connected everything.

industrial systems in the digital age

Research Challenges

Connected Everything Executive Group

EPSRC
Engineering and Physical Sciences Research Council

Contents

Executive Summary

This report summarises work that has been conducted over an 18 month period through the collected effort of members of the Connected Everything network plus Executive Group (see Appendix 2). Our future industrial systems will be increasingly digital, and this change will impact on all aspects of the manufacturing life cycle.

Science and engineering research has a dual goal – to address real and priority industrial challenges, whilst maintaining a focus on discovery and insight. Our approach to ensuring that both of these goals were addressed was to work collaboratively, through multidisciplinary teams, to analyse different thematic topics in depth, and then to identify cross cutting topics which could form the basis of future challenges to be addressed.

Our team identified six themes which were then examined through a deep-dive approach, utilising expert review, focus groups and workshops.
The themes were:

- The Industrial Internet of Things
- Data Analytics and Decision Making
- Service Design and Customisation
- Design for Future Manufacturing
- Cyber-Physical Production Systems
- The Future Industrial Worker

Key common issues emerged from the analysis of these themes, and the teams worked together to identify four research 'challenges' which can act as catalysts for future research and innovation activities. They are intended to be provocations, which stimulate debate and discussion, and provide the basis from which specific research gaps can be identified. The identified challenges are:

- One hour from design to delivery
- Right data, right format, right time
- Feeling the 'pulse' of the factory
- The responsive supply chain

Since the development of these first challenges, a significant amount of work has been conducted to further refine and review them, and they are feeding into activities including the collaborative 'Made Smarter' activities which are now part of the Industrial Strategy Challenge Fund.

This report provides further detail of the work conducted, and is intended to support those working in research and innovation in digital manufacturing and future industrial systems in their analysis and strategies for future work.

Background

Connected Everything is the EPSRC funded Network Plus focussed on industrial systems in the digital age. Our aim is to identify the key challenges we face as digital technologies transform our industrial systems. We are creating and developing new collaborations between academics from diverse disciplines to address the key issues.

Our approach takes as its starting point the proliferation of connections - between machines, data and people - which characterises the changed context within which UK industries are operating and to which they must respond. UK industries must be supported to take advantage of opportunities arising from rapidly advancing digital technologies and herein lies a pivotal role for academic research.

Connected Everything's outputs are contributing to the strategic choices being made with respect to future UK research funding. To this end, a series of activities has been initiated, which are informing the debate about our future research priorities. We are funding a set of 11 feasibility studies designed to deliver new knowledge, specifically by demonstrating how techniques and approaches can be transferred from other disciplines into industrial and manufacturing contexts. These studies are producing demonstrators of what might, or might not, be possible and, as such, provide fertile grounds for debate. We also support knowledge transfer activities, including two summer schools for PhD students and recent PhD graduates and three annual conferences where the views of people working within industry, as well as academics, are given a platform and collaboration between academics and industry is facilitated.

A primary focus has been the identification of key thematic areas and the development of a road map to highlight the specific strengths and opportunities for the UK. Following widespread recognition of the need for a strategic and co-ordinated effort, and since Connected Everything began, the government has announced its Industrial Strategy and expressed support for the Made Smarter initiative. This has highlighted the strategic importance of the activities around our thematic areas work.

Process

Our launch event in October 2016 provided an opportunity to get input from academics and industry representatives, who were asked to respond to the question:

"What do you believe need addressing to research industrial systems in the digital age?"

The feedback results (detailed in Appendix 1) were then analysed to identify common themes, which were then developed into the following thematic areas:

- The Industrial Internet of Things
- Data Analytics and Decision Making
- Service Design and Customisation
- Design for Future Manufacturing
- Cyber-Physical Production Systems
- The Future Industrial Worker[a]

Members of the Connected Everything Executive Group were approached to take on the role of Champion for each of the identified thematic areas. Each of the thematic area champions were asked to co-ordinate work that would result in a document that sets out a synthesis of publicly funded research being undertaken in the UK relevant to that thematic area. This work was facilitated via specific workshop events, structured interviews or other means.

The thematic area reports were to provide a definition of the thematic area, outline its importance/value to Industrial Systems in the Digital Age and identify current research, including areas of excellence as well as possible gaps where funding could be directed. The six draft reports were discussed in detail at the D4I Group (industry) meeting in December 2017 and at the January 2018 Connected Everything Executive Group meeting, where a number of potential research challenges were identified and subsequently mapped against the thematic areas. A table illustrating this mapping can be found in Appendix 3. Further work was undertaken to refine and consolidate this mapping to identify four key research challenges.

[a] The theme of Future Industrial Worker was added later in the process.

Thematic Areas

The full reports from each thematic area can be found at:

The Industrial Internet of Things

Data Analytics and Decision Making

Service Design and Customisation

Design for Future Manufacturing

Cyber-Physical Production Systems

The Future Industrial Worker

Each thematic area is defined below.

The Industrial Internet of Things
Champion: Professor Duncan McFarlane, IfM, University of Cambridge

The Industrial Internet of Things (IIoT) is frequently cited as one of the key enablers of the set of new industrial IT capabilities in the digitalisation of manufacturing, and is considered a core part of the German initiated Industry 4.0 activity and US initiated Industrial Internet Consortium. IIoT enables connectivity between machines, devices and objects in multiple locations by supporting standards [not all yet exist] in the areas of identity, data collection and transport, data discovery, querying and cataloguing and for the analysis and use of the data. IIoT is cited as being the glue between industrial IT systems and Operational Technology systems. It is the application of Internet of Things developments to (create value for) industrial processes, supply chains, products and services. This is because it explicitly includes the role of products and services within its scope as well as industrial processes and operations.

It supports flexibility of manufacturing operations by allowing resources beyond the domain to be considered if needed. It supports productivity by allowing additional information associated with a manufacturing operation to be brought to bear on the decisions associated with its day to day functioning – e.g. access to logistics challenges in the transport network which might influence deliveries or procurement, the ability to access consumer usage data and channel it directly into the design and production decisions.

The areas where Industrial IoT might provide the best immediate impact are applications in:

- Integrating data from suppliers, logistics providers, customers
- Introducing data from new technology, peripherals, tools, equipment
- Distributed production requiring addition of new data sources, locations, owners
- Sensors on board raw materials, parts, products, orders passing through organisations

Service Design and Customisation Champion: Professor Roger Maull, University of Exeter

Over the last century, the United Kingdom has seen a steady transition from a predominantly manufacturing-based economy to a predominantly service-based economy. Within the context of manufacturing, the two key dimensions for this transformation are the extent of a focus on 'outcomes' rather than through ownership of goods and the extent of personalisation of manufactured goods to meet users' needs. Together, these represent the twin challenges of service design and customisation.

Digital technologies and customer-centric decision-making both contribute to a move from value being embedded in manufactured goods alone, to a deeper understanding that value is clearly recognised by consumer and manufacturer at the point of use. The application of digital technologies through service design and customisation offers a huge potential to impact productivity, growth and commercial resilience. While some businesses in the UK will realise these opportunities through new value creation and capture, others will lose out as competitors, exploiting the potential for digital technologies, move into and disrupt their value networks. The national need is therefore to rapidly accelerate the innovation of these digitally enhanced service offerings throughout the UK.

The particular challenge for digitalisation, as a means to achieving servitisation, is that all parts of the business will be affected, both in terms of the internal activities, and also their relationships with each other. Traditionally, manufacturing companies have seen their essential role as adding value to raw materials by turning them into tangible goods. Internal processes are typically focused on different aspects of adding elements of value to the processed materials. The servicised manufacturer seeks to allow value to be created at the point of use. Hence, the digitalised transformation of the organisation is now focused on capturing and understanding the customers' role in the value creation process, and feeding this information back up the supply chain to inform the constituent processes both within the factory and supply chain.

Design for Future Manufacturing Champion: Dr Fiona Charnley, Cranfield University

The future of design for manufacture needs to incorporate the specific requirements emanating from the digitisation of downstream activities, particularly manufacturing and services. Without a systematic consideration of these requirements, the benefits of digitisation cannot be fully realised in manufacturing. Although current research has investigated the exploitation of digital technologies within design, manufacturing and services separately, there remains a need to research the implications that digital manufacturing and digital services have on design. This will ease the adoption of digital technologies in manufacturing and services and enhance the benefits from their adoption. The key research question is how to design the next generation of products that are digitisation-ready and furthermore enable communication from such products to be analysed and used in such a way that added value is enabled for stakeholders throughout the value chain including the customer, designer and manufacturer.

A new methodology is needed that will incorporate specific requirements to enable the integration of sensors in products, the communication of products with machines, other products, humans and manufacturing environments, and the capture and analysis of manufacturing and in-service data. The UK has strong design and creative industries and has leadership in research in these areas. The UK also has world-leading research in systems engineering which will be a key component of research in this design theme.

One of the key challenges is to develop a deployable "Design for Digitisation" methodology that is customisable for a range of product types. This methodology should be able to disrupt the current design processes to address the above technical requirements. Another key challenge is to demonstrate the proposed methodology on a specific example and demonstrator. A holistic picture of the skills and abilities necessary to apply Design for Digitisation tools and methods should be investigated to ensure successful deployment.

Cyber-Physical Production Systems
Champion: Professor Svetan Ratchev, University of Nottingham

Cyber-Physical Systems (CPS) bring together the physical and digital systems dimensions into a common infrastructure. Cyber-Physical Production Systems (CPPS) consist of autonomous and cooperative elements and subsystems that are connected based on the context within and across all levels of production, from processes through machines up to production and logistics networks, with three main characteristics that describe them:

- Intelligence (smartness), i.e. the elements are able to acquire information from their surroundings and act autonomously and in a goal-directed manner

- Connectedness, i.e. the ability to set up and use connections to the other elements of the system, including human beings, for cooperation and collaboration, and to the knowledge and services available on the Internet

- Responsiveness towards internal and external changes.

In some cases CPPS are supported by digital twins designed as digital replicas of the real systems. A digital twin can be defined as an evolving digital profile, collating information about the historical and current behaviour of a physical object or process. This includes the creation of virtual products which continually update to reflect all processes performed upon them. Digital Twin Shop-floors (DTS) are another aspect of the digital twin concept encompassing the combination of a physical shop floor and its virtual representation as updated in real time.

Key areas of future development should include but are not limited to:

- Architectures and morphology of future CPPS
- Embedded devices and IIoT
- Human-centred processes in CPPS
- Data analytics and cloud data services
- Autonomous control in CPPS
- Factory level integration and digital supply chain
- Standardisation and interoperability

The Future Industrial Worker
Champion: Professor Sarah Sharples, University of Nottingham

Work 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, which 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.

With the impact of the revolution in the nature of manufacturing on work, the very nature of jobs and workplaces is changing. 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.

In future, people and technologies will work in closer 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. 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 being having sufficient workload to maintain their attention and ability to have full situation awareness.

Research supporting the future industrial worker will need to be multidisciplinary, supporting the role of technology, data and people in partnership in design, production, maintenance and use of goods.

Key areas for future development include:

- Flexible people, processes and organisational systems
- Ubiquitous sensing and modelling
- Liability, responsibility and ethics

Data Analytics and Decision Making Champion: Professor David Brown, University of Portsmouth

Data Analytics are qualitative and quantitative methods and processes used to convert information collected during the manufacturing process into a format that will help to inform decision making with a view to enhance productivity and efficiency. Most Tier 1 and large OEM companies have in-house data analytics capabilities. The challenge is to encourage mid-level companies and SMEs to adopt the state-of-the-art IoT, connectivity and communication protocols that would enable them to harness the data generated during the manufacturing process to improve their productivity and business gains.

With the development of smaller and cheaper smart sensors, the miniaturisation of data collection units and the development of onsite processing, industrial systems are set to be enabled with prompt decision making by accessing a wide range of data, at different time intervals and in different formats in order to support the entire business model itself.

One specific aspect of data analytics that commands further consideration is artificial intelligence (AI) and machine learning: technologies that will enable decision-making from data. Using algorithms that iteratively learn from data, machine learning allows computers to find hidden insights without being explicitly programmed where to look and with the arrival of "big data" the ability to automatically apply complex mathematical calculations to big data – over and over, faster and faster – is a recent development that coupled with growing volumes and varieties of available data, computational processing that is cheaper and more powerful, and affordable data storage, is leading to quicker and smarter ways to use data to make robust and accurate decisions.

And this is where deep learning, defined as a subfield of machine learning that is concerned with algorithms inspired by the structure and function of the brain called artificial neural networks, can really now become powerful as the data is more readily available and computer processing power is enabling data scientists to run more complex models of these artificial neural networks and in so doing achieve considerable advances in image and speech recognition.

In light of the above, and with the real opportunity offered by the technology advancements; fast sampling sensors systems, the miniaturisation of embedded data collection units and the development of powerful onsite processing, there is now real opportunity to enable decision making sometimes within milliseconds, this will enable organisations to make smarter, quicker and more accurate decisions.

Research Challenges

As mentioned above, the six thematic area reports were discussed in detail at the January 2018 Connected Everything Executive Group meeting, where they were consolidated to identify four research challenges.

One hour from design to delivery

Changes to distribution networks, increased use of digital technologies to enable design and manufacture, and the transformation of the role of the consumer in design is rapidly developing our expectations of reduction in time from generation of idea to delivery of product. The 'Amazon' model has now made it the norm for us to be able to order a product on a personal device in our home, and expect it to be delivered within a short period of time, often within 24 hours or less. This vision is not limited to the home consumer environment – replacement parts for civil infrastructure, or high value components in safety critical mechanical systems will also benefit from this rapid reduction in turnaround from identified need to delivered part. Digital manufacturing technologies will result in a further step change in the experience and expectations of the customer in reducing the time from design to delivery.

- Additive manufacturing technology developments will enable consumers or users to design and specify their own products, and initiate automatic manufacture of the products through additive technology. To enable this requires research in technologies to interpret consumer-led designs into feasible, reliable and efficient additive manufacture designs; continued integration of multiple functional materials into additive manufacture; and 'more than Moore' reduction in time and cost of additive technologies.

- Autonomous vehicles will be key to enabling delivery of components and parts within a production environment, and in facilitating rapid delivery of products to users/consumers.

- VR/AR technologies will enable user-led design, along with remote monitoring of production processes; work to understand the appropriate interaction metaphors to be used in a manner which allows users and managers to engage with systems, whilst managing bandwidth and communications requirements is key – identifying what needs to be visualised, when, and how.

- Industrial internet of things and connectivity will enable real time monitoring of production processes remotely, and ensure that production technologies are autonomously updated to reflect behaviour of parts in real world use.

- User interfaces and skills will need to be developed to understand when professional input is required in design, and when design tasks can be safely and appropriately handed over to the end-user. Tacit and explicit understanding of production processes, interactions between design, materials structures and performance must not be lost, and systems to integrate this knowledge need to be established.

Right data, right format, right time

The continued integration of sensors into parts and systems, use of peripheral devices to monitor systems, and use of cloud technologies to connect parts, machines and databases across the world, has resulted in an unmanageable proliferation of data. However, this data is also an asset, and, when used effectively, can transform understanding of materials behaviour and enable powerful collaboration between multiple users and organisations. It is also a liability, as the ownership of data may also imply responsibility to act (e.g. if data are able to detect a safety issue) and presents challenges in terms of security of personal and industrial data.

- Methods of appropriately managing personal data, confidential data related to intellectual property, and protecting against sabotage require cybersecurity expertise

- Visualisation of data, through media such as personal devices, or dedicated large scale VR/AR systems, is also required to ensure effective diagnosis of issues and a proactive response to design, production and distribution

Recognition of challenges associated with integrating personal use data into design decisions, including machine learning methods for data extraction and integration, and analytics to inform predictive algorithms is required.

Feeling the pulse of the "factory"

Advances in both peripheral sensors and integration of sensing within materials and parts means that we face a radical transformation in our ability to understand workplaces in which manufacturing and production occur. Our notion of the workplace itself is also challenged, potentially comprising of a series of distributed units, as well as our traditional expectation of single, large, integrated, dedicated designed spaces. The notion of 'feeling the pulse' refers both to the realistic proposition that we will no longer need to use laboratory based approaches to simulate and understand real work – we will be able to sense people and systems in a real work setting.

- This changes our data from a sample to a population, and thus demands new approaches to data analytics and visualisation (e.g. using VR/AR).
- Multiple, miniaturised sensors will need to be integrated to demonstrate a full system performance – whether that system is an aircraft, a collaborative robot, or a person working with a manually controlled machine. This sensor data integration requires new forms of Multiphysics modelling to understand how different parts behave together, particularly with the introduction of parts produced through new methods such as additive manufacture.
- The introduction of new technologies into work contexts can bring resistance and uncertainty. In addition to measuring performance, we require methods to understand and capture human responses to changes in work environments, on a sample and population level.

The responsive supply chain

This challenge is about responding to the demand from the customer for one that is made for me. The challenges from the 'market of one' are that most supply chains are built on a logic of economies of scale not economies of scope. Traditional manufacturing is based either on batches or on continuous process in the case of chemical and some food production. As we move from fixed, dedicated production settings to customisable designs, whether we are designing pharmaceutical products or personal devices, we need to understand how current processes can adapt to smaller, rapidly configurable scales, associated with a step change in reduction of production time. Personalised, on demand production can radically transform how we contract with the customer, be it corporate or consumer. The opportunity to move to outcome, availability or value based contracting offers the potential to massively reduce waste as the supply chain moves from 'push' to 'full pull'.

- Machine learning that can optimise production flows within the factory and throughout the supply chain in near real time to adjust for demand changes.
- Development of modular design methods alongside Application Lifecycle Management (ALM) that enable configuration as late as possible and as close to the customer as possible.
- Sensors on the packaging that enable smart packaging to identify problems in, for example, food storage.
- Developments in service platforms that allow for data from IoT in the home to provide early warning of equipment failure and opportunities for local service providers to intervene before failure.
- Distributed Ledger Technology (DLTs) offer the potential for ensuring provenance, enforcing traceability and providing security of data. DLTs can be used as the basis for value tokens (e.g. cryptocurrencies) to transfer value, rather than use existing financial systems and state currencies. They can also be used to store smart contracts which can perform simple operations on an "if this then that" basis. This enables payments/release of value to be made immediately on receipt of goods, removing process duplication and the need for working capital.
- New approaches to robotics technology will allow rapid production of items on a nano scale.
- Better utilisation of vehicles in logistics to greatly reduce empty vehicles through the use of AI that enables optimisation of scheduling and routing.
- Home based sensors that provide data on commodity (food, clothing etc) usage and to identify recycling opportunities or match with local foodbank needs.

- Tighter connectivity with customer needs will lead to "near net shape" production to order with significant reductions in waste and unwanted goods.

Next Steps

The work conducted within this programme has already been influential through the use of the individual reports by research and innovation teams, as well as through informing collaborative industry-academic discussions. The challenges within this report are being continually refined and debated, notably at the Connected Everything 2018 conference, D4I industry events in collaboration with the High Value Manufacturing Catapult, and in further cross-academia-industry discussions led by EPSRC.

It is hoped that this consolidated basis of work and analysis will support the continued identification of challenges to ensure that research and innovation in digital manufacturing addresses real industry needs through science and engineering discovery.

Appendix 1

"What do you believe need addressing to research industrial systems in the digital age?"

Network challenges and scope

Greater government funding for these areas – what levels have each country contributed so far? Who is leading?

How does the research in manufacturing aim to influence and create demand for future technology, i.e. look beyond advances possible via state-of-the-art technology?

How will the network positively influence the feasibility studies? How do we know that we have the right studies?

Is the Industry 4.0 a multidisciplinary effort work?

What is manufacturing? What is media?

What should be included into industrial systems?

What are the intellectual / scientific challenges that we should be addressing? How are they different to post challenges / research?

What aspects of manufacturing are NOT digital manufacturing?

Industry 4.0 needs a definition of scope similar to Web 2.0

What mechanisms do we have to set up a feasibility study project?

How can the UK differentiate its efforts in "Industrie 4.0 type" activities of other international players, to create competitive advantage?

Do the many EPSRC projects (100+) that link to Industry 4.0 have any connection? Should we create an intelligent repository for UK projects?

How to improve the communication and exchange of ideas between businesses, researchers, scientists and society?

How to share research more easily than with refereed journals that take years, is peer/subject specific and doesn't allow multiple disciplines to come together and have a voice? This will be key for future cross / multi-disciplinary research/output

Network challenges and scope / Whole system/boundaries

What's in, what's out of the network? Some boundaries may be useful

What is the "system" when talking about industrial systems of the digital age (e.g. does it have boundaries, if so where?)

How can data be collected to cover whole system?

Network challenges and scope / SMEs

A public repository for SME enthusiast to use smart objects (e.g. algorithms, methods, sensors, evaluation tests, graph tests) which will benefit them, their business

A public repository with large useful datasets for SME enthusiast to compare and evaluate against, or basic dataset like anthropometrics etc.

Some strategically important manufacturing is still dependent upon the know-how and skills of crafts people, even when they are using CNC machine tools. These individuals are typically aging. How can this informal body of dispersed knowledge be effectively coded and formalised?

Network challenges and scope / Other industries and contexts

What does industry want? Where are their roadmaps?

Service design and customisation

As a generalisation, today a product is designed to meet a functional specification. Then a manufacturer optimises processes to meet the design spec at minimum costs and time and risk. In principle, it should (in certain appropriate cases) be possible to unify optimisations so that the manufacturing is optimised to meet the ultimate functional requirements, not the intermediate detailed design spec. This could, in principle (and with all kinds of caveats) improve productivity and give a faster route-to-market for innovation.

What research and development is required to enable bespoke mass customisation?

Product / service design

Should consider

- Customer centric
- Digitally enabled
- Lifecycle of products and circular economy
- Should be fast flexible and responsive

What are the required changes in the supply chain design to support digitalisation of industrial systems?

How can you capture the "process" context for <u>future</u> data mining?

How can we use advanced digital information to improve lifecycle sustainability performance of manufacturing?

Cyber-physical systems

How do we enable people in future cyber-physical systems?

How do you capture human knowledge and rationale for use in autonomous systems?

How do we enable decision makers and human actors to deal with the complexities of the interconnected world (manufacturing)?

What is the role of the human in an Industrial System of the Digital Age?

What aspects of industrial activities <u>should</u> we automate? What should we prioritise?

For future factories, what are the challenges on the cyber version? What are the challenges on the physical version? What are the challenges on the communications linking up these two worlds?

What is the key different requirement between digital age and old age?

Why is the decision-making nor one of the automatic requirements in the digital age?

What is the operational model of people/engineer/machines in the digital age?

If smart => intelligent => data for automation, how can digital manufacturing also build human capability?

Capability of physical systems ⇔ digital ⇔ human ⇔ robot interaction - learning ability, mobile factory

Data analytics and decisions

What are the techniques to digitise skills-intensive manufacturing?

Should/can the semantics of the information be captured and fused with semantics of value adding processes to create factories that “understand” what they are doing?

How can we access and shape creative industry methods for gamification, visualisation and multiple user interactions for use by industry?

How do we solve data interoperability and information standards challenges to create connected infrastructures?

Big data analytics: real time data driven manufacturing (Industry 4.0 as a service)

Is industry ready for real-time data-driven manufacturing? If not, how far away?

How do we enable dynamic acting to maximise the opportunities from data analytics, to act on decisions?

What is the implication of collecting / storing data, in terms of skills, management responsiveness?

How to share data within/outside manufacturing businesses? Improving data availability, curation, labelling so that it is useful for smart algorithms

Can we develop techniques that can convert Industry 4.0 data from manufacturing and services into information that can inform engineering design?

How can we link manufacturing activities to standards which influence processes for data generation, storage collection and data flow?

Power of data analysis and visibility

Clustering data into specific cases and generic cases

Learning from numerical and categorical and pictoral and linguistic datasets

Smart data visualisation platform

How to track provenance of data (authenticity) outside the factory gates?

How to get more training datasets to perform more simulations, predictions, skills development

What value we need to deliver to customers to foster data sharing? How to give control?

How can we develop the AI and tools to build knowledge from data that will be required in the future?

This should harness research and capabilities developed by maths and computing researchers and take on board the need for machine learning, intelligent operations (optimisation, scheduling, planning) and the use of models in real-time in closed loop operations

Data analytics and decisions / Cyber-physical systems

The role of humans in future digital systems is key. How to study/sense/collect data form humans without them perceiving future smart systems as a threat?

Data analytics and decisions / Sustainability Service design and customisation

What are the implications of the availability of new data streams from digital manufacturing on engineering design and sustainability?

How to integrate data from different sources to support decision making

Skills and jobs

How do we address future required (new) skill sets?

This is the first proposed industrial revolution that makes no positive proposition to workers – you will be more insecure, used more flexibly and probably paid less. How can the needs of workers and society for production, rewarding work be safeguarded, promoted and given representation?

Outreach program to help prepare workforce and change the education content and context with industry

What skills do graduates for digital manufacturing require? Do our degrees provide this?

Human requirements

Actual end user needs / requirements need to be understood and clarified and common themes addressed

Cybersecurity

Cybersecurity research is important to resilient organisations?

Data analytics and decisions / Cybersecurity

Data collection, transparency, security

SMEs

How can this Network identify what SMEs really need?

How can smaller manufacturers (with limited R&D budgets) benefit from digital manufacturing?

How do you create SME engagement?

Design for production

What about design for production?

Product + process + production efficiency and effectiveness…. Where do digital tools address?

Risks of digitalisation

To define measures for added value to manufacturing through digitalisation

To identify potential risks of digitalisation in manufacturing

Internet of things

What are the implications of the emerging hyperconnectivity (i.e. sensorisation of wearables, ubiquitous social networks) for industrial systems in the digital age?

Appendix 2: Connected Everything Executive Group

Professor Sarah Sharples	The University of Nottingham
Professor David Brown	University of Portsmouth
Dr Fiona Charnley	Cranfield University
Professor Mike Chantler	Heriot Watt University
Paul Clarke	GKN
Dr Andrea Johnston	CMAC, University of Strathclyde
Professor Kerry Kirwan	WMG, University of Warwick
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Dr Michele Nati	Digital Catapult
Professor Svetan Ratchev	The University of Nottingham
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Professor Ashutosh Tiwari	University of Sheffield
Professor Paul Watson	Newcastle University
Professor Ken Young	MTC
Professor Hongnian Yu	Bournemouth University
Moira Petrie	The University of Nottingham

Appendix 3: Initial Mapping of Research Challenges to Thematic Areas

The table below is the outcome of discussions at the January 2018 Executive Group meeting.

	Design for future manufacturing	Cyber-physical production systems	The future industrial worker	Industrial Internet of Things	Data analytics and decision making	Service design and customisation
Digitalisation of design	x				x	
Data for digital manufacturing	x	x			x	
Customer and manufacturer	x					x
Open design of sensors	x			x		
Data persistent beyond the product					x	x
Miniaturisation of sensors (new models of sensing)	x	x	x	x	x	
Digital certification and evidence testing		x		x	x	
Flexible skills, people, processes and organisational systems			x			x
“From kilos and years to grams and months”	x	x	x	x	x	x
“One hour from design to delivery”	x	x	x	x	x	x
Actively experiencing and simulating products	x					
“Right data, right format, right time”		x	x	x	x	
Cybersecurity of supply chain “you are only as secure as the weakest link in the chain”		x				x
“Variety at volume”	x	x	x	x	x	x
Data and materials recyclability and RI	x				x	x
Machine learning-driven customisation		x			x	x
Customer-in-the-loop	x					x
“Feeling the pulse of the factory”	x	x	x	x	x	x
Leadership through disruptive change			x			x

Ubiquitous sensing and Multiphysics modelling	x	x	x	x	x	x
Liability, trust, responsibility and ethics	x		x	x		x
100% recyclability	x				x	x
Incomplete manufacture						x

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industrial systems in the digital age

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