connected everything.

industrial systems in the digital age

Future Industrial Worker

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Contents

1. Overview

The impact of the revolution in the nature of manufacturing on work that people do is becoming clear. Trends included in the notion of digital manufacturing relate to increased automation, analytics and sensor data to inform decisions about design and manufacture, reduced reliance on 'craft-based' skills and the increasing role of the user in the design and manufacturing process. Future technologies and associated legal and regulatory requirements will need to ensure that humans remain 'in the loop' – able to intervene when systems fail, and complete maintenance and oversight tasks, and have accountability for the way that things are produced, whilst having sufficient workload to maintain their attention and ability to have full situation awareness.

The very nature of jobs and workplaces is therefore changing. The notion of a factory as a large, dedicated building within a city or town is being challenged by notions of distributed manufacturing, and the nature of the supply chain is being disrupted by agile management of materials and technologies with the support of machine learning. The oversight of manufacturing processes is changing from a group of individuals who can directly observe, inspect and certify operations and stages of a design process, to a distributed team comprising robots, technical services, consumers and experts.

In the future, people and technologies will work in partnership to deliver a joint cognitive system which will complete tasks, have goals, and deliver activities in flexible, agile manners. The skills required of people to work within these systems will rapidly evolve, and current skills may be lost. The way that such joint cognitive, distributed systems will be represented and understood will need to be radically redesigned, and may not rely on metaphors associated with physical systems which we currently use. And the factory itself may become a 'hostile environment' for people – rather than designing our current environments so that they can also accommodate robotics, we will design factories for robotics that can also, occasionally accommodate people, as well as having dedicated spaces where people and robots can collaborate, without being restricted by physical barriers or cages.

This report outlines the fundamental, multidisciplinary research that will be required to enable this disruptive change, and support the role of technology, data and people in partnership in design, production, maintenance and use of goods.

2. Definition of Thematic Area

The Made Smarter Review (2017) notes "The greatest barrier to Industrial Digitalisation Technology adoption is the lack of skills" (p.75). However, skills are only one part of a wider picture of future industrial work. As shown in Figure 1 (overleaf) tasks are completed through the interaction of people, technologies (robotics, machines, data) and artefacts (objects, documents, products). The way that they combine to complete tasks is influenced by their individual and combined goals. These are set within an individual and wider physical and virtual workplace, and influenced by the organisational setting in which they are based.

External influences of finance, technology, law and society also change the effectiveness of the combined work of people, technology and artefacts.

Within the Made Smarter Review, five key technologies are referenced: Additive Manufacturing, Artificial Intelligence, Automation and Robotics, Connectivity and the Industrial Internet of Things, and Virtual and Augmented Reality. The evolution and implementation of each of these technologies will change the nature of work, and the requirements of the Future Industrial Worker (Table 1).

Figure 1: Role of people in Future Work systems and organisations

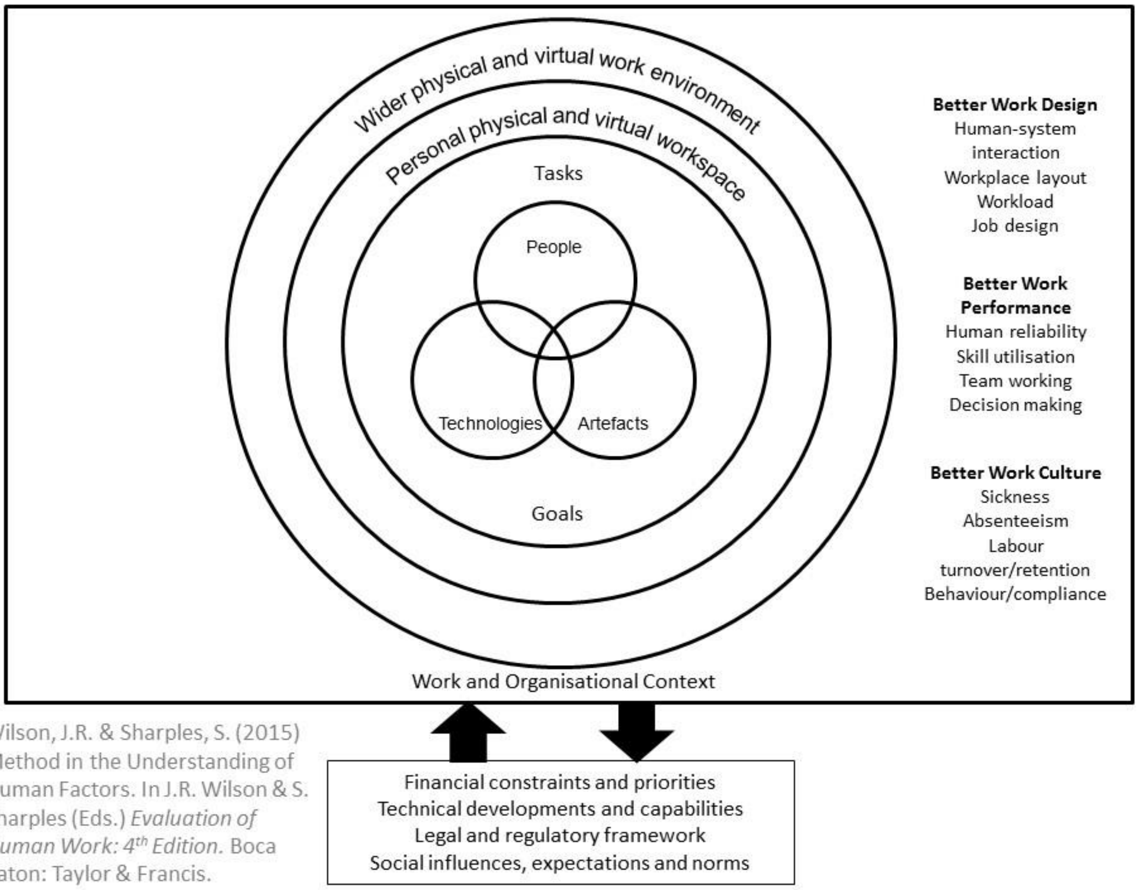

Table 1: Technologies of relevance to Future Industrial Worker

Technology	Relevance to Future Industrial Worker
Additive Manufacturing	Home users may be able to design products according to their wishes and specify bespoke designs to be produced. Software needs to enable them to take into account the manufacturing and performance implications of a design, whilst retaining their empowerment in owning and influencing the design process. As multiple materials become realistic to use as part of additively produced parts, designers and engineers need sophisticated models to enable them to predict performance of multi-material, functional designs.
Artificial Intelligence	Decisions more complex than people can make or comprehend will be made through the application of machine learning to big data. The 'irony of automation' that this presents is that a user will be required to validate or provide oversight of an activity that they have no chance of fully understanding. This therefore requires novel metaphors for communicating actions and outcomes driven by machine learning. The use of intelligent systems for design, decision making and operation also presents challenges for maintenance, as well as the potential loss of the 'knowledge based' generation of new ideas at which humans are currently highly skilled. Issues of audit and traceability are key, both in maintaining institutional knowledge of design, production and use and in demonstrating liability and accountability in design, manufacture, use and disposal.
Automation and Robotics	Introduction of automation takes advantage of sensing manipulation and control systems that already work at several magnitudes of granularity of accuracy greater than human sensory systems can. It will also reduce the need for humans to be in situations which are hazardous, or for them to complete tasks that may be liable to human error due to fatigue or distraction. However, the introduction of automation and robotics is not a panacea – some manual manipulation tasks are highly complex and difficult to replicate through robotics, and even if they are replicated, the use of robotics rather than people to complete these tasks may not be cost effective. From a societal point of view, the wholesale removal of jobs has significant implications, certainly for parts of society and geographical locations where manufacturing or design, and industries associated with the supply chain, have had a dominant presence. Finally, it is only when automation is combined with highly sophisticated machine learning that we can have true 'intelligence' in robotics; in this scenario, the ethical and legal implications of decisions made and enacted by robots needs careful thought.

Table 1 continued

Technology	Relevance to Future Industrial Worker
Connectivity and Industrial Internet of Things	The internet of things in the home is already being seen; the industrial internet of things, where not only are parts, designs and locations connected during design and production, but also the use and disposal of systems is monitored, presents significant opportunities in terms of agile management of the supply chain, and rapid reconfiguration of design and production in response to consumer and industrial use. However, it also presents significant concerns related to professional and personal intellectual property, personal privacy, liability associated with data ownership and technical and financial management of massive and rapidly expanding data sets.
Virtual and Augmented Reality	Virtual Reality (VR) and Augmented Reality (AR) present a distinct opportunity to visualise and manage large, dynamic data sets. It has developed so that it no longer specifically requires expensive dedicated hardware, and significant value can be gained from using relatively low technology solutions such as AR displayed on smart phones as overlay. New AR and VR, particularly at the design stage, need to ensure that design takes into account user needs, and recognises the critical role of physical interaction with products, as well as person to person communication, as a key part of the design experience. This requires integration of diverse and reliable models of human performance and behaviour into VR-based design systems.

3. Current Research

Current research activities are principally funded by EPSRC through the Manufacturing the Future and Digital Economy programmes. In addition, some of the feasibility studies which have been funded through Connected Everything have specific relevance to the notion of the Future Industrial Worker (see Table 2). Table 3 lists EPSRC funded projects of potential relevance to this theme.

Table 2: Relevant Connected Everything Network Plus feasibility studies

Feasibility of capturing crafts-based knowledge in an AI system for future autonomous precision surface manufacturing University of Huddersfield and University of Nottingham
Investigating spoken dialogue to support manufacturing processes University of Sheffield
Digitisation of collaborative human-robot workspaces Loughborough University
A digital garment simulation tool for fashion design linking consumer preference and objective fabric properties University of Leeds
ICHORD: Integrating Cognitions of Human Operators in digital Robot Design Cranfield University

Table 3: EPSRC funded relevant projects

EP/R032718/1 Digital Toolkit for optimisation of operators and technology in manufacturing partnerships (DigiTOP). University of Nottingham. Sarah Sharples. £1,904,381
EP/R021031/1 New Industrial Systems: Chatty Factories. Cardiff University. Pete Burnap. £1,467,376
EP/M012123/1 Feasibility of cognitive based Computer Aided Engineering Design (CAED). University of Strathclyde. Alex Duffy. £908,946
EP/K018205/1 Evolvable Assembly Systems - Towards Open, Adaptable And Context-Aware Equipment And Systems. University of Nottingham. Svetan Ratchev. £2,151,284
EP/K018388/1 Metrology concepts for a new generation of plasma manufacturing with atom-scale precision. University of York. Timo Gans. £1,979,776
EP/N018494/1 Aerial Additive Building Manufacturing: Distributed Unmanned Aerial Systems for in-situ manufacturing of the built environment. Imperial College London. Mirko Kovac. £2,317,561
EP/M02315X/1 From Human Data to Personal Experience. University of Nottingham. Derek McAuley. £4,062,954
EP/K014196/1 The Language of Collaborative Manufacturing. University of Bath. Ben Hicks. £1,951,554
EP/M017591/1 Re-Distributed Manufacturing Networks	The role of makespaces. Royal College of Art. James Tooze. £467,177
EP/K014161/1 Cloud Manufacturing - Towards Resilient and Scalable High Value Manufacturing. University of Nottingham. Svetan Ratchev. £2,364,080
EP/K014250/1 Intelligent Decision Support and Control Technologies for Continuous Manufacturing of Pharmaceuticals and Fine Chemicals. University of Strathclyde. Ivan Andonovic. £2,481,976
EP/M017559/1 RDM Healthcare Research Network. University of the West of England. Wendy Phillips. £467,417
EP/M01777X/1 Re-Distributed Manufacturing and the Resilient, Sustainable City (ReDReSC). University of Bristol. Colin Taylor. £491,658
EP/L015129/1 EPSRC Centre for Doctoral Training in Financial Computing & Analytics (covering Computational Finance, Financial ICT, Regulation, Retail). UCL. Philip Treleaven. £4,160,711
EP/L015463/1 EPSRC Centre for Doctoral Training in My Life in Data. University of Nottingham. Steve Benford. £3,356,613

Centres of Excellence and Areas of Strength in the UK relevant to the Future Industrial Worker

There are a number of internationally-leading research teams in the UK which are of direct relevance to the area of the Future Industrial Worker (listed in Tables 4 and 5).

Table 4: Centres of Excellence

Human Factors Research Group (University of Nottingham)	Design School (Loughborough University)
Engineering Design Centre (University of Cambridge)	Engineering Systems of Systems Research Group (Loughborough University)
Institute for Manufacturing (University of Cambridge)	Human Performance and Experience Research (Nottingham Trent University)
Edinburgh Centre for Robotics (University of Edinburgh and Heriot Watt University)	Bristol Robotics Laboratory (University of the West of England and University of Bristol)

Table 5: Areas of research strength in the UK

Robotics and automation	Edinburgh Centre for Robotics Bristol Robotics Laboratory UK RAS Network
Digital Economy	Horizon Digital Economy Research PETRAS Research Hub Digital Economy Network Digitally Enhanced Advanced Services Network+
Cybersecurity	PETRAS Research Hub Academic Centres of Excellence in Cyber Security Research
Artificial Intelligence and web science	The Alan Turing Institute Open Data Institute

Human-centred studies of manufacturing

The discipline of Human Factors specifically considers design of work environments for human performance. In 2015 and 2018, the UK Chartered Institute for Ergonomics and Human Factors published documents entitled 'The Human Connection'. These documents describe case studies which have applied human factors evaluation methods in a range of contexts and Table 6 lists cases which are of particular relevance to manufacturing:

Table 6: "The Human Connection" Case studies

Increasing productivity and removing risk on assembly lines	The Human Connection I: Case study 10, page 28
Reducing and preventing musculoskeletal injuries	The Human Connection I: Case study 20, page 48
Optimising product images	The Human Connection II: page 6
Using machines for manual handling	The Human Connection II: page 22
Reducing motion sickness from work on conveyors	The Human Connection II: page 24
Designing frames to handle heavy parts	The Human Connection II: page 26

4.0 Key research challenges

This report outlines a series of research priorities that were identified at a workshop held as part of the 'Connected Everything' network plus event in November 2017. The workshop was attended by members of the academic and industrial community who are familiar with different technologies and manufacturing contexts.

At the workshop a structured process of analysis of future industrial work scenarios by a multidisciplinary team of experts resulted in the following emergent top level research themes and priorities. These themes are

4.1 Flexible people, processes and organisational systems

This theme refers to the rapid evaluation and flexibility in tasks that will exist in all parts of the design process and supply chain. Whether a designer who receives multiple customisation requirements from users who is working to incorporate these into manufacturing specifications, a maintainer who is dealing with algorithms and large data sets as well as a range of state of the art equipment, or an operator who is working in partnership with an evolvable manufacturing system, technologies and systems need to be designed to enable people to respond appropriately to increasingly varied and changing environments. This may range from research into the way that systems interact and communicate (e.g. development of natural language interfaces), to understanding what data needs to be synthesised in order to enable operators to remain 'in the loop' – i.e. retaining their situation awareness of the current and predicted future state of a manufacturing system, or reconsidering the design of organisations to incorporate skills and activities that have perhaps not traditionally been considered as part of 'core' engineering.

Expectations of design and production will change; it is not impossible to imagine a future where there is a little as an hour between an individual producing a bespoke design on their home computer, and that designed product being delivered to their home. This radical reduction in time from *design to delivery* will dramatically disrupt the current supply chain, perhaps encouraging materials and component delivery to be increasingly distributed, local and agile. It will also change the nature and design of factories themselves – the factory may in fact become a hostile environment to humans, or may consist of areas where humans and robotics work in partnership (*cobotics*).

This will also present challenges – as well as considering the recycling of products and materials, we will need to consider the storage, management and reuse of data – the *data lifecycle.* Included in this are issues of interoperability of software and hardware, and the need for maintenance of the ability for 100 year reversibility (i.e. the use of future, not yet invented, approaches to data analysis, production and materials disposal for example).

4.2 Ubiquitous sensing and modelling

A future workplace will have truly *ubiquitous embedded sensing*, with sensors not merely peripherally added to components or people, but as part of them. Advances in materials science make this increasingly feasible within a five to ten year timescale. This will allow real time understanding of the collaborative human-robotic production system, remote monitoring of the response and use of components and products (and associated updates to design, materials and production in response), and high granularity multiscale models of complex systems.

This firstly requires advances in science to develop sensor technologies in such a way that they can be embedded within systems. Secondly, new methods in machine learning, image processing and mathematical modelling are required to integrate the different physics models of system elements in a manner than can be processed in close to real time. The integration and presentation of such data requires new protocols for interoperability of files and communications. Finally, the presence and use of such data to support decision making requires new methods of data presentation, and careful consideration of the ethical and privacy consequences of data ownership and use.

4.3 Liability, responsibility and ethics

New approaches to manufacturing remove the focus from the ‘factory’ – it is realistic to consider a product where no one single physical location provides a point of ‘sign off’ of a design or product. This approach disrupts the regulatory process, and presents challenges to traditional approaches to safety and audit of production processes. The challenge of ensuring that a system which evolves or learns can also be effectively tested within regulatory requirements has been acknowledged for several years. If we are to enable robotics and people to truly collaborate in a safe manner, then systems of prediction and regulation are essential. In addition, new approaches to digital manufacturing significantly increase the amount of data, both personal data and commercially sensitive data, which are required in order to continually inform product and process design. The existence of this data presents challenges, in terms of computational storage and legal liability. Finally, the introduction of ubiquitous sensing technologies presents ethical challenge in terms of ownership and use of data – who owns data that is collected at work, but is personal data? What are the associated rights and responsibilities for people and organisations associated with such data?

New models of future industrial work will require new models of process oversight, ensuring that those who are given authority to make decisions, or who are legally responsible for performance or safety, are provided with sufficient information of the correct form and granularity to enable them to make decisions effectively.

5.0 Support for industry vision

In addition to these challenges which require new, fundamental, multidisciplinary research, there are a number of ‘pull’ factors from industrial visions which will influence priorities and provide the basis of collaborative research partnerships between industry and academia.

- **Next generation supply and distribution**

Digital manufacturing disrupts current dedicated and fixed models of supply chains. Supply chains may become more agile, more local, and machinery may be shared between multiple companies and users on a regular basis. This presents challenges for future industrial work – we may see the increase in the notion of a 'gig economy' for manufacturing workers, and the demand on an SME may be less predictable. This will also affect the way that we deliver and distribute products and goods, with the likely increase in use of autonomous transport technologies to enable rapid delivery and distribution.

- **Interoperability, protocols and obsolescence**

Digital manufacturing has integration of systems at its heart; this presents considerable technical challenges in enabling multiple system types to work together. There has traditionally been a tension between an approach, which is viable in a dedicated and fixed organisation, or stipulating ontologies or protocols within communications; versus a flexible and learning approach to data formats and communications tools. New models of interoperability which are appropriate for future digital manufacturing contexts are required. We should also acknowledge the inevitable presence of legacy systems within a manufacturing that should remain, and ensure a focus on ensuring that obsolescence within systems is carefully managed.

- **Security, responsibility and IP**

As noted earlier in this report, the introduction of increased connectivity between products and manufacturing processes presents significant challenges for security, responsibility and protection of Intellectual Property. If we are truly to harness the potential benefits of Digital Manufacturing we need to also ensure that industrial partners are comfortable that their commercial assets, whether held in data or processes, are not being risked or compromised in any way

6.0 Next steps

On the basis of our workshop and contextual analysis, we have identified the following gaps in research and knowledge which are a priority to address:

- Integrated systems analysis of digital manufacturing

- Embedded sensing and Multiphysics modelling (for people and products) in manufacturing contexts

- Systems and technologies to manage accountability, privacy and liability in future production

- Design of future methods of complex data visualisation and integration for management of future manufacturing

These challenges will require multidisciplinary consortia to ensure that they are considered and addressed in as valuable a way as possible. In addition, there is considerable benefit in establishing a system through which the currently distributed (and sometimes siloed) knowledge about the different and distinct elements which will contribute to a future, digital, industrial digital manufacturing system can be shared and discussed

Digital manufacturing offers huge potential to transform the way that we live and work. Considering the way that this will change the fundamental nature of work, and the way that we therefore design the technology and systems which will enable the future workplace is key to the delivery of future safe, effective and productive workplaces.

7. Bibliography

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Appendix 1: Attendees at the Future Industrial Worker thematic area workshop

23 November 2017, Nottingham Conference Centre

Adam Burch	Jaguar Land Rover
Corinna Burger	Jaguar Land Rover
David Branson III	University of Nottingham
David Walker	University of Huddersfield
John Erkoyunco	Cranfield University
Matthew Jenner	Jaguar Land Rover
Max Wilson	University of Nottingham
Moira Petrie	University of Nottingham
Murray Sinclair	Loughborough University
Neil Mansfield	Nottingham Trent University
Phillip Stanley-Marbell	University of Cambridge
Rebecca Ferrari	University of Nottingham
Sarah Sharples	University of Nottingham
Sion Pulford	Jaguar Land Rover
Steve Burchill	SB Work Design

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