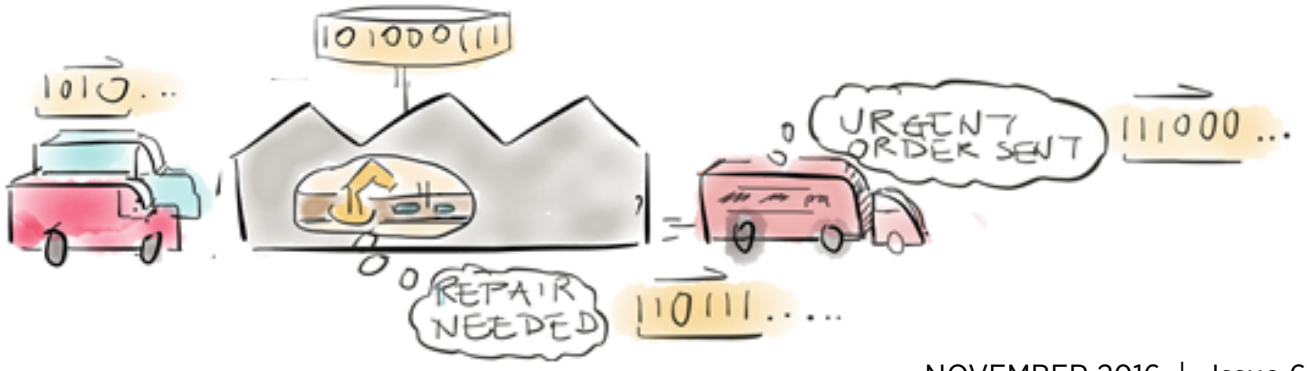

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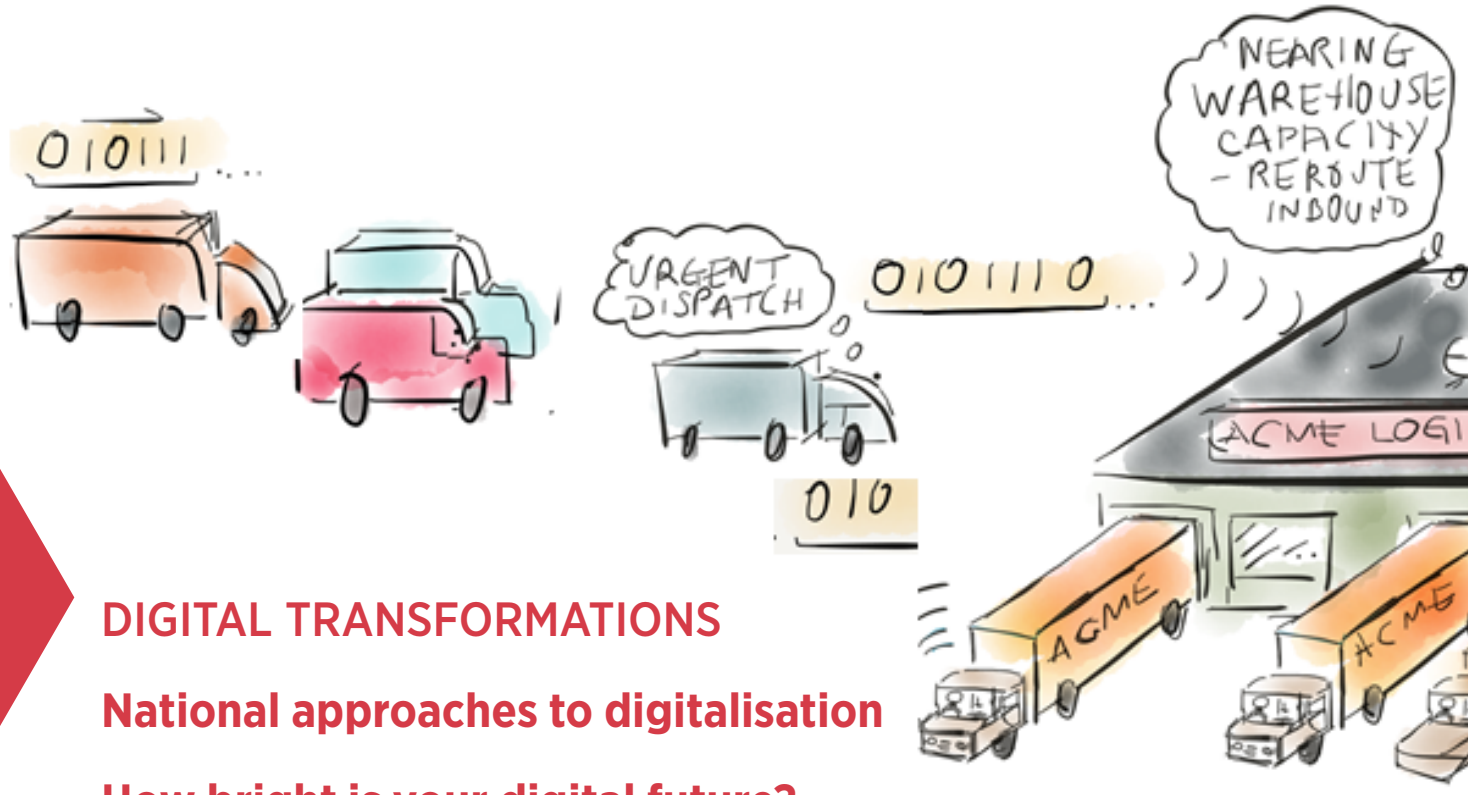
Institute for Manufacturing REVIEW



DIGITAL TRANSFORMATIONS

National approaches to digitalisation

How bright is your digital future?

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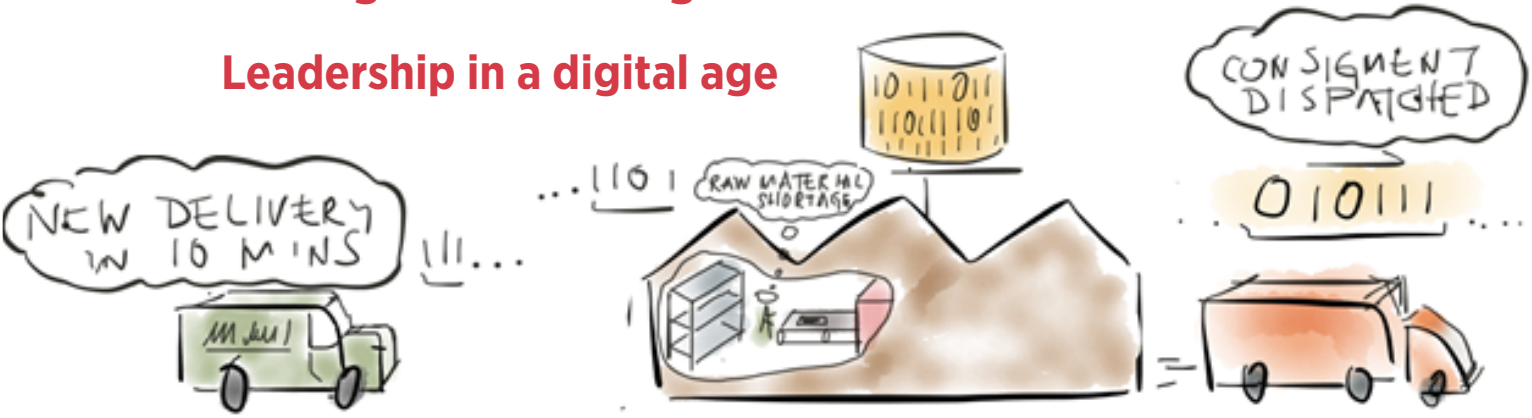
Leadership in a digital age



UNIVERSITY OF CAMBRIDGE

IfM MANAGEMENT TECHNOLOGY POLICY

INSTITUTE FOR MANUFACTURING: IfM

With a focus on manufacturing industries, the IfM creates, develops and deploys new insights into management, technology and policy. We strive to be the partner of choice for businesses and policymakers, as they enhance manufacturing processes, systems and supply chains to deliver sustainable economic growth through productivity and innovation.

IfM EDUCATION & CONSULTANCY SERVICES LIMITED: IfM ECS

IfM ECS is owned by the University of Cambridge. It transfers to industry the new ideas and approaches developed by researchers at the IfM. Its profits are gifted to the University to fund future research activities.

Contents

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www.ifm.eng.cam.ac.uk/ifm-review

Digital Manufacturing at the IfM

One of the challenges of digital manufacturing is that it means different things to different people. For some, it's all about smart factories and rapid prototyping. For others the emphasis is on distributed manufacturing, or supply chain optimisation or on delivering complex services with real-time asset monitoring. Whatever the particular focus of your company or sector, the key to digital manufacturing is being able to take advantage of the opportunities that digital technologies and data-driven processes can bring. And for many organisations the biggest impact of digitalisation will come from outside – when a competitor or new entrant uses it to change the rules of the game.

We know it's going to happen. We have already seen it in the consumer world. We read and listen to music online, we buy things from Amazon, we hail cabs from Uber and we use Airbnb when we travel. As customers, we know what digitised data and a well-designed platform can do for us. Our expectations have been raised. We are also living in turbulent times. The global economy is under pressure. China's growth is slowing. How Brexit will play out is contributing to uncertainty and to fluctuating exchange rates.

Amongst all the talk, two things are clear. First, digitalisation will have an impact on all aspects of manufacturing, right across the value chain. Second, there will be winners and losers. When a sector has been digitalised it has been disrupted. For the incumbent companies this presents a threat as well as an opportunity. And it is precisely why the IfM is well placed to help companies address the challenges they face.

IfM research

We have been researching aspects of digital manufacturing for more than twenty years. Indeed, Duncan McFarlane, Head of the IfM's Distributed Information and Automation Lab (see page 15) was part of the team that coined the term 'Internet of Things' all the way back in the twentieth century. In recent years we have added to his team's work on IoT, smart logistics and big data analytics, with other research areas such as additive manufacturing processes, digital supply chains, data-driven services and how – by understanding where the value lies – companies can change their business models in order to exploit these new technologies. Eoin O'Sullivan and his team at the Centre for Science, Technology and Innovation Policy (page 8) are looking at the policy environment in which all this innovation is taking place and contributing to the development of the UK's industrial strategy.

We thought that it would be useful to give you a glimpse of some of our research in this area for the *IfM Review*. But for reasons of space this is just part of the story. There's nothing here, for example, on additive manufacturing from a technology, design or business model perspective. Tim Minshall, the newly appointed Head of the IfM's Centre for Technology Management, is a member of the steering

group currently developing the UK strategy for additive manufacturing, due to be published in April 2017. There's also nothing on distributed manufacturing. Or on the risks associated with digitalisation of which cyber-security is clearly significant. Or on the implications for business model innovation. These are all topics we will cover in future issues.

How we can help

I see our role as two-fold. As researchers, our job is to try to have the big ideas that are derived from a rigorous evidence-based understanding of the here and now. That might be thinking about how the pharmaceutical sector could transform the way it delivers care to patients. Or how machines in factory networks could co-operate with each other using their own 'social network of things'. Or how to 3D print new advanced materials at the microscale. Or how policymakers can best support the digitalisation of manufacturing.

However brilliant an idea it's not going to make a difference unless it is put into practice. And that's the other equally important half of our job – making sure that industry and government benefit from this new thinking. Arguably, one of the things that's distinctive about the IfM approach derives from the fact that we are part of the Engineering Department. Our engineering ethos is not only to spot a problem, but to understand it and fix it.

So we are trying to develop a vision of a digital future and help companies in the here and now understand both the opportunities that digital manufacturing brings and the challenges they need to overcome. The work Jag Srai has been doing (see page 11) to develop a set of digital scenarios against which companies can measure their aspirations and current performance has been designed to do just that.

In my own area, the Cambridge Service Alliance has been looking at the internet of things and big data analytics and their effect on service businesses. Firms are looking for new digitally-enabled business models that deliver customised solutions whether its smart health services, smart transport solutions or guaranteeing uptime, availability and output from complex equipment.

One of the ways of helping to mitigate risk is by the development of standards. Through our dissemination arm, IfM ECS, we have been working with BSI (see page 18) to look at how standards and good practice are going play a vital role in supporting the development of manufacturing both in the UK and globally.

Digital skills and leadership

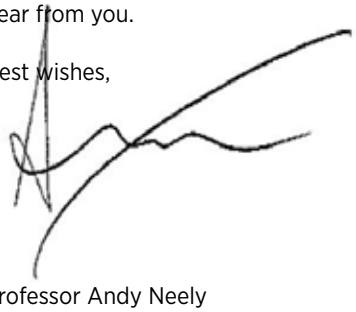
A lack of digital skills and awareness is one of the challenges faced by companies. We have recently created a new lectureship (not something that happens very often at Cambridge) in Digital Manufacturing. Dr Alexandra Brintup took up her post in September and her appointment will not only bolster our research activity in this area but also ensure that our students emerge with a strong foundation in all things digital.

And on page 22, I share some of my thinking, based on the work we have been doing in the Service Alliance, on how manufacturing leaders need to change in a digital age.

If some of the large companies we work with are struggling with how to exploit digitalisation, at the other end of the spectrum there are legions of entrepreneurs looking to be the next big digital disruptor. And Cambridge, Europe's largest technology cluster, is one of the best places to be doing that. The alumni interview on page 25 gives us a fascinating insight into that world of possibility and how ideaSpace, the University's hub for early-stage innovation (with management support from IfM ECS) is providing a place in which new ideas can flourish and where companies are being 'born digital'. All thanks to the vision of IfM alumnus and entrepreneur, Stew McTavish.

We hope you enjoy this issue of IfM Review. Please do get in touch if you want to find out more – we will be delighted to hear from you.

Best wishes,



Professor Andy Neely
Head, Institute for Manufacturing

IfM news

IfM ECS publishes major reports on UK manufacturing

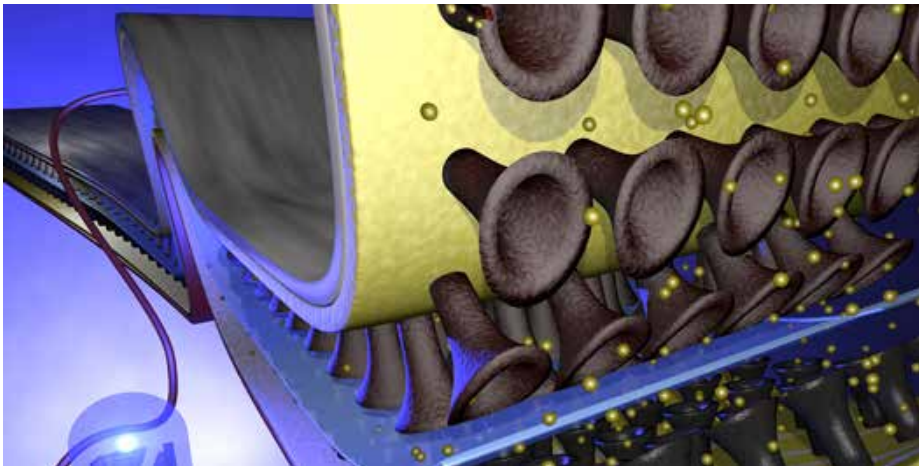
In September we published a consultation document on the UK's **High Value Manufacturing (HVM) landscape** over the next 15 to 20 years. Commissioned by Innovate UK and building on our 2012 HVM Landscape, it focuses on the challenges facing UK manufacturers in this period of rapid change. It will help inform UK industrial strategy and how best to support HVM which is currently worth around £275 billion to the UK economy each year.

"This report outlines a number of very important challenges which the UK needs to exploit in order to be at the forefront of this global revolution." *Clare Marett, Head of Manufacturing at the Department for Business, Energy and Industrial Strategy*

Download the HVM report here: bit.ly/2fKPPQU

In October we published ***Application of digital technologies to innovation in manufacturing***, commissioned by BSI and produced in conjunction with Cranfield University and University of Nottingham. This report looks at the challenges and opportunities digital manufacturing presents manufacturers and how standards and good practice can help them on their digital journey.

See article (page 18) and download the report here: bit.ly/2fxddfS



Introducing the ultraflexible battery

Researchers from the IfM's **NanoManufacturing** group have created an innovative carbon nanotube structure which makes it possible to create high performing, extremely flexible batteries. Drs **Shahab Ahmad**, **Davor Copic** and **Chandramohan George**, led by Dr **Michaël De Volder** have designed carbon nanotube (CNT) microstructures shaped like small cones, which are attached to a flexible current collector to create a battery. Tests showed that, from a performance point of view, CNT cone electrodes outclass existing flexible electrodes in terms of flexibility. The applications of this ground-breaking product can be endless thanks to its thinness, flexibility and durability.

This project appeared in an article in the journal *Advanced Materials*: http://onlinelibrary.wiley.com/doi/10.1002/adma.201600914/full

IfM Head awarded IET Achievement Medal for Manufacturing

Professor Andy Neely, Head of the IfM, has been awarded the Achievement Medal for Manufacturing, one of the Institution of Engineering and Technology's (IET) Achievement Awards.

The IET Achievement Awards acknowledge individuals who have made an exceptional contribution to the advancement of science, engineering and technology in any sector, either through research and development in their respective technical field or through their leadership of an enterprise.

Warren East, Chief Executive, Rolls-Royce, giving the keynote address at RADMA 2016

New appointments

Dr Tim Minshall, Reader in Technology and Innovation Management and Head of the Technology Enterprise Group has been appointed Head of the **Centre for Technology Management**.

The Gatsby Trust has donated £2.5 million to support the work of **Dr Eoin O'Sullivan** and the **Centre for Science, Technology and Innovation**. Eoin becomes the first Babbage Fellow of Technology and Innovation Policy.

Dr Mark Khater has been appointed Head of the **Centre for Strategy and Performance**.

Dr Mukesh Kumar has been appointed as Lecturer in Operations Management. He leads research into industrial resilience at the IfM.

Dr Alexandra Brintrup has been appointed to the new post of University Lecturer in Digital Manufacturing. Alexandra's research interest is in developing data analytics and intelligent systems for manufacturing and supply chains.

Dr David Lott has joined IfM ECS as Chief Finance and Operating Officer. He was previously Bursar at St. Francis' College, Director of Finance at the Gates Cambridge Trust and Finance Manager for the University of Cambridge's Non-School Institutions.

IfM hosts biggest ever R&D Management Conference

The 2016 annual R&D Management Conference was held in July in Cambridge. This year's conference was organised by the IfM on behalf of the Research and Development Management Association (RADMA). It proved to be the biggest RADMA conference to date with more than 450 delegates from 35 countries.

The delegates were in Cambridge to discuss the many challenges involved in managing R&D so that it delivers real societal, environmental and economic benefits. Industrialists played an important part in the conference, sharing their experiences and challenging the research community to help them create the conditions in which innovation can flourish and new technologies can be brought successfully to market.

Hamid Mughal, Director of Manufacturing at Rolls-Royce talks at IfM

In October, staff and students gathered to hear Dr Mughal's views, experience and lessons learnt. In his inspiring talk he explained what has made UK manufacturing successful in the past and what challenges we are facing now and in the future. A recurring theme was standards and how they can support manufacturing businesses in becoming more successful.

IfM news

Leonardo da Vinci: the first systematic study of friction

Professor Ian Hutchings, Head of the IfM's **Inkjet Reseach Centre**, has been in the news with his research into Leonardo da Vinci's studies of friction. Ian Hutchings is also the co-founder and co-director of the Cambridge Tribology Course and it is his interest in tribology – the science of friction, wear and lubrication – that led him to make this discovery. Some jottings in one of Leonardo's notebooks which had previously dismissed as 'irrelevant' by an art historian represented, Ian realised, the very first statement of the laws of friction.

You can read more about it here: bit.ly/2apZc3y or listen to Ian talking about his discovery here: bit.ly/2bbhol2

Growing your service business in an age of digital disruption

The Cambridge Service Alliance hosted its annual Industry Day Conference in Cambridge on 11 October, Speakers included Brian Holliday, Managing Director for Siemens Digital Factory (below left) who talked about the impact of Industry 4.0 and Siemens' experience to date of its digital factory initiative. Fred Jones, General Manager, UK Expansion, Uber (below right) described the Uber journey and the importance of platforms and markets in creating a disruptive business model.

Find out more about the Cambridge Service Alliance at: cambridgeservicealliance.eng.cam.ac.uk/

2016 Design Show

Each year the third-year **Manufacturing Engineering Tripos** (MET) students work in teams to develop a new product which has real business potential. The students need to identify a customer need, research the market, develop original design concepts and a full business plan.

This year's projects included a continuous flow waffle production device for commercial use, a robot that can construct brick walls autonomously at low cost and a way of recycling and reforming waste plastic bottles into building bricks for the developing world, eliminating the use of concrete and reducing landfill waste (below).

The 2017 Design Show will take place on 7 June at the IfM. Industry visitors are very welcome. If you would like to come along, please email ifm-events@eng.cam.ac.uk.

Cambridge International Manufacturing Symposium 2016

Around 100 delegates attended the 20th Annual International Manufacturing Symposium with speakers from leading companies including ABB, Amazon, Caterpillar, Celsio, IKEA, SAP and Wavin. The theme was Architecting the Digital Supply Chain - the implications of digitalisation for global manufacturing. See page 11 for more on digital supply chains.

Prize-winning agri-tech entrepreneurs

Two IfM graduate students reaped the rewards of their entrepreneurial approach to agri-tech. Armand de Durfort and Arsalan Ghani took part in Agri-Tech East GROW, a competition to encourage entrepreneurship in the agri-food industry. Armand, who has recently completed his MPhil in Industrial Systems, Manufacture and Management at the IfM, won the first prize with his automatic harvester, Softharvest. Doctoral student, Arsalan was a finalist with his food-sharing platform, Share Your Foods.

Armand de Durfort

Arsalan Ghani

White paper on Business Model Innovation

In June the IfM's **Business Model Innovation Group**, led by **Dr Chander Velu**, published a white paper on Business Model Innovation, developed jointly with the University of Exeter. Growth and productivity remain major challenges in the global economy: business models often act as the bridge between new technologies and the ability to deliver a compelling customer value proposition. Being able to experiment with new technologies and develop associated business models is, therefore, potentially a major source of productivity gains for both new and established firms.

Read the report at: bit.ly/2dIMFea

Roadmapping for industry and academia

In June, IfM ECS Senior Industrial Fellow, **Dr Nicky Athanassopoulou** ran a roadmapping workshop which brought industrialists together with Cambridge academics to develop a shared strategy for bulk superconductivity research.

The Bulk Superconductivity Group at the University of Cambridge Department of Engineering researches superconducting bulk materials which have the potential to replace conventional permanent magnets in things like motors and generators, with considerably superior performance. Representatives from the Group and from companies including Siemens, Boeing and CAN Superconductors worked together to scope potential future developments of the field and align research activities with the needs of industry.

Professor David Cardwell, Group Leader and Head of the Department of Engineering said: "Every academic group which wants its work to have societal impact should take advantage of the expertise offered by IfM ECS in facilitating academia-industry collaboration."

IfM ECS runs roadmapping workshops, based on research from the IfM's Centre for Technology and Management, to develop vision and strategy for a wide range of organisations.

Find out more about IfM ECS roadmapping workshops at: www.ifm.eng.cam.ac.uk/roadmapping

Become an IfM member

The IfM has two membership schemes which aim to build closer, long-term relationships between companies and our wide range of expertise, and to provide tailored support.

Corporate membership: for access to research-based strategic, technical and business expertise, geared to the needs of large international companies.
Company membership: for access to strategy and capability development for small and medium-sized companies, plus discounts on IfM services, training programmes and workshops.

For more information, go to: www.ifm.eng.cam.ac.uk/membership

The digitalisation of manufacturing economies

New digital technologies are radically changing the ways firms manufacture products, the business models they adopt, and even how they innovate. At a national level, digital technologies promise to reshape national manufacturing systems and redefine sources of competitive advantage. For governments around the world, this Fourth Industrial Revolution offers opportunities and challenges in key policy areas such as employment, productivity, competitiveness and sustainability.

Dr Eoin O'Sullivan, Head of the IfM's Centre for Science, Technology and Innovation Policy, reflects on different policy perspectives, priorities and initiatives in the key manufacturing economies – USA, Germany and Japan – and considers the implications for the UK.

"... it is worth noting that many national priorities for the digitalisation of manufacturing build on long-standing national industrial strengths and established national manufacturing capabilities."

Policymakers around the world are taking a keen interest in digital manufacturing for a number of reasons. They see its potential for enhancing productivity and economic growth, for (re)connecting manufacturing and innovation and for creating entirely new markets based on new products and services. Digitalisation also has the potential to improve resource efficiency and therefore help with costs, supply constraints and the sustainability of natural resources. But alongside opportunities lie challenges. Digitalisation has implications – both good and bad – for manufacturing jobs in high-wage economies. It brings with it significant concerns about the cyber security of industrial systems and utilities. And it threatens to disrupt business models in important sectors of the economy, offering opportunities for international competitors to gain market share.

Three dimensions of digital transformation

One of the most striking aspects of the 'digitalisation of manufacturing' is the variety both of the language used to describe it and the policy programmes designed to support it. This is, perhaps, unsurprising given the complexity of the technologies and manufacturing systems involved. The convergence of 'cyber-physical systems', the 'internet-of-things' and 'big data' technologies, among others, offer a variety of ways to connect and integrate ever more complex manufacturing supply chains and production systems. Equally, unsurprisingly, different aspects of these systems are more relevant for particular national manufacturing strengths and weaknesses – and for policy challenges where governments have different priorities.

A useful way of cutting through these variations in terminology is by framing the discussion in terms of three manufacturing 'dimensions': the *vertical* integration of flexible and reconfigurable manufacturing systems within businesses (often discussed in terms of 'smart factories' or 'smart manufacturing enterprises'); the *horizontal* integration of inter-company value chains and networks (or 'smart supply chains'); and the *product lifecycle integration* of digital end-to-end engineering activities across the entire value chain of a product and the associated manufacturing system.

There is a growing realisation among policy makers that the 'digitalisation of manufacturing' is not just about advanced automation and 'smart factories' but needs to embrace all of these three dimensions. These dimensions also provide a useful lens through which to understand the genesis of particular national innovation priorities and policy emphases, some examples of which are outlined below.

Different national approaches

Different governments are using a range of mechanisms and initiatives to address the opportunities and challenges of the digitalisation of manufacturing. While the following examples, from the US, Germany and Japan cannot represent the full breadth and variety of programmes in each country, they do highlight some key national priorities and some important flagship initiatives.

USA

One of the most high profile initiatives in the United States is the Digital Manufacturing & Design Innovation Institute (DMDI) based in Chicago. DMDI is one of the new Manufacturing USA innovation institutes (similar to UK Catapults) with a mission to develop and demonstrate new digital manufacturing and design capabilities in advanced analysis, intelligent machining and advanced manufacturing enterprise. DMDI has 190 member companies, as well as partners from universities and other organisations and funding of $320 million ($70 million of which comes from the government). DMDI's research agenda is often explained in terms of the so-called 'digital thread', an important concept within US thinking about the digitalisation of manufacturing. The term reflects an integrated approach to managing information related to a particular product (or asset) 'woven' throughout its lifecycle – a 'supply chain of data' from design to manufacturing to product-support.

Many research and innovation activities related to the 'digital thread' involve efforts to integrate data from different, traditionally siloed, functional engineering perspectives by developing protocols, information-exchange methods, tools and standards. A complete two-way 'digital thread' should enable manufacturing firms to deal more effectively with the complexity of modern products and manufacturing systems, reducing cycle times and increasing productivity and competitiveness.

Germany

In digital manufacturing terms, Germany is most associated with Industry 4.0 and its emphasis on smart factories and smart manufacturing enterprises. But it also attends to that other source of German manufacturing strength – small and medium sized enterprises.

One of the most high profile investments of the Federal Government's Industry 4.0 initiative is the 'It's OWL' (Intelligent Technical Systems OstWestfalenLippe) cluster. It's OWL is an alliance of over 170 businesses, universities and institutes in OstWestfalenLippe – a region with a number of industrial and research strengths. The alliance is funded through the Leading-Edge Cluster program which supports top-performing commercial and scientific clusters. It's OWL has received over €100 million over five years, funding 46 research projects to develop intelligent technical systems. While it has a significant focus on research, the cluster is also very much concerned with helping SMEs develop their capabilities.

Japan

The Japanese government's most recent review of manufacturing highlights that, although Japan is adopting the 'Internet of Things', it may have fewer value capture

"The levels of international policy interest, investment and urgency, reflect an expectation that digitalisation will radically reshape manufacturing systems, value chains and sources of national competitive advantage."

opportunities than the United States or Europe. The US has opportunities to capture value particularly through internet platforms and big data analysis (through firms like Google) and Germany has opportunities related to the connectivity of production machines and smart factories, through firms like Siemens. Japan, on the other hand, is comparatively strong in advanced robotics and its government has prioritised efforts to lead the world in 'robots for the Internet-of-Things era'. The Japanese Robot Revolution Council Initiative, backed by over 200 companies, universities and research institutes, aims to expand the use of advanced robotics throughout Japanese industry, with the aim of growing sales from ¥600 billion a year to ¥2.4 trillion a year (roughly £19 billion a year) by 2020.

Although most major economies have research and innovation efforts related to the digitalisation of manufacturing, there are, then, significant variations in emphasis and perceived opportunities. The US has, perhaps, a greater emphasis on the opportunities associated with new product design (and speed to market) and the knowledge management enabled by 'big data'. Germany has a relatively stronger emphasis on 'embedded systems' and the 'smart factories' of the future. Japan has identified national opportunities in cyber physical systems and 'advanced robotics for the 'Internet of Things' era. These are all new opportunities enabled by new ICT and manufacturing technologies, but it is worth noting that many national priorities for the digitalisation of manufacturing build on long-standing national industrial strengths and established national manufacturing capabilities.

What about the UK?

So what are the implications of the digitalisation of manufacturing for the UK? What are the opportunities (and challenges) given Britain's existing manufacturing and innovation base?

Britain may not be home to the headquarters of giant global internet firms like Google, or have a 'Mittelstand' of manufacturing engineering SMEs like Germany, or have a national tradition and passion for robotics like Japan, but it does have an extremely strong engineering and design base, and a thriving ICT community. And from a policy perspective, the UK has adopted a systematic policy approach to 'industrial strategy', which may well be ideally suited to addressing the opportunities and challenges of digitalisation.

In recent years, UK industrial strategy has focused on long-term strategic support of key sectors through the co-ordinated development of skills, technology capabilities, key infrastructure and access to finance. At the same time, flagship initiatives such as the Advanced Manufacturing Supply Chain Initiative and the Catapult network of intermediate R&D centres have an important role to play in enhancing the critical linkages throughout the UK's innovation and manufacturing systems.

More recently, in July 2016, the Government announced a major overhaul of the UK business ministry, giving it a new name – the Department of Business, Energy and Industrial Strategy – suggesting further commitment to strategic, systematic and joined-up policy-making. This systematic approach will become ever more important as digitalisation continues to transform and integrate manufacturing technologies, systems and supply chains, creating new sector-specific opportunities, but also others that cut across traditional sector boundaries and require common innovation infrastructure, skills and R&D investment.

The policy challenge

For manufacturing economies, policy initiatives related to the digitalisation of manufacturing are, therefore, about much more than just digital technology research and innovation. In particular, there are significant efforts to address market failures related to skills and workforce development, ICT infrastructure, SME capacity-building, as well as standards development, data transparency and trust, IP rights and cyber security.

The levels of international policy interest, investment and urgency, reflect an expectation that digitalisation will radically reshape manufacturing systems, value chains and sources of national competitive advantage. The complexity of digitalised manufacturing systems, the variety of perceived opportunities and challenges, and the different policy approaches to addressing them suggest there is still no consensus on how the 'Fourth Industrial Revolution' will play out, how value will be (re)distributed throughout global manufacturing networks, or which capabilities will determine who wins and who loses. The revolution is coming, but there is everything still to play for.

Find out more

Digital Manufacturing and Design Innovation Institute: dmdii.uilabs.org

Manufacturing USA: www.manufacturing.gov/nnmi

Germany's 'It's OWL' cluster: www.its-owl.com/home

German Federal Government's Industrie 4.0 initiative: www.bmwi.de/EN/Topics/Economy/Industrial-policy/industrie-4-0.html

Japan's recent review of manufacturing: www.meti.go.jp/english/press/2015/pdf/0609_01a.pdf

Japan's Robot Revolution Council Initiative: www.jmfrri.gr.jp/english/outline/establishment.html

For more information contact:
Dr Eoin O'Sullivan, Head of Centre for Science, Technology and Innovation Policy

How bright is your digital future?

Dr Jag Srai, Head of the IfM's Centre for International Manufacturing (CIM), and his team have developed a new way to help companies embrace the challenges and opportunities of digitalising the extended supply chain.

»

Photograph: © Andrew Payne: Fusing stainless steel powder with high power laser diodes

The combination of new technologies, IT infrastructures and data analytics holds out an alluring possibility of a world in which the end-to-end supply chain is utterly transformed – highly connected, flexible, efficient, resilient and truly responsive to customer needs. Each of those attributes sounds attractively incremental but put them together and you have a completely new way of doing business and one in which customers are not just on the receiving end of a product or service but are central to it.

A good example of this – and one that we know well – is the pharmaceutical sector. As part of the REMEDIES project (see page 14), we are working with the major players in the UK pharmaceutical supply chain to address some of the challenges they face, such as tackling the hundreds of days' of inventory sitting in the supply chain and the vast quantities of waste caused by patients not taking the drugs they are prescribed.

Using digital technologies and data-rich systems to make the pharmaceutical supply chain much more efficient is one thing but we are also mapping an entirely new business model in which drugs can be manufactured to order – possibly at the local pharmacy – to meet a patient's individual medical needs, and where the consumption and effects of those drugs can be continuously monitored to help doctors better support their patients. A brave new world, in other words, of personalised medicine enabled by digital manufacturing processes, digital infrastructures and lots of data.

Developing an end-to-end digital supply chain involves a major transformation both at a conceptual level and in execution.

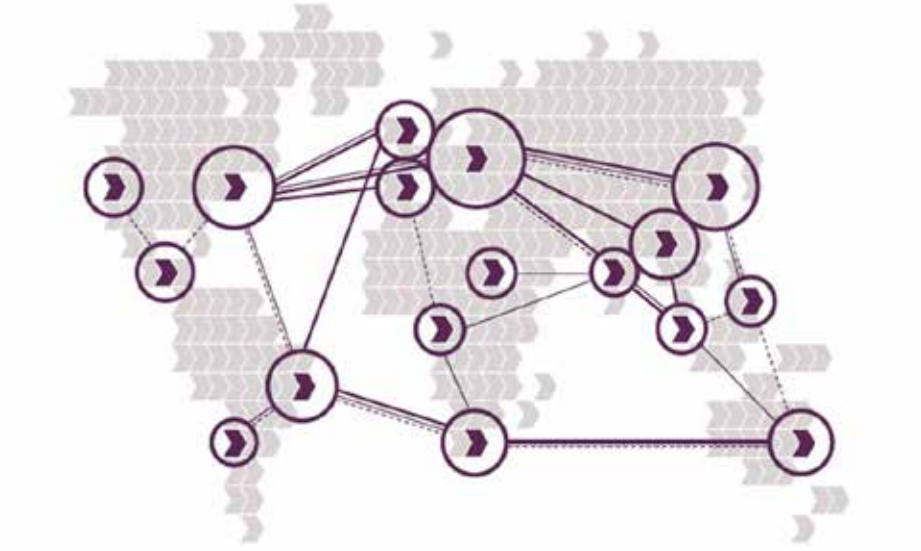
But realising this vision of a digital future remains elusive, particularly for the largest global businesses. Many of these companies recognise the need to digitalise aspects of their supply chain, often in response to particular challenges. They may, for example, as in the pharmaceutical sector, have a pressing need to solve the intransigent inventory management issues that bedevil many supply chains. They may have an issue with quality and see digitalisation as the best way to ensure their products are of a consistently high quality and their provenance is traceable. Or they may be losing competitive advantage through poor customer service and see a digital agenda as a way of regaining market share, possibly while supporting their ambitions to reduce environmental impact.

But developing an end-to-end digital supply chain involves a major transformation both at a conceptual level and in execution. And while thought leaders and change agents within big companies may see the prize, CEOs and shareholders will be much more cautious given the levels of investment and organisation-wide disruption it entails. This is particularly the case for the global giants with a history of merger and acquisition and an array of legacy systems to integrate. Even without the complication of M&A, all large companies have to organise themselves into manageable structures, which have a natural tendency to turn into silos and hence become obstacles to organisational change.

There is also the wider question of a lack of digital skills and attitudes across the board – at senior and middle management levels as well as within day-to-day factory operations. Companies may be able to see the opportunity, acquire the technology and capture the data but a shortage of both skills and mindset presents a significant barrier.

One of the challenges with the digital supply chain vision is the sheer scale and ambition of it. At CIM we have begun to conceptualise what a digital supply chain might look like and break it down into ten key areas or 'scenarios' (see opposite) to help companies understand the key ways in which digitalisation can impact on their organisation. We have been doing this by talking to companies both individually and as a non-competitive group.

Having identified ten key areas we have been developing 'maturity models' against which companies can benchmark their current performance, identify where the greatest opportunities lie and start to think about where to prioritise their efforts.



Factory design and production processes

The ten scenarios include factory design and production processes as digital developments in these areas underpin the extended supply chain. The flexible factory is an important concept in this rapidly moving environment: how can you design and configure a factory for technologies which you don't yet know. In this context, factories need to be modular and reconfigurable. One of the questions our framework helps companies consider is this: it is relatively straightforward to design a state-of-the-art, highly flexible

plug-and-play factory – but is it cost-effective? Is it where companies will be able to create and capture most value?

Making the most of data

Some companies are already very good at gathering product and customer data but the challenge is how to integrate that data and use it to make better decisions about, for example, product lifecycle management, sales forecasting and designing products and services in response to customer needs. Data ownership is fast becoming an important issue in the supply chain and service delivery context. When partners are involved who owns and can access the data is a critical question. Data sharing and connectivity also raises the question of open source versus 'black box' and developing common international data standards across sectors. In this area we must also consider the resilience of these digital supply chains and understand the cyber security challenges they may present.

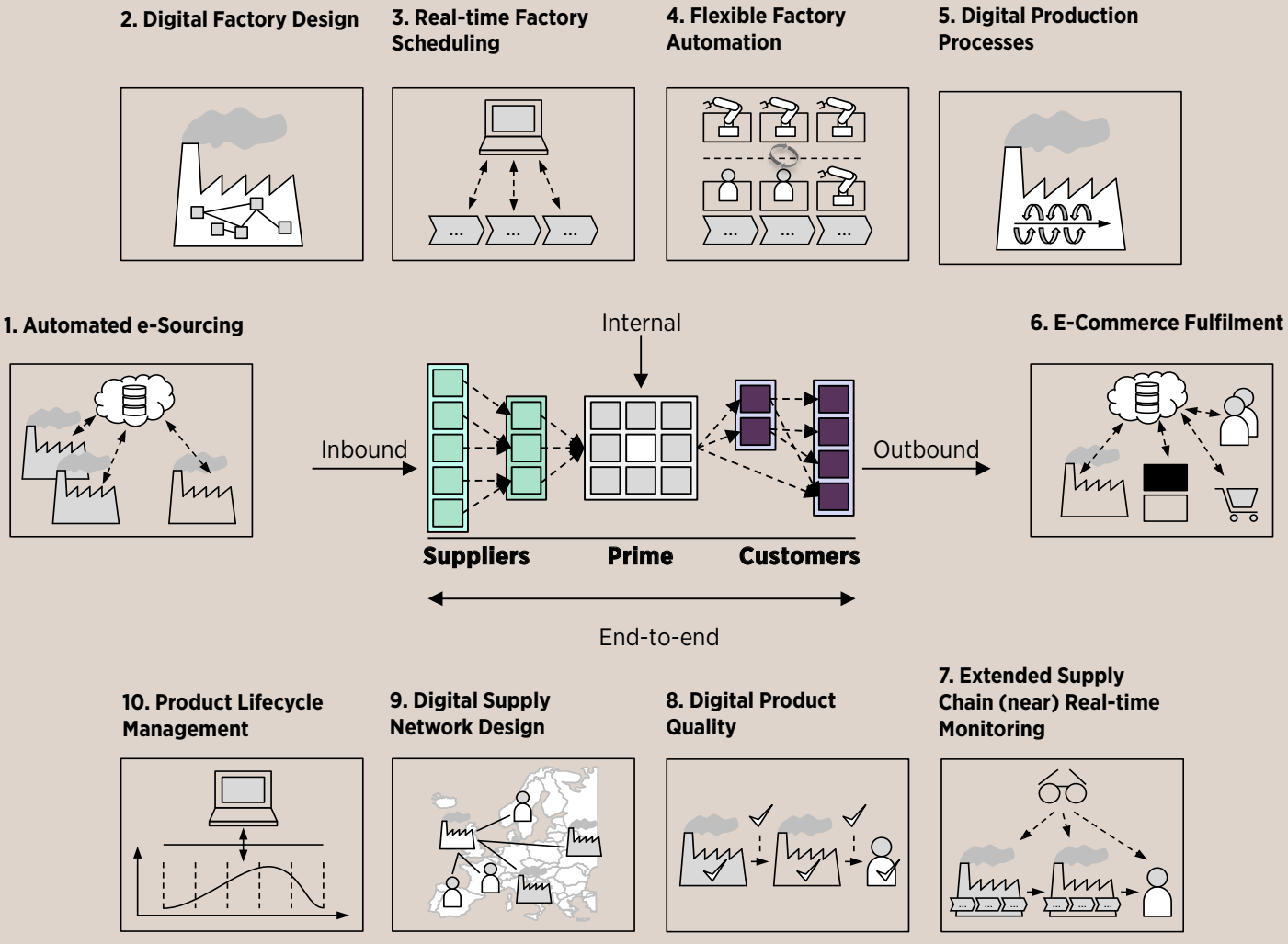
Flexibility versus connectivity

One of the conceptual and practical challenges for organisations is whether to build monolithic, enterprise-wide systems that can connect supply chains. Clearly, for many companies – particularly those with a history of M&A – it would require a huge act of organisational will, not to mention significant investment, in order to move to a common platform. And, would doing so actually deliver a sufficiently flexible and reconfigurable solution? Instead, companies are talking about developing a 'digital backbone' which can interface with other systems to provide more networked and flexible approaches to optimising the end-to-end supply chain. And this digital backbone is more than an IT system – it should embody the critical touch points and interfaces between organisations as well as the data architectures and analytics. It also signifies a cultural shift to digital.

The last leg

Using web-based systems to fulfil orders and manage the complexity of last-mile logistics is something that we have seen business-to-consumer companies do with impressive levels of sophistication and achieve corresponding levels of competitive advantage. For many large manufacturers there is still work to be

Digital scenarios



done in developing systems which can support product delivery to multiple points of sale and ultimately direct to the end customer. But the opportunities are clear and create a virtuous circle. By delivering better customer service you not only attract new customers (and retain the old ones) but you also get access to better customer data which in turn can improve both the product and the service you offer. There are also many efficiencies to be had from digitalising this last leg of the supply chain though better stock management and reduced transport costs.

Towards the digital supply chain

By breaking down the digital supply chain into ten distinct but connected scenarios against which companies can measure their performance and aspirations, we believe we have created a powerful framework which will help them develop their digital supply chain capabilities. The ten scenarios help to clarify thinking and develop a strategic approach to digitalisation which is both deliverable and will create maximum value for the company. The next step is to put the strategy into action.

ReMediES
RE-configuring MEDIcines End-to-end Supply

REMEDIES: reconfiguring UK pharmaceutical supply chains

The REMEDIES (RE-configuring MEDIcines End-to-end Supply) project, launched in 2014, is headed by GlaxoSmithKline with research led by the IfM's Centre for International Manufacturing. The project brings together key players in the end-to-end pharmaceutical supply chain, including major contract manufacturing organisations, equipment manufacturers along with regulators, knowledge transfer networks and healthcare providers.

The project, due to be completed in March 2018 has several technology based application projects underpinned by two platform projects: clinical trials supply chains, led by GSK, and commercial supply chains led by IfM.

For more information go to: remediesproject.com

Digital supply network design tools

CIM has developed a set of tools that enables us to map, analyse and reconfigure supply networks, taking an end-to-end supply chain perspective, where new data points provide visibility, assurance and alternative manufacturing footprint and product replenishment models.

For more insights into these tools and digital supply chains more generally, contact: Dr Jag Srai: jss46@cam.ac.uk

Join our new Digital Supply Chain Consortium

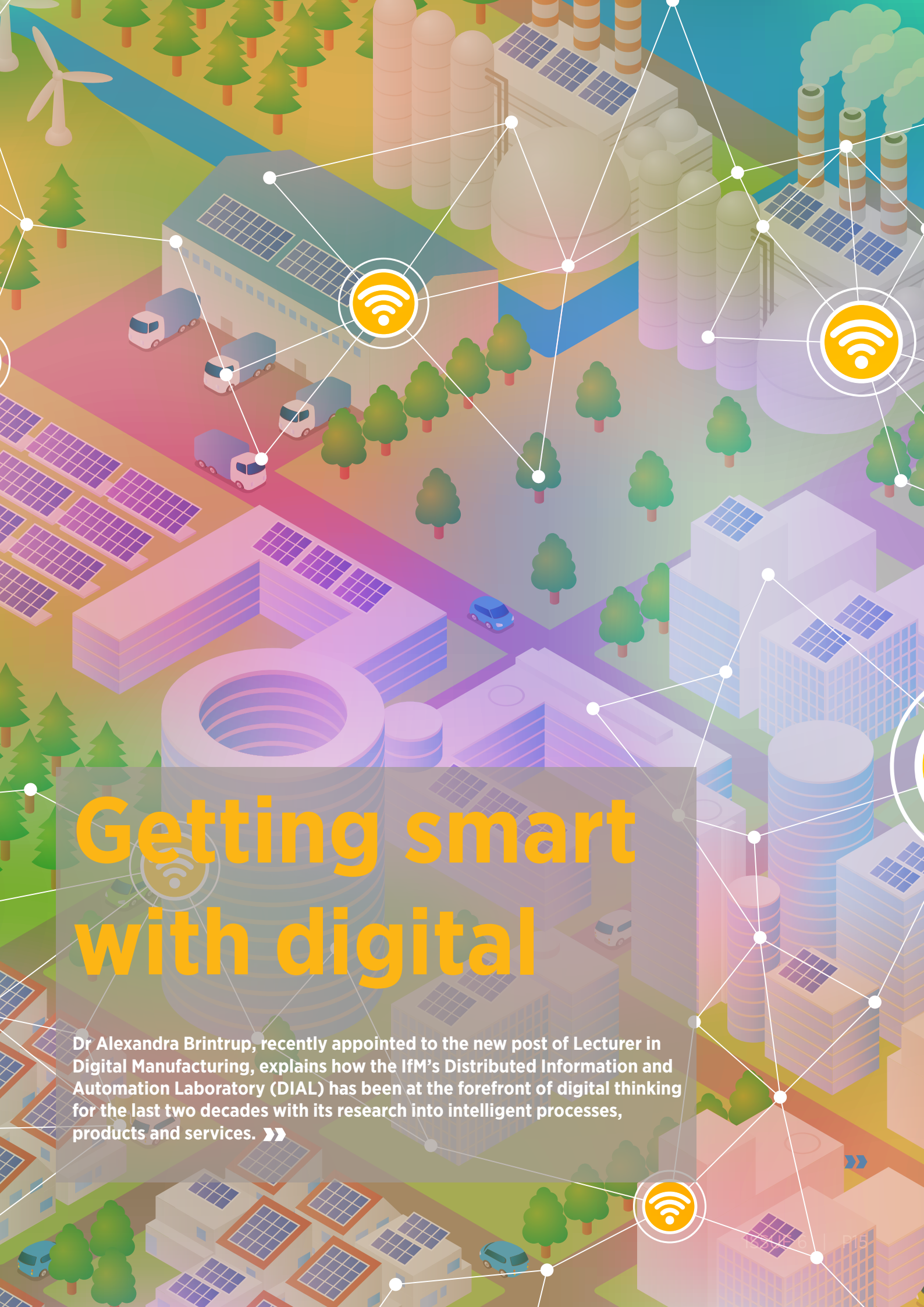
The ten digital scenarios have been used as a framework for thinking about digitalisation in a number of contexts, most recently with a group of thought leaders from some of the world's leading manufacturers: ABB, Caterpillar, Grundfos, GSK, IKEA, LEGO Group, Philips, Rolls-Royce and Wavin.

We are now setting up a pre-competitive consortium to:

- Facilitate sharing of experience and best practice amongst like-minded strategists.
- Define frameworks and tools to guide capability development in digital supply chain technologies and skills.
- Undertake pilot projects in member companies (optional) that develop and embed those capabilities to enable rapid digital supply chains transformation with real business impact.

For more information about the consortium go to:
www.ifm.eng.cam.ac.uk/research/global-networks/digital-supply-chains-consortium

If you are interested in joining this consortium, please contact: Paul Christodoulou, Principal Industrial Fellow, IfM ECS: pac46@cam.ac.uk



Getting smart with digital

Dr Alexandra Brintrup, recently appointed to the new post of Lecturer in Digital Manufacturing, explains how the IfM's Distributed Information and Automation Laboratory (DIAL) has been at the forefront of digital thinking for the last two decades with its research into intelligent processes, products and services. »

© Duncan McFarlane

Digital manufacturing may be at the forefront of everyone's mind right now but we've been working on it for more than twenty years. We research digitally-enabled, data-driven intelligent systems for industrial applications such as machinery, assembly, packaging, material handling and warehouse management. Our automation lab is central to trialling and experimenting with these technologies. While it's fair to say that the 'Fourth Industrial Revolution' has been underway for some time at DIAL, the speed at which technologies are now evolving and computational power is increasing means that digital manufacturing is now coming of age – and with it widespread innovation and disruption.

We explore how the combination of identification technologies, data capture and analysis can underpin supply chain transformation. By linking computer networks to sensors almost any information about an individual product or component can be obtained in real time – from its temperature to when, how and where it was made. But the value of data is in how it's used. Worldwide traceability of components and finished goods can be used to spot product failures, support new service offerings or meet legislative requirements. By analysing the information, identifying patterns and creating algorithms we can support the development of smart, flexible and responsive manufacturing systems that are more productive, more efficient and better at meeting customer needs.

Our research into digital manufacturing can be clustered into three main – and connected - strands: data capture, data analytics and management, and intelligent systems.

Getting better data

If data analytics are going to be useful, we need to make sure that we capture good quality information that will be susceptible to analysis. But the quality of the data is often problematic. It tends to arrive unstructured, in different formats, at different timescales and riddled with errors.

Data capture has been one of the primary focuses of DIAL research, initially through the development of RFID technology and increasingly through sensors to extract fine-grained traceability data from industrial environments. In 2000 DIAL became the Cambridge partner in the Auto-ID Labs, a group of labs from seven of the world's leading research universities which pioneered research in RFID. As a result of this work, we have taken part in several EU projects looking at how item-level data improves food supply chain and manufacturing traceability, asset condition monitoring, and recycling operations.

We are currently working on an 'intelligent data' concept to help manage uncertain and volatile information. For example, when pickers in a warehouse misplace products, data in the system becomes increasingly disconnected from reality, leading pickers to the wrong locations when items are required. Using a combination of real-time shelf data and algorithms, the quality of data in the system is tracked to help pickers avoid or discover and correct these misalignments. We are also looking at tools and techniques for cleaning, combining data from multiple sources, and evaluating data sets for purchase.

So much data – but what does it all mean?

Data analytics is the science of studying data to uncover and interpret hidden patterns and trends. Through data and analytics we aim to unify the whole manufacturing system, including the extended supply chain and associated logistics, as well, as external factors such as weather and market conditions. This will enable manufacturers to get a much clearer picture of how they interact with their external environment, improve their efficiency and achieve competitive advantage.

As supply chains become increasingly complex, involving many different companies often scattered around the globe, it has become more and more difficult for everyone in the supply chain to keep track of products and components. This creates risk. But a manufacturer often does not know about a disruption until it hits them or one of their tier 1 suppliers. While RFID and sensors can be helpful in improving visibility along the supply chain,

"Our aim, ultimately, is to connect every step of the manufacturing process across all phases of its lifecycle, and across its geographic and industrial boundaries, to create self-adapting, resilient manufacturing systems."

they only work if everyone in the supply chain is using them.
Sharing knowledge with partners about real-time problems across the inbound and outbound supply chain is one thing but there are other external factors which can disrupt supply – and for which publicly available data exists. We are developing a new analytical tool which combines data from, for example, social media and newsfeeds about things like weather and traffic conditions, with internally available supply chain delivery data. By combining this data we can find correlations that can help predict disruptions so that the factory can be continuously adapted to mitigate predicted changes.

'Big data' is one of the pillars of digital manufacturing but it is not a panacea. Applying analytical methods to manufacturing is often a 'bespoke' task which needs detailed knowledge of the context in which it is being used in order to be effective. This means new methods need to be developed from scratch for each application. But these industry-specific analytics are much more successful at identifying dependencies in supply chains than black-box, machine-learning approaches. Our aim, ultimately, is to connect every step of the manufacturing process across all phases of its lifecycle, and across its geographic and industrial boundaries, to create self-adapting, resilient manufacturing systems. To achieve this, we need to understand which analytics approaches work best under what circumstances.

Making systems smarter

Our early work in RFID led to the pioneering idea that data from individual objects could be identified and exploited using object identification and internet

'Big data' is one of the pillars of digital manufacturing but it is not a panacea.

technologies. Over time that concept has, of course, evolved into the 'Internet of Things'. During the last two decades, DIAL researchers have developed a number of IoT systems that allow companies to monitor their products in use. The EU PROMISE project, for example, was an IoT system that enabled products to be recycled back into production at the end of their lives and resulted in one of the first proof-of-concepts supporting the circular economy. Before that DIAL had been involved in the development of modular 'intelligent' manufacturing operations which challenged conventional 'command-response' approaches to controlling operations to more flexible strategies where machines 'talked' to each other to determine the best control approach. We worked with an AI technology – intelligent software agents – to give machines the thinking power we wanted to achieve.

We have also designed an IoT system that allows engineering assets to monitor their condition, talk to each other to create batch orders, and negotiate with selected suppliers to order parts autonomously. The system eliminated communication bottlenecks that arise from manually placed standard orders. We are currently pushing the boundaries of the IoT concept by developing a 'Social Network of Things'. This enables machines to report their 'status' into a common data-sharing platform analogous to a social network. By doing this we can create a single view of how the whole factory – or production network - is running. Algorithms that run on the social network platform look at these updates and determine the best maintenance plan for the factory or network as a whole, rather than maintaining every machine on a reactive basis.

How we capture and manage data and how we turn it into actions through algorithms – these are at the heart of what we do at DIAL. In recent years, we have seen our pioneering work tend towards the mainstream. Most large manufacturers have already embarked on the digital journey or take it for granted that they should. But our work is by no means done. Putting current thinking into practice is challenging enough but with technologies – and business models – changing so fast, we need to be exploring the next generation of digital thinking.

To find out more about Digital Manufacturing at the IfM, contact Dr Alexandra Brintup: ab702@cam.ac.uk

To find out more about DIAL, contact Professor Duncan McFarlane: dm114@cam.ac.uk

The importance of

in a digital world

IfM has just published a report, commissioned by BSI (British Standards Institute), which looks at the challenges for UK manufacturers of 'going digital' – and how standards and good practice can help the UK benefit from the digital revolution.

"If the UK does not respond within five years, it will lose out to overseas competitors: a concerted, urgent action programme is needed."

With many of the benefits of digital manufacturing arising from data gathering and collaborative working across supply chains, developing standards and open architectures will have a major part to play in making the digital future a reality. Currently, the definitions of key terms are hugely variable within sectors let alone the mechanisms for data capture and analysis. Providing standards and establishing good practice will be fundamental to a data-driven, digitally-connected world.

In order to help it develop a clear understanding of how it can best support manufacturers, BSI asked the IfM's dissemination arm, IfM ECS, to bring together a group of researchers from IfM, Cranfield University and the University of Nottingham. The aim of the project was to understand the opportunities, benefits, challenges and barriers for manufacturing and to outline the areas where standards and good practice can make a difference. The findings have been published by IfM ECS in a report: *Application of digital technologies to innovation in manufacturing*.

Benefits of digital manufacturing across the value chain

R&D: rapid prototyping and development; digitalisation of early discoveries

Design: quick and low cost design and redesign; using real manufacturing data at the design stage

Supply management: visibility, traceability, synchronisation and collaboration; effective connection to production stage

Production: precision, efficiency, integration; making information from vast amounts of data

Distribution: track and trace, localised demand management, rapid production response to demand changes

Service: full, real-time service condition monitoring and maintenance, with feedback to design and production

Disposal/re-use: in-service data to support remanufacture/re-cycle/disposal decisions

Other: significant sales and marketing benefits from affordable flexibility, personalisation and product/service tailoring.

The manufacturers' view

The team carried out a survey of UK manufacturers to build up a picture of how important they perceive digitalisation to be, where the benefits will emerge and what are the key competences needed across the value chain.

Increasing productivity was seen as one of the major prizes – both for individual companies and for the UK as a whole. Better customer service was also perceived to be an important outcome that would derive from a combination of digital capabilities: the personalisation of products and services, smarter and faster service, lower costs, higher quality and more widespread availability. These benefits were seen as arising from flexible manufacturing, 'mass customisation' and value chain optimisation.

Digital manufacturing holds out the prospect of many opportunities, therefore, but part of the challenge is being able to see which of them are most likely to be realised in the short and medium term – and which will create the most value for companies. The two opportunities which manufacturers scored most highly were flexible manufacturing and value chain optimisation. The benefits of these were linked – both relating largely to better control and management through greater visibility and access to information.

While the consensus is that digital manufacturing is going to play a vital part in supporting a sustainable manufacturing sector in the UK, there is also a recognition that moving towards digital manufacturing is slow-going. Why is that?

Two types of challenge

The report breaks down the challenges into two broad categories: organisational and technical or logistical. Among the organisational challenges there is a sense that although the cost of adopting digital technologies is a real and significant barrier, a lack of vision and the absence of a 'digital mind-set' amongst senior executives is also contributing to the problem. Skills shortages – a perennial problem for advanced manufacturing in the UK – are even more acute in this context. The digital world provides the infrastructure for companies to work together to deliver better solutions but the companies aren't necessarily ready to embrace more collaborative ways of working.

Risky business

Security is also a very real concern for many companies who recognise the risk but aren't sure either how to quantify it or address it. Other risks are associated with digital manufacturing. Increased automation, for example, means that robots and humans will be increasingly sharing work spaces. What are the health and safety implications of that scenario?

Distributed digital manufacturing also poses new questions for quality control. In the conventional manufacturing model, if production is outsourced to a third party

there are processes in place to monitor the quality of the product build. In the new digital world, the production company will receive a design and manufacture specification which can be easily adapted. Standards will need to be developed to ensure that any variance from the original specification is fully traceable.

The importance of standards

One of the main areas of challenge was around collaboration and data-sharing. This is an area which can be supported by the development of standards.

Currently, the use of standards for digital manufacturing varies enormously by sector. Aerospace, for example, already has a large number of standards relating to digital manufacturing but it's a very different story in other sectors. Many companies are only working to their own in-house standards at worst and at best to standards that relate to their own sector. Manufacturers feel that there is a lack of transparency and a need for greater integration.

Priorities

Of the top priorities for getting digital manufacturing moving, number one is skills and training. Second is developing new, digitally-enabled, service-oriented business models. Respondents also called for governance and processes which 'have vision' but which are also straightforward to implement. The other key area is developing appropriate cross-sector policies, regulations and light touch standards to support integrated supply chain development, particularly as there will be more requirements to include digital data management in contracts and procurement.

Interoperability vs security

If the potential benefits of digitalisation are to be realised, collaboration will be key. This will be enabled by the interoperability of both machines and data which, in turn, needs open systems, architectures and common languages and data platforms. These are not yet fully developed so companies are forced to develop 'bespoke' bridges or interfaces between machines. But this in turn reinforces the need for more secure and resilient manufacturing systems and cross-enterprise digital security systems.

What next?

Developing a set of standards is clearly going to have a critical role to play if the UK is to realise its digital potential. And the report emphasises the importance of the task: "If the UK does not respond within five years, it will lose out to overseas competitors: a concerted, urgent, action programme is needed." It calls for the development of a national steering arrangement for digital manufacturing standards – led by key industrial, academic and institutional stakeholders – to ensure that there is a clear vision in policy setting.

Read the full report at:
bit.ly/2fxddfS

The IfM academic advisory group consisted of Professor Duncan McFarlane, Dr Eoin O'Sullivan and Dr Jag Srai.

IfM ECS managed this project and published the resulting report on behalf of BSI and the Universities of Cambridge, Nottingham and Cranfield.

For more information contact:
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Professor Andy Neely, Head of the IfM and the Cambridge Service Alliance, suggests that industry leaders should focus on five key areas if they want to survive the journey to a digital future.

Manufacturing leadership in the age of digital disruption

It's a fascinating time to be involved in manufacturing. During the 1980s and 1990s many manufacturers were radically rethinking their approach to manufacturing. Total Quality Management, Lean Manufacturing and Business Process Engineering were all the rage. Then the focus shifted to incremental business improvement: becoming more productive, driving out waste and improving quality and responsiveness.

Now we find ourselves on the brink of a new manufacturing revolution. And revolutions always have implications for leaders. This new digital revolution raises three key questions: what might happen to manufacturing because of new digital technologies and processes? What are the implications of these changes for manufacturing leaders? Do you have the leadership capabilities you need to ensure the success and survival of your firm?

We are living in an age where customers are shifting their focus from products to solutions. Firms are increasingly selling on the basis of the outcomes they provide, rather than the outputs they produce.

In this context, there are five things manufacturing leaders need to do.

1. Get a new perspective

The first critical capability is being able to re-imagine the future and your own organisation's business model – in particular, its role in the wider ecosystem. We define an ecosystem as 'the wider network of firms and organisations that can or could influence the way the focal firm creates and captures value through the provision of a product or service'. This ecosystem perspective is important because increasingly competition is being played out not at the level of individual firms but at the level of ecosystems.

"Manufacturing leaders have to consider carefully how they build the capability to track and monitor the pace of technological development. And to do that, they need to understand its trajectory and potential."

Take the example of laptop manufacturers. Apple retains around 60 to 70% of the money paid for one of its machines, while HP keeps only around 30%. Why the difference? Well, Apple uses its own operating system, while HP relies on Microsoft. Microsoft has significant power in the ecosystem and is therefore able to capture a significant proportion of the money paid for the laptop. Apple, with its proprietary operating system, does not have to pay Microsoft (at least for the operating system), so it is able to retain more of the money paid. Clearly, Microsoft is not the only reason for the difference between Apple and HP's ability to capture value, but it raises an interesting question for HP - namely what should HP do about Microsoft? Should HP seek to compete with Microsoft, perhaps by developing its own operating system? Perhaps this would have been possible thirty years ago, but not now.

An alternative strategy would be for HP to work with one of the open source competitors to Microsoft. If HP invests in Linux and makes Linux a more appealing operating system and more and more people start using Linux, then Microsoft's power in the ecosystem decreases and its ability to capture value is eroded. Of course, if you follow this logic through, then you would argue that HP should collaborate with Compaq, Dell and Lenovo – its traditional competitors – as it is in the interests of all laptop manufacturers for Linux to become a more appealing operating system. When taking the ecosystem perspective, you have to think much more broadly about the role of different organisations and in which domains they are competitors and in which they are collaborators.

2. Keep learning

Beyond broader strategic thinking, the second leadership implication of the digitalisation of manufacturing is the need for manufacturing leaders to understand and keep track of digital processes and technologies. It is clear that their rate of development is rapid. Everyone talks about Moore's Law, in which the number of transistors in a dense integrated circuit doubles approximately every two years. Think just of the developments in mobile phones over the last twenty to thirty years. The first mobile phones that many of us saw were 'bricks', small suitcases that carried both the phone and the associated battery. They are virtually unrecognisable as the forebears of today's smart phones. It is not just the speed of technological development, but also the range of capabilities that are bewildering. Manufacturing leaders have to consider carefully how they build the capability to track and monitor the pace of technological development. And to do that, they need to understand its trajectory and potential.

3. Keep innovating

The third implication of digitalisation is the need to innovate constantly. Unless your firm keeps pace with the technological innovations made by others you will fall by the wayside. A particular challenge here is that digital disruption in the business to consumer world is shaping

This is an abridged version of an article that first appeared in the *Manufacturing Leadership Journal*, June 2016

"We do not live in a world of 'punctuated equilibrium', periods of stability that are occasionally shocked through innovation. Instead the process is continuous."

and changing consumer expectations and attitudes. We are now used to seamless customer experiences - the apps on my iPhone are so easy and intuitive to use - that I constantly question why many of my professional interactions are not so straightforward. Keeping pace with this level of innovation is crucial for manufacturing firms in the 21st century.

4. Keep collaborating

A fourth implication arises from the increased emphasis on collaboration and communication. Particularly with digital technologies and processes, it is rare that a single firm has all of the capabilities needed to deliver them successfully. Hence firms need to partner much more directly with a diverse range of different companies and organisations. The intention is to pool capability across traditional organisational boundaries.

5. Keep evolving

A fifth and final implication is the need to evolve constantly. Clearly this links back to the issue of innovation, but the point about constant evolution is that we do not live in a world of 'punctuated equilibrium', periods of stability that are occasionally shocked through innovation. Instead the process is continuous - organisations are constantly striving to look for new and better ways of helping deliver the outcomes their customers want and nobody can afford to stand still.

Do you have the capabilities needed to ensure the success and survival of your firm?

Manufacturing leaders now need to ask themselves and their leadership teams some tough questions. Digital disruption raises five critical issues: thinking strategically at the level of the ecosystem; keeping track of technological development given its pace and scale; innovating using technology - breaking old paradigms and barriers; collaboration - building relationships and pooling capabilities across organisations; and constant evolution.

To audit your own organisation's manufacturing leadership capabilities I would recommend asking yourself the following questions:

- Do we have the balance right in our strategic discussions – are we thinking about our strategy in parallel with the broader ecosystem strategy?
- How good are we at keeping pace with technological developments, understanding changes in both manufacturing processes and enabling technologies that might help us innovate our business model?
- How clearly have we defined our digitalisation strategy, considering how manufacturing technologies and processes will allow us and our ecosystem partners to innovate our business models so we are better able to deliver the outcomes our customers want?
- How good are we at partnering with others, capitalising on their strengths and defining win-win collaborations for all involved in the ecosystem?
- Do we constantly question our existing approach, incrementally innovating and improving it so that we are forever pushing back the boundaries of the possible?

If you can answer these five questions positively it seems you have many of the manufacturing leadership capabilities in place that will be needed to survive and thrive in an age of digital disruption.

For more information about the Cambridge Service Alliance contact Professor Andy Neely
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What does it all mean? Understanding the digital lexicon.

When people talk about digital manufacturing – or aspects of it – they use a number of terms sometimes interchangeably. But there are distinctions between them. Here are some useful definitions.

Additive Manufacturing (AM) or 3D Printing

A portfolio of manufacturing processes. In many of them, layers of powdered material are bonded to create a shape specified by a digital file. Other processes are based on an extrusion of molten filaments of polymer or light-induced hardening of a liquid. Materials such as plastic, metal, composites and even food can be produced in this way. Additive manufacturing means that complex items can be produced in single units at the point of sale/need.

Big Data

The rapidly decreasing cost of sensors, data storage and computing power means that manufacturing data is now available in vast quantities. But these data sources are often scattered, large, dynamically changing, and in varying formats – all of which makes analytics difficult. This kind of data is often referred to as 'big data' – and there is a rapidly evolving array of methods and tools for extracting business intelligence from it.

Cyber-physical systems (CPS)

These are smart networked systems with embedded sensors, processors and actuators, designed to sense and interact with the physical world (including human users), and support real-time, guaranteed performance in applications.

Industrial robots

Industrial robots are becoming more intelligent and pervasive as a result of advanced digital technologies. Recent innovations include: construction robots that perform operations such as drilling, building demolition and dismantling; agricultural drones that monitor fields, spray fertilizers and pesticide, and robots that are used in asset management such as drones that inspect wind turbines.

Robots are also being used more collaboratively in the workplace with robots learning how to carry out complex operations from human workers. A related innovation has been the use of gaming technologies for robots to monitor and replicate human motion in carrying out complex tasks.

Industry 4.0

The 'four' in Industry 4.0 refers to the 'fourth industrial revolution', driven by advances in data and computation. The first three industrial revolutions refer to the changes brought about in turn by steam engine power, electric power and automation.

Originating in Germany, Industry (or Industrie) 4.0 emphasises the factory aspects of digital manufacturing. It is defined as the use of an integrated computer-based system comprising simulation, 3D visualisation, analytics, and collaboration to integrate product and process definitions simultaneously across the entire value chain.

Internet of Things (IoT) and Industrial Internet of Things (IIOT)

Where network connectivity and computing capability extends to objects, sensors and everyday items allowing these devices to generate, exchange and consume data with minimal human intervention. Within the manufacturing sector, the term Industrial IoT (IIoT) is used to describe systems that support the production and services of products.

Virtual and augmented reality

Virtual reality (VR) is an artificial, computer-created environment that allows a user to immerse themselves in and interact with a virtually created world. Augmented reality (AR), on the other hand, blends the real world with the virtual world, for example by projecting a digital image in a room. While AR users can easily distinguish the virtual from the real world, with VR this is harder thanks to the completely immersive nature of the experience.

VR/AR has found several applications within the manufacturing sector such as product design, skills training, maintenance and repair operations.

A disruptive influence

Stewart McTavish was supervised for his MPhil at the IfM by Dr Tim Minshall, Reader in Technology and Innovation Management and Head of the IfM's Centre for Technology Management. Stewart is Director of ideaSpace, Cambridge's hub for early stage innovation which has just opened a third site on the Biodemedical Campus at Addenbrooke's. Stewart and Tim met to reflect on how Stewart came to be running ideaSpace, how he has seen his vision for it become a reality, what he plans to do next – and how he invented crowdfunding.

Stewart McTavish, Director, ideaSpace

Tim: Remind me what were you doing before we first came across each other.
Stewart: I read Computer Science and after graduating started a website design business. One of my first projects was for Cambridge University Entrepreneurs (CUE). Pretty soon I was Vice-President and then became President. We initially met when I approached you about creating an online teaching / training portal for entrepreneurs which you had done an early version of for the Cambridge Entrepreneurship Centre.

One of the issues from that time was that CUE was thinking about how to accommodate the changing attitudes of the students, who were becoming increasingly concerned with making the world a better place. This meant that business plans with huge commercial potential were being judged against ones which were good for the planet.

Yes – Nicky Dee (who did one of the first PhDs on venture capital targeted at sustainability and went on to become a researcher with the IfM's Centre for Technology Management) had already started that process when I joined. We ended up with two separate competitions judged on different criteria: one was about commercial impact and the other triple bottom line (economic, environmental and social) impact. But both were about their potential to scale.

So how did the MPhil come about?
One of my main tasks as CUE president was to raise funds. Sponsors would say 'we'd love to give you some money but what exactly is it for?'

The University had embarked on its relationship with MIT (the Cambridge-MIT Institute) and in 2004 CUE hosted the Global Start-up Workshop. As we were one of the first university business plan competitions in Europe, we were perceived to be the leading UK student entrepreneurship society at the time. At the conference we met a number of universities that were trying to set up a student entrepreneurship society but didn't know how.

Having sponsored Global Start-up Week, the Cambridge-MIT Institute asked us to help get student societies going in other universities. I pitched them the idea that we could do this but to do it properly we needed a better understanding of the role and impact of CUE. To do that, I needed to do some research. They agreed to fund the work and I discovered that I could do a research MPhil at the Engineering Department.

The headline finding from my MPhil was that these kinds of competitions create a lot of value and should be continued. I compared the Cambridge and MIT business plan competitions and in both cases, for every pound given out in prize money about £100 of company value was created by the winners.

"I compared the Cambridge and MIT business plan competitions and for both of them for every pound given out in prize money about £100 of company value was created by the winners."

Tim: What happened next?
While I was doing my MPhil, I started a company called mo.jo. The idea started with a friend who developed a technique for predicting women's fertility by measuring their basal temperature more accurately than had been previously possible.

This was a brilliant idea and one which women loved and wanted to buy. The problem was that when we talked to potential investors they were predominantly men in their fifties and sixties who couldn't connect with fertility problems. So we had all these people who wanted to buy the product and all these people who weren't going to fund it. Then we thought if you asked for £100 from every woman who wanted it, you'd be funded. And that was the start of mo.jo.

At the time, we couldn't figure out how to legally enable the funding element to be any more than a donation in the UK so in the meantime we set up a website where people could discuss ideas together and build teams. We built and sold that as a service to large organisations who were trying to engage with innovative ideas.

So this was almost the beginning of crowd-funding?
Kind of, we thought of it as "threshold based public funding". An early competitor was The Point which people were using to group together to buy consumer deals. The people running it noticed this behaviour and relaunched as Groupon! We could never figure out a pathway to make the funding part of the idea work. So we ran mo.jo for long enough to give our investors a decent return and we decided as a team to disband. At which point I was starting to think about new potential companies but my wife Rosie (a MET alumna) had a suggestion. "We are going to start a family. You need to get a job that involves you being at home more than one day a month."

Hermann Hauser (one of the investors in mo.jo) had just given the University money to build the Hauser Forum and it was recruiting for a manager to run this new thing called ideaSpace and a couple of people suggested I should consider it.

At the time there was a vague concept that ideaSpace was going to be a traditional incubator. I had an almost allergic reaction to the idea that the University should set up and run a traditional incubator. Cambridge already had the St John's Innovation Centre and the incubator on the Science Park. Having started my own company I felt very strongly that what was missing from the Cambridge ecosystem was support for founders who may not yet know what their company is. When they interviewed me I pitched my idea and explained my thinking. Five days later I got a call saying they wanted to give me and the idea a go.

How would you describe what you are trying to do at ideaSpace?
We focus on the people who are creating new ventures rather than the ventures themselves. It's about creating a space shared by the entrepreneurial and University communities. When a lot of institutions support entrepreneurship they tend to attach all sorts of metrics to that support which has the effect of pushing people down a very narrow channel where they are not given the freedom to try things. And that's often a result of the funding model. If an institution or government is providing the funding they will want to be able to demonstrate how effective it is. We are paid

"We focus on the people who are creating new ventures rather than the ventures themselves. It's about providing this third space between the entrepreneurial community and the University."

for by our members – and they seem to like what we do.

The other thing that's different about us is that even though we are a part of the University we are not just for the University. When I last looked 30% of our founders had no relationship with the University except for their membership of ideaSpace. But they are often people who are on their fourth or fifth company and they provide valuable advice or suggestions to the less experienced members. Belonging to ideaSpace is all about learning to be a founder and part of that is meeting other people who have been – or are currently – doing that.

Is it fair to say that the conventional incubator model kept being pushed because it's easier for people to get their heads around if they hadn't had any entrepreneurial experience themselves?
I agree. Plus I think our model is harder to manage than a more conventional one. We were saying we will use a space to bring together a community and good things will happen. There was plenty of scepticism to start with. But ultimately we have created the thing I wished had existed when I started my first company. I basically designed if for me to begin with but it has grown with input from all our members and supporters over the years.

And your vision has been proved right.
Our original funding was to last five years after which the expectation was that we might be absorbed into another part of the University. But by the end of five years we were self-sustaining. So, so far so good.

It's also fair to say that ideaSpace fills a gap in the Cambridge ecosystem. It's not trying to compete with Cambridge Enterprise but do something genuinely different.
As part of my MPhil I looked at the historical evolution of Cambridge entrepreneurship and we designed ideaSpace to help accelerate the next phase of the ecosystem evolution. But ideaSpace is only possible because other elements of the ecosystem – like Cambridge Enterprise – are already here.

So ideaSpace West and ideaSpace City have been hugely successful. You have just opened ideaSpace South at the Biomedical Campus on the Addenbrooke's site. The model is clearly working. What next?
As part of the process of making ideaSpace a permanent part of the University we were asked to come up with a 20-year strategy. When we looked at the journeys of founders they tended to have had three broad starting points: an invention or discovery, a particular set of experiences or capabilities they explore, or a market or societal opportunity that they wanted to address. In the University for the first type of entrepreneur there's Cambridge Enterprise. For the second, there's ideaSpace. But there isn't a Cambridge programme that helps people engage on a non-research basis with societal challenges.

There are initiatives like the Centre for Global Equality

and Humanitarian i-teams but they tend to look at how you can take new technologies and innovations and apply them to a problem rather than understanding the problem first and then finding or developing the technology to solve it. So that's what we are working on now.

The working title is the innovationLab (because we lack imagination) and we are building new partnerships in Africa, East Asia, India and South America. With these culturally diverse perspectives we aim to better understand what the infrastructure for a fair global society could look like.

About ideaSpace

ideaSpace started in 2009 at The Hauser Forum on the West Cambridge site. ideaSpace City was opened in 2013 and ideaSpace South opened in August at the Biomedical Campus on the Addenbrooke's site. The sites were chosen to ensure that ideaSpace members are always within walking distance of some of the world's leading researchers, thinkers, inventors and innovators.

ideaSpace members are creating new business models which have the potential to benefit millions of people within a few years of start-up.

ideaSpace is part of the University of Cambridge and shares its commitment to making a meaningful contribution to society. Our members do not need to belong to the University but they must share its aspiration to generate significant social and economic benefits.

www.ideaspace.cam.ac.uk

ideaSpace: where companies are born digital

Many companies have started their lives at ideaSpace and many of them are using digital technologies. Recent success stories include:

GeneAdviser is an online ordering platform for clinical genetic testing set up by a team of Cambridge scientists and geneticists. It provides an independent platform for clinicians to quickly compare and order specialist genetics services, advancing the uptake of genomic medicine into the healthcare market.

Healx uses advanced data analytics, including machine learning and computational biology techniques, alongside scientific literature analysis, to identify novel drug applications for rare diseases that afflict some 350 million people worldwide. Their unique model engages directly with patient advocacy groups, allowing them to lead the way in personalised healthcare for rare diseases.

Dr Rob Phaal, from the IfM's Centre for Technology Management, is a world-leading expert on strategic and technology roadmapping.

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- **The Cambridge Tribology Course: friction, wear and lubrication**
  Intensive three-day course presenting an overview of the field of tribology.
- **Evaluating and selecting technology-based projects**
  How to evaluate and choose the right projects when useful data is scarce.
- **Global supply chains**
  Achieve competitive advantage by developing advanced supply chain capabilities.
- **Making the shift to services**
  Transform your organisation from a product-based business to one that can also provide its customers with services and solutions.
- **Manufacturing analytics: aligning KPIs and strategy in an era of big data**
  Use the new analytics to improve the way you measure performance.
- **Manufacturing footprint strategy**
  Understand what to make and what to buy, where to locate your plants and partner plants, and how to design your global network to drive synergy.
- **New tools for sustainable businesses**
  Learn to analyse how value is created in your business and how to use that knowledge to enhance your competitive advantage.
- **Product design to transform your business**
  Learn to design (or re-design) the products and services your customers really *want.*
- **Realising the potential of early-stage technologies**
  How to encourage innovation, spot the ideas with the most potential, choose the right business models to exploit them, identify and manage risks and protect your intellectual property.
- **Strategic roadmapping**
  A step-by-step guide to using this powerful tool for planning technology capabilities that support your strategic goals.
- **Technology and innovation management**
  Learn how to manage and exploit technology investments and opportunities.
- **Technology intelligence**
  How to find out about new technologies quickly and understand the threats and opportunities they present for your business.
- **Visual approaches for strategy and innovation management**
  Explore and apply the fundamental principles of visual design for presenting management information.

Many of these courses can also be run in-house, tailored to your organisation's needs.

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