in Shipbuilding 4.0 in order to survive in a fiercely competitive international maritime environment. In terms of shipyard design principles and strategy, digitisation is the key to success, involving the availability, exchange and processing of 'big data' in the shipbuilding process. Major changes to the world of human work are implied in both new job definitions and working processes. In addition to this there is a need for further simplification of production processes, continuous improvement of production quality, innovative solutions, and closer cooperation with and between shipbuilders, ship owners and bridge-connected suppliers.

The focus is heavily on technological solutions, with an implied connection to human factors through a:

> *new close cooperation between the shipbuilders and suppliers, in the very early design phase need to be defined [in terms of] main ship and production systems: energy and fuel saving solutions, main engines and propulsion systems, ship design and hull optimisation, machinery, public spaces, technical areas, cabins, deck machinery, but also shipbuilding equipment, surface preparation, welding and preliminary building technology (ibid., p. 118).*

There is limited explicit reference to the experience and needs of the shipbuilding workforce in relation to their engagement with technology in the workplace, although it is understood that where big data and analytics are used in implementing Shipbuilding 4.0, the output must be in a form that can be understood and interpreted by humans.

Largely, the focus on human factors is concentrated on upskilling in digital capabilities and knowledge, and the role of targeted education and training. The *Upskilling Shipbuilding Workforce for Europe* (n.d.) project examines the skills gaps and future needs in the shipbuilding industry across the components of manufacturing, repair, maintenance and conversion of vessels. The project includes a focus on Industry 4.0 and its implications for the sector. It also incorporates a dual focus on economic and social factors, drawing in technology, human capital, sustainability, and health and safety features.

New technologies in shipbuilding include, among others, advanced design and production technology and digitalisation processes, with ten key digital technologies: robotics, autonomous vehicles, the IoT, big data and analytics, cloud computing, cybersecurity, new materials, 3D printing, modelling and simulation and virtual and augmented reality. New systems include advanced outfitting, merging of design and construction operation, and artificial intelligence stimulating new production systems and business models. Within this, there is recognition of the importance of considering human factors in interaction with and impacted by new technologies. However, the focus of the *Upskilling Shipbuilding Workforce for Europe* project is primarily on the demand for skills and competencies generated by Shipyard 4.0, especially new, emerging and transferable skills, and how to develop these through education and training. The approach does not express a focus on human factors and ergonomics, which is key to understanding the contours of human-technology interaction and channelling this into planning and design processes within the shipbuilding workplace.

ErgoS Human Factors Engineering - a consultancy specialising in maritime application of human factors and ergonomics - highlights that consideration of human factors in manufacturing systems aims to optimise the fit between the human operator and the work environment, to achieve efficient and safe operation in a healthy and comfortable way. A key observation is that most ship design specialists have a deep technical background and expertise, but less understanding of the experience and needs of human operators. However to achieve optimal performance, a vessel should be designed with a focus on human operators as well: '*Without a crew to operate and maintain it, a ship will not sail at all*' (ErgoS Human Factors Engineering, 2016: para 1).

Current provisions for addressing a basic human factors standard in the maritime industry include flag state regulations such as Safety of Life at Sea (SOLAS) and International Maritime Organisation (IMO) standards. Fleet owners can improve this level by including human factors standards and guidelines additional to the building specifications and/or by appointing a captain or crew member delegate to participate in the project team. This has the potential however to be hampered by a lack of specific expertise in HFE. ErgoS propose a state-of-the-art human factors standard which involves adding a Maritime Human Factors Specialist to the project team or using the services of a dedicated consultancy company. A goal of engaging external HFE expertise is to build well-designed ships that support the crew to achieve and sustain the highest health, safety, wellbeing and performance standards. Human factors methodologies will enable these outcomes to be achieved through applying a systematic and user-centred approach to human participation that optimises the new systems of work that will inevitably arise from technology adoption.

The successful uptake and diffusion of advanced manufacturing and digital technologies in naval shipbuilding requires an appropriate HFE framework, infrastructure and capability. The next section explores some elements of a possible framework.

5 A human factors framework for uptake of Industry 4.0 technologies

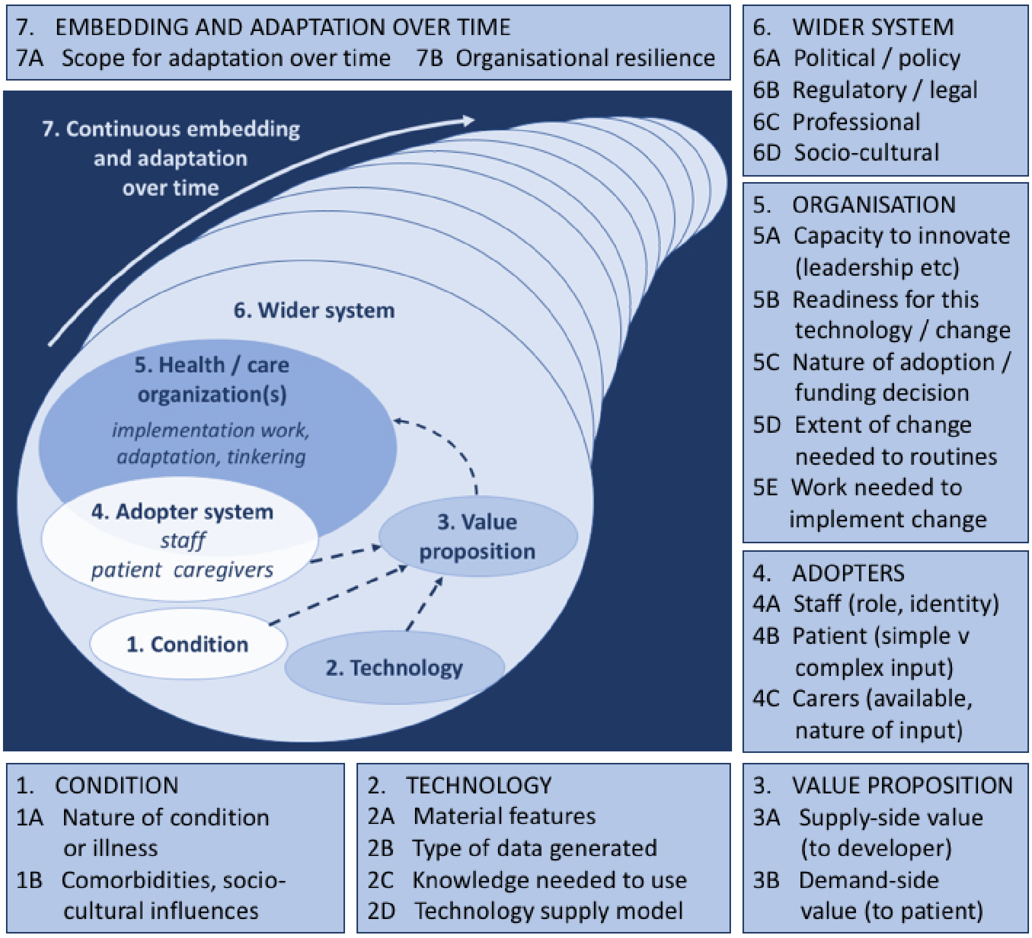
Introducing and successfully implementing advanced technologies can be a complex undertaking because it relies on systematically and holistically addressing organisational, structural, technical, and human factors information to achieve success. Implementation is a dynamic and iterative process requiring organisational change since technology adoption reconfigures work systems and roles. Different levels and groups within organisations and their wider industry contexts have diverse expectations of how existing challenges can be solved by technology e.g. maximising efficiency, improving quality, cost and safety. Multi-dimensional and nuanced evaluation throughout the design and implementation stages provides ongoing feedback, enabling expectations to be managed (Sligo, Gauld, Roberts, & Villa, 2017).

Technology adoption aims to achieve several goals to enhance organisational performance, primarily related to reducing costs and improving work quality. As exemplified in adoption of electronic healthcare, Sligo and colleagues (2017) identified several additional system-based outcomes, including ensuring system redesign is evidence-based, is empowering for end users and customers by promoting partnerships, educates and informs users by enabling information exchange, facilitates standardised communications along supply chains, and is ethical and equitable for consumers and professionals.

Successful technology implementation recognises that organisations and structures are determined by people and that structures are ultimately influenced by their strategies (Cresswell, Worth, & Sheikh, 2012). Consequently, a human factors framework requires consideration of three key areas that support technology adoption. Specifically, these include first, the structural and organisational contexts that define divisions of labour, resources, skills and competencies, and feedback processes. Second, human factors issues focus on how individual users are supported to accept and utilise technologies, as well as human resource management (HRM) practices such as training, personnel management and working relationships that align people and processes to achieve organisational objectives. Finally, technology factors that are highly influential include previous experience with technology, the mandatory use of technology, and perceptions that technology is easy to understand and use, To achieve successful outcomes, the ongoing involvement of key stakeholders and trialling prototypes with end users will encourage ‘buy in’ and enhance the likelihood of successful technology adoption (Sligo et al., 2017).

The *non-adoption, abandonment, scale up, spread and sustainability* (NASSS) framework was developed to help understand the differences between technology adoption and abandonment with electronic healthcare technologies (Greenhalgh et al., 2017). This framework acknowledges it is not discrete factors that make or break adoption of a technology, it is the dynamic interaction between them. The NASSS framework identifies seven levels of interaction between humans, technology, and systems (see Figure 2). The first level addresses the target issue – the problem or opportunity the technology is expected to solve. Technology, including its material features, the data it generates, and the knowledge needed to use it is represented at level two. Level three establishes the value proposition for both the supply and demand side of the interaction, while level four addresses the target audience adopting the technology (i.e. the end users). Factors defining the organisation, including readiness for, and extent of change are represented at level five, influenced by the wider system with its political, regulatory, and legal impacts at level six. The framework acknowledges that successful technology adoption is an ongoing process and requires embedding and adaptation over time, as highlighted in the final level seven.

Figure 2: The NASSS framework for considering influences on the adoption, non-adoption, abandonment, spread, scale-up, and sustainability of health and care technologies.



Reproduced from Greenhalgh et al. (2017)

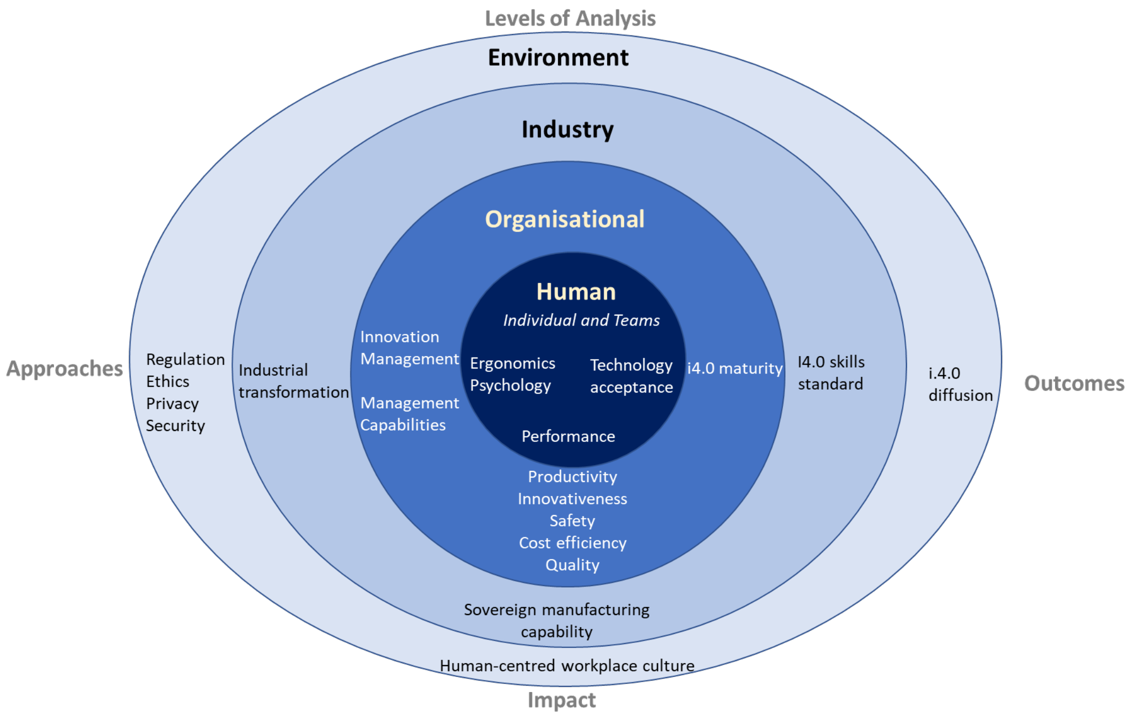
Human factors, as a design science brings together data, evidence and design principles to optimise human work and fulfil the goal of human-technology and system integration to enable transformation along the supply chain. Successful implementation of technology at scale has the capacity to the transform the future of work and in doing so reinvigorate the manufacturing industry.

A human factors framework for the adoption of advanced technologies in shipbuilding and the manufacturing supply chain acknowledges the interactions between technologies, human actors, and the design of work within organisations. Organisations are not islands – internally they consist of individuals, teams and operational divisions but they also function within supply chain ecosystems and in an environment influenced by political, economic, and regulatory factors. There are complex interactions within and between each of these entities which affect productivity, quality, safety, and costs. A business driver for technology adoption is increased competitiveness. Benefits are derived by optimising human performance through integration with technology and work redesign. Human factors research adopts a holistic approach to identifying the human performance variables that underpin the design of quality jobs to promote safety, wellbeing and productivity. Achieving integration involves fitting jobs to human characteristics, capabilities and limitations. This enhances personal performance, while creating safe, satisfying and sustainable work.

6 Towards a Naval Shipbuilding HFE Framework

This final section sets out a broad HFE framework for further development and testing of the impact of technology on work performance, organisational, and industry change in shipbuilding. A human centred approach is valuable for understanding the interactions within a complex system like shipbuilding, using multiple levels of analysis that address the organisation, industry and environment (as shown in Figure 3).

Figure 3: A proposed human factors and ergonomics framework for Industry 4.0 research



Source: Adapted from (Corlett, Wilson, & Corlett, 1995 p. 10)

In offering a holistic approach to investigating the complexity of human work, this framework draws on various approaches that elaborate multiple perspectives of human behaviour at the individual, team and organisational levels. Introducing technology fundamentally alters the design of work through changing the demands placed on individuals' physical, cognitive and social skills. Through automation, technology has the capacity to reduce the repetitive, arduous and dangerous aspects of work, while also providing opportunities to develop new skills to adapt to increasing cognitive demands. The social nature of work will also change, as teams reconfigure, and take on new roles as work becomes more distributed in time and space. Whether the introduction of technology is successful depends on how well it is accepted by individuals within the workforce. The level of confidence and trust, and perceptions of usefulness are key factors in successful technology uptake. Technology adoption must occur at scale to realise the full potential benefits for supply chain businesses and the shipbuilding industry at large. It is in the interactions between human actors, their organisational and industry contexts, and the environment in which they exist where outcomes including productivity, innovativeness, quality, health and safety and cost efficiency have their origins.

Shipbuilding is a complex, yet traditional industry, characterised by features of manufacturing and construction. The large scale, harsh environments, and potentially hazardous tasks involved in shipbuilding mean it cannot improve efficiencies without attention to work design and work health and safety to optimise workforce performance. Not only is it essential to minimise injuries and ill-health, but real benefits can be gained by fostering the capacity of the workforce to apply their creativity and flexibility to stimulate innovation. These processes need to be managed by developing new skills across all levels of the workforce, including management capabilities, to facilitate the change that comes with technology adoption and diffusion. Skills that will be valued include digital literacy, technical skills, problem solving, cognitive flexibility, creativity and emotional intelligence (Bughin et al., 2018). Within the broader operational environment, the influence of regulation, policy, ethics, privacy and security are significant brakes or accelerators in stimulating industrial transformation, given their crucial role in creating the economic climate and confidence to take the risks involved adopting technology and the inevitable need to re-make business models.

Through various industry-focused outputs (lessons learnt reports, technical case studies) and organisational human resources management outputs (addressing on-boarding and induction, human performance, training and development, and change management), HFE can contribute to a number of key outcomes associated with technology acceptance including the development of Industry 4.0 skills, workforce readiness and adoption. The uptake of industry 4.0 technologies is critical in building Australia's sovereign manufacturing capability while at the organisational level, the vital focus on the human promotes a culture of human-centred workplaces that will optimise the successful introduction, use and sustainability of technology and its benefits into the future.

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