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Foresight

The factory of the future

Future of Manufacturing Project: Evidence Paper 29

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The factory of the future

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Introduction

This report examines the trends and factors that will shape the 'Factory of the Future'. The study focuses on sectors most important to the future of UK manufacturing and exports including, aerospace, automotive, machinery & fabrications and pharmaceutical & biopharmaceutical manufacturing.

After a review of published material describing similar studies being undertaken around the world, a set of seventeen questions were identified. These were used in structured interviews with senior executives of large companies, SMEs and researchers.

The findings were evaluated and key issues identified and discussed. The emerging mental model for the Factory of the Future is of centres of creativity and innovation embedded in effective networks of relationships, where capable and talented people use world-class technologies and processes to create new ways of adding value. This is a world of challenge, interest and excitement.

Summary

This study examines the trends that will shape and influence the ***'Factory of the Future'*** (FoF). It study will seek to identify:

- Where work is underway to examine the likely nature of the FoF and the main findings of this work.
- Factories currently regarded, internationally, as examples of best practice.
- Sectors where traditional views of a factory are most likely to be challenged.
- Developments expected in the physical arrangements of the FoF.
- How demand for personalisation of products affect the viability of the current model of a centralised factory relying on economies of scale.
- Technological trends or emerging technologies most likely to have a significant impact on the factory of the future.
- The role the workforce will play in the FoF.
- How process and product innovation is shaping the FoF.
- Other trends shaping the FoF (including sustainability, management practices, communications infrastructure, and value of proximity to customers, resources & transport networks).
- How views on the FoF vary between nations including China, US, Germany, South Korea, Japan and Singapore.

There is a strong demand for UK manufacturing to evolve in order to maintain international competitiveness and promote economic, social and environmental sustainability. The concept of the Factory of the Future (Factory 2050) provides a focus for manufacturing research roadmaps and will support further initiatives in other industrial sectors, all of which will contribute to ensuring these targets are met.

It focusses on sectors most important to future UK manufacturing and in particular UK exports. This brings in scope aerospace, automotive, fabricated products, machinery & equipment, chemicals, pharmaceuticals and bio/life sciences but places out of scope food, beverages, tobacco and publishing & printing.Europe, the USA, Japan, and interviews with other experts in the area

Summary continued...

The authors of this report were asked to include some recommendations for a UK response to the findings emerging from this study. Recommendations were made in eight inter-related areas concerned with the development of:

- More integrated and optimised supply / value chains and the standards that will enable them.
- Stronger long term collaborations between manufacturing companies and UK Universities to improve innovative thinking and the rate and uptake of R&D.
- A focus on both organisational and technical innovation, each feeding off each other.
- A systems view of the FoF, integrating people, organisation and technology.
- The design of agile, reconfigurable factories and extended enterprises.
- A rebalancing of the regulatory framework to enable the rapid construction of the next generation of factories in Europe and to permit manufacturing innovation in particular for life sciences.
- A clear and sustainable UK vision that factories of the future are centres of creativity and innovation, embedded in effective networks of relationships, where talented people use the latest technologies and processes to create new ways of adding value.
- Recognition that this will require a significant cultural shift both in how manufacturing organisations operate and in how they are perceived.

The study was based on a review of published material, structured interviews with senior executives from large companies and SMEs in Europe, the USA, Japan, as well as interviews with other experts in the area.

Some might argue that this list is probably not particularly surprising. However, we take a different view. Thus, if manufacturing companies in the UK were able to deliver the changes listed above, it would represent a major cultural shift, with the potential for improved innovation and competitiveness. Such changes would make people want to work in manufacturing, thereby attracting, developing and retaining the talent that is needed.

The review of previous work indicated considerable consensus on the trends and 'hot topic' themes shaping the future of manufacturing and industrial competitiveness. These include:

- Sustainable manufacturing including recycling and minimisation of waste.
- Introduction of green manufacturing technologies.
- Improved and simplified ICT including simulation/modelling tools for design, processes and manufacturing systems.
- Automation is a given; advanced robotics and intelligent manufacturing systems.
- Next generation materials with novel functionalities.
- Manufacturing enterprise systems and responsive, distributed design and production systems.
- Straightforwardly reconfigurable facilities and systems, that are agile and capable of fast ramp up as demand grows.
- The importance of talented, well-educated and creative people.
- Business models that focus on creating, operating and exploiting more integrated value chains.

In the interviews these themes and topics represented many of the trends that leading industrialists expected to see materialise within the FoF.

Perhaps the biggest surprise in the study was that there are in fact few major surprises. The supply chain was cited as extremely important but few had the opportunity to become involved in supply chain activities or had control of the complete supply chain for major products. There is a major opportunity to integrate and manage supply chains as value systems.

Similarly interviewees recognised the importance of visiting examples of best practice and the relevance of looking at best practice in other sectors but, with the exception of aerospace and automotive, the majority had focussed on best practice within their own sector.

The technologies required in the FoF are largely already available and are perhaps commodities diffusing rapidly across the world; exploiting these technologies to enable new products is what brings competitive advantage. The FoF will make better use of the technologies, whilst the supporting software and systems will make the technologies easier to access, monitor and control. Adaptive control will tend towards self-learning and there will be emphasis on fast ramp up and the transition from manual manufacture of first prototypes, through semi automation to fully automated systems. The 'Easily Reconfigurable Factory' was identified as a highly desirable facet of the FoF.

Themes previously promoted such as 'Factory on skids', 'Micro Factory Retail Centres' and the '5-day car' do not appear high on the radar for the Factory of the Future. The general trend is towards smaller, manageable, clean, well-organised, highly flexible factories that contain updated but traditional technologies that can be quickly ramped up to meet volume and deliver 'highest quality' to changing customer and market requirements.

Factories will tend towards flatter management structures with a more highly skilled and IT literate workforce focusing more on product design, optimisation, monitoring and controlling of processes. This will lead to de-skilling of traditional process and craft skills such as machining and welding, whilst re-skilling in the new advanced technologies, the soft skills in managing operations effectively, and understanding the customer. Craft skills, however, will remain essential in the finishing of premium and luxury goods.

One striking factor has been the emphasis of interviewees on the importance of the value chain. The ability to create and operate a value chain that collectively delivers a unique value proposition to the user market is seen as the most significant source of future competitive advantage. It is seen as very important that businesses have this understanding and the skills and capabilities to both create the value chain as an integrated system – the key step – and to operate it. Operation of the value chain – essentially the co-ordination of the supply chain members to operate a cross-organisational business process – is seen as complex but less challenging than creating it. Lean supply chains balancing global and local are a given, but lean must be exquisitely balanced with resilience, especially in regulated industries, because the customer does not directly see or buy lean. Materials management and resource conservation are also critical in the design and operation of the supply chain as reflected in the Japanese concept of 'Monozukuri'.

A further opportunity arises through capitalising on the largely untapped potential for collaboration between manufacturing companies and UK universities. In this view, manufacturing companies have needs for the latest thinking, for new ideas and for innovation (and not just in engineering and technology). Universities are perpetually refreshing their skills and capabilities through young talent with aspirations, and have thousands of talented people potentially looking for operational and R&D opportunities. Whilst there are some excellent role models who manage these relationships well, there are opportunities to bring these communities together in real and substantial long term relationships that benefit all parties and the UK overall. Engaging young fresh thinking in the definition of the way forward for manufacturing is also important. This also involves much more than a more traditional view that universities simply provide the next generation of well-trained graduates.

The potential game changers have been identified primarily as advances in materials enabled by materials science. This includes graphene and nano materials, new surface coatings, new composite materials and resins including bio-composites, and biologically derived and natural, living materials. Perhaps just as important however are game changers in our vision for the factory of the future. This study is clear – the FoF will require world class organisation, people and technology working to find creative and innovative ways of adding value. The national ecosystem needs to support this.

The emerging mental model for the FoF is of centres of creativity and innovation, embedded in effective networks of relationships (for example with suppliers and universities) where capable and talented people use world-class technologies and processes to create new ways of adding value.

1. Review of previous work

- Where is work underway to examine the likely nature of the factory of the future? What are the main findings of this work?
- Which factories are currently regarded, internationally, as examples of best practice and why?
- How do views on the Factory of the Future vary between nations? Key comparisons: China, US, Germany, South Korea, Japan and Singapore.

Drawing on website information and publicly available government documents from selected countries or regions of interest, this summary provides an overview of international strategic manufacturing research and innovation initiatives and related priority research activities in Europe, Japan, China, USA, Germany, South Korea and Singapore. It particularly focusses on the manufacturing research trends/themes that are set to influence the shape and nature of the FoF.

While not providing a comprehensive or systematic analysis of international manufacturing research systems, which can be found elsewhere [O'Sullivan, 2011], the observations outlined below show significant consensus on many of the trends and 'hot topic' themes shaping the future of manufacturing and industrial competitiveness.

Europe

The Factories of the Future research programme was launched by the European Factories of the Future Research Association (EFFRA) in 2009 as one of three Public-Private Partnerships (PPP) included in the EU Commission's economic recovery plan (2008). It served to address the challenges and opportunities for manufacturing future products and economic, social and environmental sustainability. Expected to deliver results in 2013-14, the programme focussed on the following research and innovation priorities identified in its strategic research roadmap (2009-2013):

- Sustainable manufacturing (people friendly and eco-friendly factories).
- ICT-enabled intelligent manufacturing (smart factories, digital factories, virtual factories).
- High productivity manufacturing (adaptive production equipment, high-precision manufacturing, zero defect manufacturing).
- New materials in manufacturing (materials efficiency, manufacturing processes for new high performing materials).

EFFRA launched (Nov 2012) a strategic multi-annual research roadmap for the 'Factories of the Future 2020', which supports the proposed continuation of PPP activities under the Horizon 2020 framework programme for Research and Innovation. It will also form the basis for research call topics and the overall direction of research in the 'Factories of the Future' (investing EUR 7 billion). Aimed at transforming European manufacturing sectors, the 2020 roadmap identifies six research and innovation priorities (Advanced Manufacturing Processes, Adaptive and Smart Manufacturing Systems, Digital Virtual and Resource Efficient Factories, Collaborative and Mobile Enterprises, Human-Centred Manufacturing and Customer-Focussed Manufacturing) centred on realising the Manufacturing Vision 2030 under four long-term paradigms:

- Factory and Nature
- Factory as a Good Neighbour
- Factories in the Value Chain
- Factory and Humans

Under the FoF roadmap framework, a coordinated research and innovation effort will address the manufacturing challenges and opportunities by deploying the following technologies and enablers: advanced manufacturing processes and technologies (including photonics), mechatronics for advanced manufacturing systems (including robotics), information and communication technologies, manufacturing strategies, knowledge workers, modelling, simulation and forecasting methods & tools.

PARIS - JUNE 21:
GEnx jet engine (turbofan) rear view at Le Bourget Air Show on June 21, 2009 in Paris, France.
GEnx engine is one of the options chosen by Boeing to power its 787 and 747-8 aircrafts.

Image Credit
Olga Besnard / Shutterstock.com

Japan

As part of a cohesive "innovation program" (noting the broader international agenda of Japan compared to Germany and USA, which focus on national economies) the focus of themes emerging from the 4th Science and Technology Plan 2011-2015 and Japan's science and technology (S & T) strategic roadmap and linked manufacturing competitiveness strategy include:

- Emphasis on the implications of demographic changes and 'social issue targets': prioritisation on new production technologies for an aging workforce and manufacture of new products for an aging population.
- Sustainable growth, green innovation and societal development, in particular 'whole systems approach' addressing sustainable manufacturing, energy conservation and eco-friendly, low carbon, resource-efficient, smart manufacturing technologies.
- 'Monozukuri' (making things as perfectly and efficiently as possible while respecting nature in terms of both materials and the environment) features prominently, emphasising reduction in resource consumption, less waste and minimal negative environmental impact.
- Emphasis on actions to improve profitability via the prevention of technology leakage and strategic standardisation supporting reformation of business models.
- Other priority areas include rare metal substitution, new aeroplane/rocket design, next generation robots/technologies for changing demographics (especially aging), visualisation technologies and integration of IT systems with production technologies, nanotechnology ('Green Nanotechnology', 'Nano-Bio', 'Nanoelectronics'), biotechnology, medical technologies, advanced measurement and analytics technology and next generation fuel batteries.

South Korea

Relevant themes emerging from Korea's 2nd National S & T Basic Plan 2008-2012 (the 577 Initiative) [noting 3rd Plan 2013-2017 is due] and 'Vision 2025' includes:

- Seventeen future sectors identified under three broad headings: green-tech, high-tech convergence technologies and value-added services.
- Emphasis on green innovation, particularly green ICT e.g. smart grid, cloud computing.
- Focus on industrial and knowledge based technologies, particularly in ICT, life science, advanced materials, alternative energies, the environment, mechatronics and basic science.
- Focus on upgrading seven flagship strategic capabilities and supply chains: automobiles, shipbuilding, semiconductors, steel, machinery, textiles/materials; including establishing regional cluster networks, regional institutions and public and private sector funding.

China

Themes emerging from China's 12th Five Year Plan (2011-2015), the 'MLP' (Medium- and Long-term National Plan for Science and Technology Development 2006–20), the 'Innovation roadmap 2050, the Chinese Academy of Sciences roadmap for Chinese S & T development beyond MLP and China's policy of *'zizhu chuangxin'* (indigenous innovation) include:

- Key trends: globalisation, ICT integration, 'intelligent' manufacturing systems and resource efficient production.
- Emphasis on development of seven strategic emerging knowledge-based industries: new-generation IT, high-end equipment manufacturing, advanced materials, alternative energy, energy conservation and biotechnology.
- Focus on 'advanced manufacturing technologies': advanced materials, 'green' resource-efficient and eco-friendly manufacturing, digital and intelligent design & manufacturing, along with design, production and testing technologies for manufacturing at the micro- and nano-scale, advanced automation/intelligent service robots and service life prediction technologies.
- Development of eight socio-economic systems, including: a 'sustainable energy and resources system' and 'new materials and green manufacturing system'.
- Twenty-two strategic technology areas, including manufacturing-related topics such as: 'green manufacture of high quality elementary raw materials', synthetic biology and nanotechnology.

USA

Recent US policy studies, initiatives and summits related to manufacturing research indicate a high degree of consensus on priority manufacturing research challenges and research domains captured in proposals outlined in the 'President's Plan to Revitalize American Manufacturing':

- Sustainable manufacturing and manufacturing of green technologies.
- Simulation/modelling tools for design, materials process and manufacturing systems.
- Nanotechnology applications to the production/process technologies.
- Bio-manufacturing, particularly regenerative medicine and synthetic biology.
- Advanced robotics and cyber-physical manufacturing systems including intelligent manufacturing systems and strategic standards development.
- Next generation materials with novel functionalities.
- Manufacturing enterprise systems and responsive, distributed design and production systems.

Germany

Manufacturing research priorities highlighted within the German 'High Tech Strategy 2020' and identified in other research-related foresight exercises include:

- Energy, environmental and sustainability manufacturing including the development of international standards and resource efficient manufacturing and value chains.
- Market orientation and strategic product planning.
- Digital manufacturing and advanced automation including simulation and modelling, robotics and the human-machine interface.
- Production systems and processes for emerging technologies including advanced materials, biotechnology and nanotechnology, pharmaceutical factories and micro-level processing.
- People in flexible and responsive manufacturing firms - factory and working methods for older demographics.
- Flexible production networks and systems for customised production.
- Protection of production know-how and products in global manufacturing systems.
- Strategic project ('Industry 4.0') focussed on embedded systems, seamless digital networks, decentralised control of production, virtual planning of products and production and remote maintenance i.e. cyber-physical systems in production systems to provide the 'smart factory.' Based on 3 pillars; smart production, urban production and green production.

Singapore

Priority and emerging manufacturing research themes identified in the 'Research, Innovation and Enterprise Plan 2015':

- Emphasis on promotion of high value manufacturing, innovations and new technologies, including: pervasive microfluidics, printed electronics and nano-manufacturing of multi-functional products/devices.
- Green and sustainable manufacturing, including: pharmaceutical and chemical manufacture and development of methodologies and tools for assessment of sustainability in manufacturing.

People – an international theme

Analyses of the major research reports in this area revealed a consistent emphasis on the role of people in the Factory of the Future, and in particular:

- The importance of talent ("Nothing will matter more than talent" -World Economic Forum, 2012).
- The need for creativity and innovation.
- The need for flexibility, involving multi-disciplinary teams of empowered and agile employees, who can integrate their knowledge and expertise.
- The significance of demographic changes and, in particular, the ageing workforce, making it even more imperative that manufacturing transforms itself into an attractive career option for the best talent.
- In this context, the gender imbalance in manufacturing generally is significant, limiting the potential for attracting the best talent.
- The importance of continuing education and training (rather than something that is done before settling into a career). One implication of this, coupled with longer working lives, is that it makes sense to attract people into manufacturing in their mid-working lives and to develop them to the best of their abilities.

2. Method and sample analytical framework

This study took the form of a structured interview based around a number of key questions. The interviews were carried out with a sample of manufacturing leaders from a number of large companies and owners and senior managers of a number of SMEs, along with some international experts in the domain. The interviewees were selected from a range of sectors to provide a wide perspective.

The overall method for this study involved 7 main stages:

- A literature review.
- Interviews with a sample of manufacturing leaders from a number of large companies, owners and senior managers of a number of SMEs and some experts in the area, selected form a range of sectors to provide a wider perspective. The interview schedule is presented in appendix 1 of this report.
- The initial findings were presented at a high level stakeholder meeting chaired by the Rt. Hon Dr Vince Cable MP, which included senior representatives from manufacturing, service, research and governmental organisations.
- The findings were then presented to a working group of experts appointed by the Department for Business, Innovation & Skills (BIS) to oversee and interpret this work.
- In light of the feedback received, we undertook a small number of further visits, meetings and interviews.
- Written feedback was given on the report by two independent referees (solicited by BIS officials).
- The report was finalised and submitted.

2.1 Structured interviews

Key people were interviewed as listed in table 1 below:

Table 1: List of people interviewed

Name	Company	Sector
Colin Sirrett	Airbus	Aerospace
Salvatore Milletarì	Avio (Italy)	Aerospace
Geoff Kirk	Rolls-Royce	Aerospace
David White	UTAS	Aerospace
Eberhart Bessey	Consultant	Automotive
Daniele Bassan	CRF (Fiat)	Automotive
Tony Walker	Toyota	Automotive
David Newble	TAP Biosystems	Bioinstrumentation
Chris Decubber	EFFRA	Cross sector
Richard Cook	AES Seals Ltd	Fabricated metal products
Hugh Facey	Gripple	Fabricated metal products
Rikardo Bueno	TECNALIA	Fabricated metal products
Kieron Murphy	GE Healthcare	Life sciences
Neil MacDonald	AES Seals and Master Cutler	Machinery and equipment
Angelo Merlo	CESI (Italy)	Machinery and equipment
David Robinson	Charles Robinson (Cutting Tools) Limited	Machinery and equipment
Craig Mckay	Evenort	Machinery and equipment
Christoph Hanisch	Festo	Machinery and equipment
Enrico Tamburini	Fidia	Machinery and equipment
Christopher Jewitt	Footprint Sheffield	Machinery and equipment
Cameron Mclelland	Polypipe	Machinery and equipment
Jan Edvardsson	Sandvik Tooling	Machinery and equipment
Engelbert Westkämper	Uni Stuttgart IPA	Machinery and equipment
Nick Medcalf	Smith & Nephew UK Ltd	Medical device/life sciences
John Wilkinson	MHRA	Medical device regulation
Mark Bustard	Healthcare & Medicines KTN/BioProcess UK	Pharma/life sciences
Joyce Tait	INNOGEN	Systems biology
George Kilburn	Cutlers Company	Trade body
Alan Marsden	Arup	Various
Andrew Ainger	Selex Galileo	Various
Tim Page	TUC	Various

2.2 Core findings

Context: What are the main trends shaping the FoF?

People interviewed were asked to consider both the medium term (to 2020) and long term (to 2050) aspects of each question. Where appropriate, the results for each of the main questions are tabulated and summarised graphically in appendix 2.

1. Are you aware of where there is work underway to examine the likely nature of the factory of the future? This might be research, development, practice, consultancy.

What are the main findings of this work?

It is clear that many focus attention on best practice within their own organisation and sector, but few, perhaps because of their focus on the day-to-day management of their business, had awareness of work in the FoF or of best practice in other sectors. The major activities have already been reported above and the outcomes of these should be further disseminated.

2. Which factories are currently regarded, internationally, as examples of best practice and why? (For example, the VW transparent factory in Dresden, and the Nissan factory in Sunderland). Please cite particular examples you think we should know about.

Several examples of best practice were identified including both large and small companies. These included:

UK SMEs

Gripple (Sheffield &Loadhog (Sheffield) - both have won the SME Factory of the Year.

TapBiosytems (Royston): Automated cell culture systems.

UK Large Enterprises

BMW (Hams Hall, Warwickshire): Automation, processes and customised assembly.

Toyota (Burnaston & Japan): Emphasis on manufacturing systems and their green agenda (involving products, processes, people and technology).

AES Seals (Rotherham): Factory layout, introduction of advanced technology and systems.

Renishaw (Gloucestershire): Automation.

McLaren Production Centre (Woking): Factory layout and organisation.

Bentley (Crewe): Investment in their production line.

EU

BMW (Leipzig, Munich): Automation, customised assembly.

Festo (Germany): Innovative working environment.

Scania (Sweden): Working environment, machine monitoring.

Volkswagen (Dresden, Kemnitz): Modular design flexible product factory.

USA

Boeing 787 Assembly Facility (Seattle): Assembly with minimum fixtures and tooling.

Xcelleres: Single use disposables and novel clean room configurations for biopharmaceuticals.

BMW (Spartanburg): Automotive.

Elsewhere

Embraer (Brazil): Aircraft manufacture.

There are clearly some excellent examples of best practice and some very innovative factories, a number of which are in the UK and include SMEs. It would be beneficial to encourage more people to visit these excellent facilities.

Figure 1: The workshop environment, AES Seals Ltd, Rotherham showing many facets of the FoF. (Lean, clean, bright, reconfigurable, CNC machine tools grouped in flexible cells). Photograph reproduced with kind permission of AES Seals Ltd, Rotherham.

3. In which sectors are the traditional views of a factory most likely to be challenged (for example in pharmaceuticals - factory in a cell/body in a cell, or chemicals - additive layer manufacturing of a customised factory[2])?

The most general perspective was that there would not be radical change in the view of the FoF other than it should have a smaller footprint. Factors such as fast ramp up and fast movement from manual through semi-automated to automated manufacture are expected to play an increasing role in the FoF.

Product life cycle was identified as a critical factor that governs many aspects of the FoF. In the aerospace sector, the life cycle is approaching 50 years. Regulation, including validation and certification of components also inhibits rapid change. The aerospace industry is largely governed by large aircraft platforms such as the Boeing 787 and 737 and the Airbus 380, 350 and 320. As both Airbus and Boeing will be competing with a new single aisle, 150 seat aircraft early in the 2020s, both companies will be incorporating many of the technologies currently available and in use. Major changes will be in areas such as the production of large monolithic parts and methods to reduce assembly and tooling costs.

Production rates at the Airbus A30X factories (replacement for the A320) are anticipated to reach 60 per month with the switchover from the existing A320NEO within 18 months. This will prove to be a significant challenge for the UK. A further challenge in the UK will be the volume of wings manufactured that need to meet the tolerances for Natural Laminar Flow (NLF).

In other sectors where the product life cycle is much shorter (e.g. electronic and photographic equipment) the emphasis is on flexibility and quick reconfiguration of existing facilities, fast ramp up, rapid automation and self-learning.

Lengthy, 50 year, product life cycles in aerospace must have a stable factory and production system. Excess manufacturing capacity, as for example in automotive, is also seen as a barrier to radical change despite the continuing emphasis on leanness and operational excellence, for instance the use of automotive supplier parks. Changes were, however, expected as a consequence of the rebalancing of global and local supply. Some anticipated that high street products could take advantage of technologies such as 3D printing to allow local and close to customer manufacturing.

Significant changes in the pharmaceutical business model with the growth of personalised medicine, the death of the blockbuster (the margins associated with it) and the growth of stratified medicines were identified as drivers for significant change in pharmaceutical manufacturing. However, this much change would require regulatory change to enable it to happen. ‘Cells in culture’ was identified as an industry. The factory in a cell is seen as established technology, particularly with the emergence of disposable production systems. Despite this, the cell as a product is still seen as very challenging especially in the ‘factory in the hospital’ setting of some regenerative medicines. Synthetic biology is a fluid and fast moving field where manufacturing and scale-up issues are already being explored, including the use of living plants as factories. Commercial wins will go to those who have the courage and insight to exploit its complexity.

In aerospace, the long product life cycle and the close proximity of the next generation aircraft leads to the observation that the design of the FoF is already known and the major influences are associated with the selection of materials for major components. The selection of composite or aluminium wing, and composite or aluminium fuselage will determine the final shape and design of the FoF and associated supply chain.

[1] Human body on a chip: DARPA – MIT collaboration (http://web.mit.edu/newsoffice/2012/human-body-on-a-chip-research-funding-0724.html)
[2] Chemical Engineering: 3-D printer produces custom vessels for chemical synthesis (http://cen.acs.org/articles/90/i16/Chemical-Reactors-Demand.html)

4. What lessons can be learnt from examining cross-sector issues, e.g. would the factory of the future in the bioscience/pharma sector benefit from thinking in the aerospace/automobile sector or vice versa?

In what ways might they benefit?

Cross sector learning is seen universally as a 'good thing'. Divisions between industrial sectors are seen to some degree as historical and artificial, and there are potential gains to be made by learning from others and from working at the intersections between sectors. For example, some organisations which regarded themselves as production-oriented are now providing services. However, there are certain caveats to such positive statements.

Firstly, many of our experts proved to be quite sector focussed – they knew significant amounts about their own sectors, but less about others. This may be a reflection of our sample, but in our experience, this is not unusual. Learning lessons from elsewhere is not a major focus of effort in many organisations, perhaps in part because it requires an investment of time. There is also an argument, that people tend to stay in their sectors as their careers progress, developing depth rather than breadth of expertise as this is necessary to retain a competitive position.

Secondly, one clear exception is where something becomes fashionable and something of a management fad, as exemplified by the interest in the Japanese manufacturing miracle through the 1990s and in management techniques such as just-in-time manufacturing, concurrent engineering, business process re-engineering, continuous improvement, supply chain partnering and the like. Interestingly the opportunities here for learning are concerned largely with the operational and organisational aspects of manufacturing rather than with hard technologies. Indeed it is these 'softer' issues that are most readily transferable.

Thirdly, there are clearly recognised and well established opportunities for cross sector learning. This is particularly true in closely aligned sectors, such as the automotive and aerospace industries. For instance, in the automotive industry, there are higher levels of automation, more efficient flowlines, and better management of supply chains, and the aerospace industry can, and is learning from these. In turn, the aerospace industry has greater levels of flexibility and the automotive industry can learn from this. In addition to adopting the large system integrator and supply chain management models, aerospace has also benefitted from studying the automotive industry's experience of discontinuing a successful high volume product and replacing it with a novel new model.

Fourthly, further potential lies in learning from IT (e.g., how to gain benefit from cloud computing), the evolution of the internet (what Cisco terms the 'Internet of Everything') the pharmaceutical industry (e.g., intellectual property), and new companies such as Amazon (in their use of outsourcing and operation of supply chains). Notwithstanding the above, few people in our sample raised the prospect of learning from sectors other than manufacturing – e.g. from gas, petroleum, retail, and service industries.

Finally, there is a resonating impression of a fragmented and rather inwardly facing world, which, as discussed later, is further reinforced by apparent fragmentation between practice and academia outside of the well known exemplars of best practice.

Figure 2: Shop floor environment Loadhog, Sheffield.
Photograph reproduced with the kind permission of Loadhog Ltd.

5. What developments can be expected in the physical arrangements of the factory of the future, i.e. would it be centralised, distributed, or reconfigurable?

Have you witnessed such arrangements being effective?

How does this differ by sector?

The physical arrangement will depend on the various needs and requirements and it is clear that there is no one answer that fits all. There is clearly a desire to have highly reconfigurable, facilities within a flexible workspace. This is discussed at length later in this report.

In the automotive and aerospace sectors where product life cycles are longer, there is more potential for supplier parks. There is also increasing focus on value chains.

The desirable physical arrangements are not specifically related to industrial sectors and include factors such as:

- Smaller factories.
- High visibility with clear lines of sight of all operations.
- Perception of a light, spacious and clean working environment.
- Good workspace utilisation.
- 'Open', welcoming factories offering access to customers, suppliers, universities and the general public (with role models emerging especially in the automotive sector.
- Increased urbanisation and potential to build factories in the city.
- Factories with a 'wow' factor that are attractive places in which to work.

A good example of these attributes is demonstrated at Loadhog who manufacture innovative handling and logistics products including reusable pallets and storage devices. They are housed in a refurbished, traditional factory in the industrial centre of Sheffield and won the Institution of Mechanical Engineers Manufacturing Excellence Award for Best SME 2011. The photographs show the shop floor working environment and offices with the 'wow' factor.

Figure 3: Office environment at Loadhog, Sheffield.
Photograph reproduced with the kind permission of Loadhog Ltd.

6. Will demand for personalisation of products affect the viability of the current model of a centralised factory relying on economies of scale (e.g. the rise of 'single use' disposable or multi-use factories)?

As reflected in the discussion in Question 3, there are few surprises. While recent US reports emphasise 'the tyranny of bulk', there are few mentions of the 'Factory on skids' or 'Factory in a container' and there are no '5 day cars' or 'Micro Factory Retail Centres' mentioned in our interviews, but 'time to customer' is seen as perhaps more important than personalisation. It is also understood that, given the increased amount of electronics in products – mobile phones and cars being cited as examples – that self-customisation of products will become increasingly important. There is, however, an expectation that some of the factory will move closer to the customer given the trend to personalisation but that 'the vital organs' of manufacturing will be centralised, giving rise to the potential for a hub and satellite configuration. The consequences of this in the life science industries have already been addressed in Question 3 and are discussed in the sectoral analysis elsewhere in this report.

Civil aerospace programmes have always started with the assumption that the design will not change once certified. This is now being challenged as new technologies become available e.g. A320 to A320NEO, which introduces new engines and wing devices. There is a clear desire in many industries to have reconfigurable factory space.

Discussion here has to be considered with that on physical structure in Question 5 and the supply chain in Question 9; location of the factory is critical. Production is getting closer to consumption to ensure the right product is at the right place and at the right time and to permit local customisation and personalisation. A hub and satellite configuration also enhances the opportunities for re-configuration of the extended enterprise. However, existing and overcapacity in traditional industrialised countries slows change. Consequently, emerging markets with little infrastructure could be and are the destinations for some of the newest approaches to manufacturing. Such destinations will include the BRIC countries but may include the oil-rich Gulf States such as Dubai if manufacturing goes direct to consumer.

7. Which technological trends (including robotics and new design methodologies) or emerging technologies (including nano-technologies) are most likely to have a significant impact on the Factory of the Future?

In what ways will they have an impact?

The two dominant trends mentioned by most responders are the influence and use of automation & robotics along with the consequences of environmental pressures and zero waste approaches on the recycling of materials and products within the supply chain. These are both a given. The factory is seen as digital, having increasing intelligence and or exploiting the opportunities of big data. Even more significantly, software tools are increasingly being seen as much simpler and easier to use, in addition to being more intuitive. 'New robotics' and SME friendly robotics are seen as important with emphasis being given to stimulating UK businesses to use these technologies in the best way.

In the survey 26% of the respondents identified nano technology as having the potential to make a significant impact. This may be in the form of nano coatings and nano materials, which can produce a step change in materials performance.

In the vast majority of cases, the technology required in the FoF is seen to be already available within the more traditional industry sectors and it is the focus on the exploitation and use of the technologies that is becoming important. For instance 5-axis CNC machine tools and robots are readily available but the optimum operation of these machines and the move from in-process measurement and monitoring and adaptive control to self-learning will be realised in the FoF.

The FoF will include systems designed to reduce ramp up times dramatically, allow for autonomous code generation, support the quick change over from manual to semi-automatic to automatic and allow the reuse of existing equipment in new lines.

Terms such as fast ramp up and reconfigurable factory infer a considerable change in both the level and use of enabling technologies such as the GPS-enabled factory, not using a conventional flow-line, flexible adaptive tooling and the ability to self-datum. Robotics are used accurately with feedback control to remove variation in what are, today, heavily manual production processes. Rapid reconfiguration and fast ramp also implies increased use of simulation and modelling, testing factory layouts and processes in a virtual reality environment, virtual factory design and virtual factories, in addition to increasing use of plug-and-play technologies.

Design led factories, design enablers and design methodology enablers were also seen as critical by many because of their potential impact on the generation of new products and because of their 'design for manufacture' impact. An example of this is 'Modularer Baukasten', the modular matrix of VW/Audi product design, enabling significant factory design simplification. The focus will be on more rapid introduction of design modifications, lower tooling capital expenditure and lower overall recurring cost of the product. There are opportunities associated with getting young designers to understand more about manufacturing and encouraging them to reinvent manufacturing.

Figure 4: Mill turn capable of machining complex parts on one machine, reducing set-up and increasing accuracy. Photograph reproduced with the kind permission of AES Seals Ltd.

Some responders and a reviewer of an earlier version of the report highlighted that the impact of 'big data' and pervasive computing would be significant in the factory of the future.

Many respondents mentioned 3D printing. While some were experts others had little or no experience of the technology. The technology risks being overhyped until it is seen to deliver robust functional products. If the potential is achieved, the technology could be a significant game changer in the manufacture of low volume specialised products. The potential impact of 3D printing is discussed later in the concluding comments.

The technology trends likely to impact the FoF and their impact are inevitably an area of uncertainty and debate. Following a challenge from the High Level Stakeholder Group to be more visionary with respect to the FoF, the work here was validated with other thinking, especially that of the Manufuture platform. This is of significance because of its development in the EU economic setting. Current thinking is that the key mainstream technologies of importance for conventional manufacturing and their trends are seen to be clear up to 2030. Post 2030 perspectives are much more uncertain due to a number of factors. Process technology of 3D printing is likely to be important. Enabling of the creation and operation of value systems using ICT is likely to be significant. Together with the opportunities of emerging science and materials, for instance graphene and living materials are likely to drive dramatic change. Determining the technology likely to deliver epochal change in manufacturing - at the level, for example, of the combination of numerical control and computer aided design, needs to remain a focus of the research community. There is also a need to continually consider the technologies that will be required by individual market sectors as a consequence of their different products and requirements – the FoF solution will be different for different businesses.

8. What role will the workforce play in the Factory of the Future? How will this be optimised?

For example will the trend be towards up-skilling staff? Or deskilling?

Or some combination of both?

The workforce will play an increasingly important role in future manufacturing, although technological advances will lead to the automation of many existing manual processes. Rather than replacing people, these developments will change their roles towards more knowledge-based work. The rise of smart technology will be a key driver of this shift, with people required to work as part of an integrated socio-technical system. There will be a change from 'doing' the manufacturing to monitoring automated processes in real-time and responding to feedback from machines to optimise process capability. The review of international perspectives has shown automation is a given, as is mechanisation. However, there were sensitivities from some respondents with respect to the replacement of people and jobs by robots – robo-sourcing[1]. This highlights the requirement in two ways. Firstly, to communicate the reality of international economic competition for manufacturing added value and manufacturing jobs to all stakeholders, to ensure that skills are maintained and enhanced. And secondly, focussing technology innovation on business problems, where manufacturing technology gives significant rather than incremental benefit.

These changes in people's roles will occur throughout the factory, from the shop floor through to those designing engineering processes. Whilst there may be some de-skilling in traditional trades, there will be widespread up-skilling in areas related to technology, and the organisation and management of processes particularly with respect to meeting the needs of the customer. In essence, re-skilling will be required. Technological advances will be rapid and will need to be matched by continual training and development, and flexible non-bureaucratic processes. For some a change in mindset will be required such that training is viewed as investing in the future rather than a short-term cost. In addition craft skills will remain essential in the finishing of premium and luxury goods, an important component of UK exports, an area where considerable investment is being made.

The knock-on effects that changes have on employees described elsewhere in this report are acknowledged and reflect our view that these are inter-connected systems. Examples of heavy demands placed on employees include, the need for innovations in products, processes and business models, the move towards re-configurable enterprises, the challenges created by integrated value chains and the need to understand and work with customers. These are consistent with the wider literatures described in section 1 above. This is likely to mark the end of the pervading culture of command and control, necessitating a shift towards empowered and engaged employees.

An emphasis was placed on the need to attract, develop and keep talented people. These are viewed as the sources of innovation and creativity. Attracting talented individuals into manufacturing represents a major challenge, especially in the context of an ageing and gender-imbalanced workforce. Here, the bright, clean, innovative working environment of the FoF can be a major factor. It is also recognised that the trend towards longer working lives opens up the opportunity to attract mid-career people into manufacturing. As is already becoming evident, careers need no longer be a choice people make when they are in their 20's.

A further issue concerns the attractiveness of careers in manufacturing for Generation Y (i.e. those born between 1983 and 1999). It is widely thought that this generation is, in comparison with its predecessors, more likely to be devotees of social technology, gaming and the internet, less formal and less accepting of bureaucratic structures and processes, used to diversity and globalisation and more environmentally conscious.

Figure 5: Investment in Best Gun Making at Westley Richards, Birmingham. Demonstrating the transformation of traditional buildings to create a modern factory environment.
Photograph reproduced with the kind permission of Westley Richards.

Figure 6: Gun making at Westley Richards, Birmingham. Demonstrating the use of traditional skills to produce high value products.
Photograph reproduced with the kind permission of Westley Richards.

Greater collaboration is required between education and industry to ensure that graduates and school leavers are equipped with the skills required for these future manufacturing environments. Further integration between universities and industry would facilitate this change. Industrial placements for students will become more frequent, and organisations could sponsor degree programmes tailored to their specific requirements. This is addressed later.

[1] *Expressed in a similar way to "out-sourcing" or "back-sourcing" i.e. the onshoring of jobs.*

9. What role could the supply chain play in the Factory of the Future?

For example, are these likely to get more global? Or more local?

Are they likely to get leaner? Or to build in redundancy to cover threats to resilience?

The most striking thing about this survey has been the emphasis of interviewed on the importance of the value chain and the opportunities for improvement in this area. The ability to create and operate a value chain that collectively delivers a unique value proposition to the user market is seen as the most significant source of future competitive advantage. It is seen as very important that businesses have this understanding and the skills and capabilities to both create the value chain – the key step – and to operate it. Operation of the value chain – essentially the co-ordination of the supply chain dyads to operate a cross-organisational business process – is seen as complex but less challenging than creating it. Lean supply chains are a given, but lean must be exquisitely balanced with resilience, especially in regulated industries. This is because the customer does not directly see or buy lean. Materials management and resource conservation is also critical in the design and operation of the supply chain as reflected in the Japanese concept of 'Monozukuri'.

The global or local supply chain question is driven by conflicting demands. On one hand, there is a desire in some industries to have a global supply chain to support global marketing and sales campaigns, in addition to supporting risk reward strategies that depend upon global participation. This is particularly true in the aerospace industry.

On the other hand, there is a push to have local supply chains and supply park models that go further than existing models. In addition to proximity, there is support for sharing resources locally to cope with demand (resource pooling) and the requirements for specialist expertise or knowledge (e.g. NDT or process modelling). An example of this is the 'Proving Factory' concept being discussed for the automotive industry, where new manufacturing concepts can be trialled in an industrial environment on an industrial scale with potential partners.

Economic clusters of activity in the form of Science Parks, Advanced Manufacturing Research Centres, Catapults and similar innovative forms of organisations, are likely to become more prevalent and significant. These will be based around world class universities and promoting closer working relationships. This opens up the possibility that the potential game changers for manufacturing lie in organisational innovations, as much as in technical inventions (see below).

The potential for a hub and satellite configuration is also likely to be consistent with the trend towards re-configurable extended enterprises (see later).

10. How important is process and product innovation in shaping the Factory of the Future?

Can you provide examples of such innovation?

Product and process innovation are seen as absolutely essential, as competitive 'givens'. But there were also various nuances to the argument.

Firstly, not all such innovations need to be disruptive – continuing incremental improvement is seen as key. In passing we note that a fine example is provided by the British Olympic cycling team with its emphasis on continuing marginal gains, across all aspects of its operations and performance (including bike technology, clothing design, training regimes, diet, health, facilities, squad selection, the culture – the whole system). Indeed, some believe that evolutionary rather than revolutionary changes are a key element of the FoF. In this view there are considerable potential gains to be made by understanding and implementing what is already known about manufacturing as a system and performing it at a world class level.

As one might expect, there is a powerful counter argument. Thus, whilst it makes sense for the British cycling infrastructure to strive to evolve through continuous improvement across all of its activities, they are already world leaders. What about those trailing behind (i.e. the majority)? A view strongly held by some is that UK manufacturing needs a revolution in its thinking and its practices, a cultural shift no less. Incremental improvements will not be enough.

Secondly, as mentioned earlier, important as they are, innovation is not solely a matter of new technologies. There are other important forms of innovation, examples including new business models (such as servitisation, see later), new offerings and new organisational arrangements. Examples of the first are provided by Rolls-Royce in its development of 'power by the hour'. Examples of the second are provided by Toyota which is exploiting its capability to design and deploy robot technology in manufacturing to develop robots for use in the home, and its capability to store energy to operate the home and the family car as an integrated energy system. Examples of organisational innovations include new forms of collaboration between manufacturing companies and universities (such as the AMRC model developed by Boeing, Rolls-Royce, a range of SMEs and the University of Sheffield).

Thirdly, these kinds of innovation may well be linked. Thus, whilst it's hard to predict what may be the technical game changers of 2030 and beyond, it is clear that some companies will be better placed to respond to the opportunities that arise because of their closeness to the sources of invention and their agility in responding and capitalising on the opportunities presented.

Fourthly, some argued that companies are better at their product innovations than they are at process innovation/improvement, for which there are many reasons. Process innovation can be difficult because it can involve changes in technology, work organisation, working practices, skills, metrics and the like. Furthermore, product innovation is usually the initial focus and prime driver, and once products are established, attention turns to the process of making the product more efficiently. As implied above, it was felt that innovation should be addressed as an integrated system, as changes in one aspect will often necessitate changes in the other. A prime example of this concerns the increasing use of new composite materials in manufacturing – such as carbon fibre to manufacture products previously made of metal alloys – and the very different products and processes resulting from this.

Fifthly, some argued that in Europe we still under-utilise a major source of improvement, i.e. people on the ground. In this view, the people near the action have lots of good ideas, but these are often not developed and implemented (and this does not just apply to shop-floor staff).

Finally, there is an important change in mindset that will help shape the FoF. The traditional view, i.e. that manufacturing should focus on operating the latest technologies and processes that need controlling and managing under regimes of command and control, is due for replacement (and this is one part of the cultural revolution referred to earlier). The mental model for the FoF is that these are centres of creativity and innovation, where capable and talented people use the latest technologies and processes to create new ways of adding value. Furthermore, manufacturing companies are more likely to be in a position to do this by working closely with customers, suppliers and universities. This is a world of challenge, interest and excitement requiring significant change in management and leadership.

11. What will be the impact of 'servitisation'? Is this likely to increase?

Servitisation is moving us into the fourth generation for manufacturing business models in the UK. This is a powerful concept that is not well understood. Servitisation is about manufacturers offering services tightly coupled to their products. It is about moving from a transactional (just selling a product) to a relationship based business model (delivering a capability). In a servitisation model, manufacturers see themselves as service providers. For example, by the provision of product based services, as contract manufacturers supplying skills and manufacturing capacity, and the transformation from machine makers to the provision of manufacturing processes within an original equipment manufacturer (OEM). They exploit their own IP (know how/ know why emerging from design and production competence) to deliver and improve business processes for their customers. Generally, companies have long-term, incentivised (risk & revenue), 'pay as you go' contracts. Clearly it will be necessary to generate enabling technologies to permit servitisation, in particular the information technology to permit remote monitoring of enterprises, products, processes and machines.

The interviews highlighted that many companies have not considered servitisation as an appropriate business model. In the West, servitisation is likely to gain popularity as it enables the supplier to increase the level of supply and it can tighten the relationship between supplier and customer. From a customer viewpoint, servitisation can change a large capital expenditure into a more controllable and predictable revenue spend.

Examples of companies using servitisation include:

- Rolls-Royce offers TotalCare or power-by-the hour contracts: reporting that approximately 50% of its ongoing revenue now originates from such service agreements.
- Alstom offers train life services with Virgin using the Pendalino trains on the west coast mainline.
- MAN offers fleet management packages for trucks. This includes companies such as Shell.
- Xerox has a managed print service for Fiat group, Proctor & Gamble and has this year reported 50% of total revenue from services.
- Toyota offers personal mobility plans.

12. What will be the impact of other changes in underlying business models and emerging standards in this area?

The major changes are reported in the value chain emphasis, an improved understanding of supply chains, the potential for supply parks and the increasing use of technology to become competitive. The technologies will be important enablers in the realisation of the reconfigurable factory (and the wider reconfigurable enterprise) with the ability to manufacture a range of products. This need for rapid transition from one product to another will be aided by greater use of distributed manufacture where components are made locally within the supply park. Few radical changes in underlying business models were reported, though there was recognition of the string emerging trend towards servitisation.

Evidence of risk reward sharing models has already been seen in the aerospace sector. Due to the increasing cost and complexity of developing new aircraft, there is likely to be an increasing emphasis on true risk reward sharing in sectors with high development costs.

In the pharmaceutical, biopharmaceutical and medical device sectors there was pressure from businesses to change the regulatory framework in order to permit innovation and manufacturing economics in a market place where the pharmaceutical blockbuster is no longer achievable, and where product technologies are now convergent. This was in striking contrast to the results of a similar exercise carried out in 2007 where the perspective was that the FoF would fit within the existing direction of travel of the regulation. Such changes will require both public debate on the role of the regulator and the generation of evidence, using regulatory science, to permit regulatory change.

The impact of regulation has also been broadly recognised within Europe (in particular Germany) to identify that the regulatory burden in Europe when compared to other candidate locations, in particular the BRIC countries, makes it problematic to construct new manufacturing capacity – factories – within a competitive timescale. This therefore accelerates the potential for the offshoring of manufacturing.

Leadership in the setting of standards was seen as especially important for the enabling of new business models, in particular the creation and operation of the new generation of complex distributed manufacturing and supply systems that are necessarily enabled by ICT, and as a strategic way of gaining share in emerging industries. There is the potential for the UK to take a leadership role in the creation of such standards.

13. What are the other trends shaping the Factory of the Future, for example:

a) The green agenda (reducing energy, water, waste)
b) Changes in management practices and processes
c) Changes in communications practices and social networks
d) Changes in demands for proximity to customers
e) Changes in the costs of resources
f) Changes in the costs of transportation
g) Changes in performance metrics – e.g. increased emphasis on quality, lead times and customer satisfaction, as opposed to machine utilisation and efficiencies
h) Changes in regulatory frameworks – e.g. in health and pharma?
i) Changes in the speed at which research and development innovations get translated into use and get widely deployed? (e.g. will such lead times get shortened?)

These are all seen as important and many have been covered elsewhere in this report. Here we restrict ourselves to some summary views and comments.

a. The green agenda is seen as important, especially acknowledging the need to reduce energy and waste – "zero waste" was a mantra for many. Recycling extends to the end of the life cycle and companies like Rolls-Royce and Toyota are investing considerable effort in this regard. Reduction in the amount of materials used in the product and transported was identified as critical; material content per unit must be reduced and kg miles should be a metric for the whole supply chain. Less emphasis was placed by this sample of participants on the need to reduce the use of water, but this is believed to become an issue for the FoF.

There are some strong role models here. For example, Toyota stress that it is making green products (hybrid cars), using green processes in a green factory, operated by green employees who are encouraged to take their green behaviours home (they are offered training and qualifications in this). The company also has a nature reserve at its Burnaston factory, which is unusual in our experience.

b. Changes in management practices and processes were discussed under question 10.

c. Changes in communications practices and social networks/social media were mainly seen as significant through the potential immediacy of customer feedback, especially if things go wrong as it has the potential for widespread reputational damage. We note however, that this is one area where our sample is likely to be biased, selected as they were because of their experience, the corollary of which is that their age may mitigate against them being well developed about this subject. For example, the new media have the potential to link globally dispersed communities. In the case of companies such as Rolls-Royce for whom more than 50% of their order book involves services (rather than products), such technologies provide opportunities to create new social networks between design communities in one part of the world with service communities spread around the globe. Similarly, such technologies will have the capability to provide informal social networks between people working in hub and satellite configurations.

Such media is part of the habitual pattern of life for Generation Y and it will become important aspects of the effective operation of the FoF, probably evolving in ways we currently do not anticipate.

d. Changes in demands for proximity are seen as an issue, in part related to the costs of transportation (see 13f below) but also to the need for greater understanding across the supply chain, and with customers. The proposition is that proximity helps promote understanding, which is desirable. Indeed some major manufacturers strongly encourage their suppliers to have a local base (e.g., Nissan in Sunderland). (See also 13f below).

e. Changes in the costs of resources are supporting the waste minimisation, green product and sustainable factory initiatives. Energy costs are continually rising and the FoF will have a range of energy saving devices such as ground source heat pumps, heat reclamation systems, minimum quantity lubrication etc. The cost of raw materials also supports the recycling and high quality reuse of materials, which is a significant departure from the recycling for low grade use that has been the norm in the past.

f. Changes in the costs of transportation are seen as significant especially for bulky parts. In addition, there are two further considerations influencing choices of suppliers. Firstly, the use of local suppliers is seen as more likely to promote supply chain understanding and integration. Secondly, there is a trade-off between lean supply chains and redundancy in supply. For example, the tsunami in Japan in 2011 created unanticipated problems for British manufacturing companies (amongst others) because of disruption of the supply of microchips. Local suppliers make the potential for such problems more visible and it is recognised that some redundancy in the system mitigates against partial failure.

g. Changes in performance metrics are seen as very important. The perceived trend sees a move away from an 'old fashioned' operational focus on machine efficiencies and machine utilisation to more customer-focussed metrics, centred on the highest quality, shorter lead times, and customer satisfaction (even delight!).

This is clearly important but it also has far-reaching implications for how the FoF is managed and operated. Such metrics potentially incorporate the notion that customers are welcome in the factory, that employees know who their customers are and indeed meet them. Manufacturing in this view is not done in a silo or bubble, and handed over the wall to the next anonymised stage in the process. Manufacturing has a real user who is known and understood. It also embraces the notion that the employee is a skilled and talented partner engaged in this process.

h. Changes in regulatory frameworks are seen as especially important in areas such as the life sciences and this is discussed earlier in this report. It is important that regulatory frameworks do not function in a way that disadvantages UK manufacturing.

i. The speed at which research and development innovations get translated into use and widespread deployment generated some interesting discussions, often focussing on the links between manufacturing industry and UK universities. Two disparate views emerged. Some believed we in the UK have got this about right, and we are improving as we would hope. Universities are better linked to manufacturing than ever before and there are R&D schemes available and in use.

However, a much more critical perspective was also offered. In this view we are woefully inadequate and there are untapped opportunities in both directions. Thus, manufacturing companies have need for the latest thinking, for new ideas, for innovation (and not just in engineering and technology). Universities have thousands of talented people potentially looking for projects, R&D opportunities and exposure to the day-to-day reality of operations. Furthermore, universities are perpetually refreshing their skills and capabilities through young talent and aspiration. There are considerable opportunities to bring the two together in real and substantial long term relationships. There are some world class trail-blazers in this regard, most obviously companies such as Rolls-Royce and their global network of University Technology Centres and Advanced Manufacturing Research Centres. However, these are the exceptions.

In our view, this represents a major missed opportunity, especially, if, as a nation we are opting for the innovation/valued added route for the FoF. Put another way, the FoF will need University partners. This will require a cultural shift. Furthermore, organisational innovations of this kind enable manufacturing companies to capitalise on technical innovations as they arise.

14. What do you think are the potential game changers for manufacturing? i.e., things that will lead to a genuine shift in the factory of the future

Game changers are seen as:

- Value chain and systems thinking at a value chain level.
- A focus on reconfigurable enterprises (including reconfigurable factories) including technologies such as robotics and 3D printing, which could make single customised part production a reality.
- New raw materials, for example graphene and new materials derived from plants and other living natural materials.
- The changing of the regulatory environment in healthcare to permit product innovation and manufacturing economies. This is now being demanded by the industry.
- The increasing affordability and commoditisation of production technology – competitive advantage deriving from the know-how of understanding how to operate it.
- The UK becoming a low/lower cost country.
- New ways of working together, involving supply chains and universities.
- New mindsets on the FoF, based on the requirement for world class organisation, people and technology working to find creative and innovative ways of adding value.

15. How do views on the factory of the future vary between nations? In particular comparing: China, US, Germany, South Korea, Japan and Singapore.

What do you think is causing these differences?

The world is much more connected than it has been in the past, enabled both by technological advances and the growth of multi-national corporations and consultancies. Innovations of all kinds have the potential for widespread adoption. It would appear that earlier scepticism over the extent to which good ideas from one culture can be translated and adopted elsewhere have been answered, for example by the successes of Toyota and Nissan operations in the UK.

There are a number of initiatives in Europe considering future manufacturing processes. Recent investment has also led the USA to undertake exploratory research into future manufacturing. Recent US thinking recognises the critical 'inflection band' between 'demonstrating viability' and 'scaling production'.

While the West is still a world leader in some areas, it must maintain its manufacturing base. In recent times, the outsourcing of manufacturing to other regions with low labour costs has resulted in some disruptions. Furthermore, outsourcing of core manufacturing activities has the potential to lead to a decline in associated knowledge and capability, with attendant development of new capabilities elsewhere. This has far reaching implications.

Through the post-war period there has been a progressive shift in manufacturing from West to East. Asia has changed rapidly and will continue to do so. China is advancing in science and technology and, when allied with its low labour costs and vast population, its manufacturing capability will increase dramatically. Japan, Singapore, and South Korea are already highly technologically advanced and leading the world in many areas. A major strength of theirs is the integration of micro technologies into products, with photonics being a prime example. Some believe their progress is partly driven by large government subsidies and by very substantial investments in their university systems.

Whilst the profiles of capability and opportunity may vary when comparing mature and rapidly developing economies (including BRIC), we have found no evidence that this has resulted in different mental models regarding the FoF. So far, as we have been able to ascertain, the summary presented in figure 5 has widespread applicability and support.

16. How should the UK respond to any suggestions of what the Factory of the Future would look like? Can the UK benefit by being ahead of the game?

This report signals the trends affecting the FoF, not its end state and identifies the requirement for Modern Re-industrialisation in the UK. The authors, and in turn the community we represent, have been challenged to put our vision for the FoF 'on steroids'. As we do this, we should recognise that the drivers in each manufacturing nation are different and that we should use our legacy as a differentiator as do the Germans, Swedes and Swiss. We need to work out what the business model is for manufacturing in UK plc. – the UK must have, and maintain, an unbeatable value proposition.
We also need to define the future state of manufacturing together.

This process should engage the young who will work in manufacturing and those who will invest in it. As one of our interviewees said; "We must not be incremental and muddle along, we need to work from the future state. We are not going to get rich quick; you have to be good before you can get rich."

Our recommendations for how the UK responds to the emerging opportunities for the Factory of the Future are summarised in the final section below.

17. What trends will affect the Factory of the Future as far out as 2050?

The FoF is a concept that brings together best practice and optimum working procedures and systems. The FoF could give the UK considerable competitive advantage but if the demand for global trading grows as predicted, the FoF may need to be transplanted into other locations worldwide. If this happens it will be difficult to keep the competitive advantage without further continual improvement.

Within the next 10 years over 30% of our most experienced engineers will retire. In addition, there remains a shortage of women working in manufacturing and this exists at all levels and in most, if not all, skillsets. One of the greatest challenges will be to attract a new generation of knowledgeable and innovative forward thinkers to create the FoF.

The younger generation are increasingly aware of the green agenda and the need to reduce energy usage and develop sustainable manufacturing processes and there is a trend towards optimum sizing of production equipment, reducing waste and material and energy use.

The emerging economies (BRIC) and the implications of trading with these countries could impact in a number of areas including the availability of rare materials, availability of energy and resources, potential market and the need to develop a local supply chain.

The products of 2050 will have crossovers between traditionally separate aspects and technologies within a design (e.g. the systems and battery supplies of vehicles and aerospace products will probably be increasingly embedded in the structures, to save on weight and minimise assembly including electronics, pipes, optics, etc.). Complex high integrity electronic processing and health monitoring can be embedded into structures with minimal impact on unit cost, no impact on weight.

Specific tooling in aerospace and automotive manufacturing will have largely been eliminated as these are expensive and dedicated items. An example being the progress already made and planned with the 787 production line for minimal and flexible tooling is the start of the process of tool elimination rather than as far as it can go. The next generations of products, both military and civil will take this further with a tool free or transient adaptive tooling being the competitive edge in 2050.

Multi product manufacturing in factories will be common, where the flexibility of the manufacturing processes and assembly capabilities will enable different products to be made simultaneously and the optimum production rates on each product will continually change to meet market demand.

A completely digital design and development environment will be evident - with the elimination of many of the high cost test facilities such as wind tunnels and electromagnetic facilities. Modelling and simulation will be at a level of fidelity that will allow formal evidence to be accepted from the virtual world, with only very occasional real world validation. This is a key aspect to rapid design and the increased use of independent computing that can design with a reduced need for design engineers. The ability to rapidly iterate and synthetically integrate complex products to prototype and then to full production standard would produce a significant competitive edge with multiple variants able to be considered before production.

The eco/green drivers will have eliminated many of the processes that use chemical treatments and new techniques such as laser/sonic treatments for cleaning and finishing will be well established, which will complement the water jet cutting environments.

Power usage in manufacturing will also be minimised. The economic position of the nation will determine the pressure on costs, but clearly a nation that still relies on fossil fuels will be struggling in this time frame when it comes to cost and acceptability of excessive energy usage.

Powering the FoF 2050 will be potentially a significant factor. The eco drivers will have a major influence on how the factory is powered and there may be a demand for very difficult challenges surrounding carbon footprints and self-sufficiency.

Will there be a competitive advantage to be able to take back products and recycle when out of use? Currently recycling is largely indirect in how for example vehicles (cars, aircraft etc.) are recycled. In the FoF will there be a requirement to employ technology that allows direct disassembly and reuse?

Research work on the use of metastable materials and morphing should be mature enough for new structures to be envisaged. This would allow materials to change state and morph into new structures by the implementation of inbuilt rules and controlling embedded systems. This is at a low level of technical maturity today but has high potential for aerospace and military products, so it would be reasonable to assume availability by 2050.

3. Analysis of sectoral perspectives

i) Aerospace

In aerospace, the product life cycle is typically 50 years. Aerospace is also highly regulated and the opportunity to change design and manufacturing methods once an aircraft and components have been validated is difficult and costly.

The next commercial aircraft manufactured by Boeing and Airbus will be the next generation 150 seat designs, which will replace the Boeing 737 and Airbus A320. These are likely to be replaced early in the 2020s. In each case the key decisions will relate to the fuselage and wing materials - the options being aluminium or composite fuselage and aluminium or composite wings. This decision will have huge implications on the manufacturing methods and potentially the location of the assembly facilities and supply chain.

From a UK perspective the major interest will be that the wing for the replacement A320 is manufactured in the UK. Additionally, UK companies will compete to supply both aircraft manufacturers with wing components and major components such as flight controls, control surfaces and landing gear. Given the product life cycle it is clear that the manufacturing methods used will be based on existing technologies. It is also clear that the design of the FoF is already defined.

Figure 7: Boeing 787 Assembly facility showing limited use of tooling. (Photograph reproduced with kind permission of the Boeing Company).

The assembly facilities will continue to follow the large scale system integrator model originally developed in the automotive industry to bring together large monolithic parts. The facility will be clean, well-organised and use a minimum amount of tools and fixtures. This is demonstrated in the Boeing 787 assembly facility shown in figure 7.

The facility relies on a global supply chain with wings manufactured in Japan, cockpit manufactured in Wichita & Kansas, USA, and other key components manufactured in the UK and Italy. The facility uses GPS and laser alignment technologies during assembly.

This can be compared to the more traditional aerospace assembly facility, which assembles smaller components (figure 8).

The UK supply chain will need to produce competitively priced components against global competition.

Aero engine manufacturers are following the same model, which is dictating the design of the FoF. Suppliers (including in-house suppliers) will need to provide competitive components using an appropriate level of automation and flexibility. As volumes are lower; specialist manufacturing lines are not appropriate and flexible cells capable of manufacturing families of parts for a range of engines is more appropriate.

Figure 8: Traditional aircraft assembly facility (Boeing 767) showing the dependence on large tooling facilities (Photograph reproduced with kind permission of the Boeing Company).

ii) Automotive

The automotive industry uses the large-scale system integrator model with a large supply chain. The assembly lines need to cope with design variations with a high level of customisation. Volumes are much larger than aerospace but there is considerable variation in models and vehicle specifications. Products are segmented from low to high end offerings with European suppliers tending to focus on high end, high value products for international markets.

The automotive product life cycle is much shorter than aerospace but the manufacturing volumes are much higher. Traditionally, automotive factories were characterised by large investments in fixed automation. This is being replaced by more flexible and reconfigurable automation including robotics. The system can be classified as mass customisation, combining mass production and customisation. This is achieved by rigorous production control, lean manufacturing and a highly developed and organised supply chain.

Suppliers need to produce large volumes of components at a competitive price. The need for fast ramp up and automation in the supply chain is pushing the design of the FoF which will be much as described earlier, i.e. flexible, easily reconfigurable, automated and capable of fast ramp up.

The leading players in automotive demonstrate an emphasis on customer oriented goals, simple and robust processes, advanced technologies, a culture of continuous improvement and capable people. They exemplify a commitment to a systems approach to designing and managing their manufacturing environment.

The current automotive supply chain is dominated by engine and power train supply, body-in-white manufacturing and components supply. The increased hybridisation of the drive train to include both electrical, fuel cell and internal combustion engine prime movers will continue to affect manufacturing as will the inevitable increase in the electronic content of cars.

Automotive was identified by a number of interviewees as a sector where personalisation of the product is becoming increasingly desirable and where there is advantage in the customer seeing ‘their car’ being manufactured. This suggests that the late personalisation of a standard product and open customer access will be part of the automotive FoF.

iii) Pharmaceutical and biopharmaceutical manufacturing

Drawing on a review of website information, selected life sciences reports, stakeholder consultation and internal expertise, this summary provides an overview of the high value manufacturing innovation landscape in the pharmaceutical and biopharmaceutical sectors, focussing in particular, on the trends/'hot topics' that are set to determine the shape and nature of the FoF in these sectors.

Note: This overview does not specifically consider the cell and gene therapy sectors. Further study is required to expand the distinction between 'manufacturing therapies in the cell' and 'manufacturing the cell as a therapy' in order to identify applicable cross-sectoral learning from biopharma' and where additional levels of complexity require further innovation in the cell and gene therapy value chain.

Many of the trends highlighted (emboldened) below are driven by capacity uncertainty, product complexity, and the need to minimise capital/operating expenditure, financial risk/liability early in the value chain and increase the speed to market. Typically these trends reflect incremental improvements but the leading edge of the new pharma'/biopharma' manufacturing base, seen particularly in vaccine manufacturing and in niche rare disease and personalised/stratified medicine, represent transformational changes that are changing the manner in which material is produced.

Flexible, agile and adaptable production facilities to deliver a new value proposition and business models incorporating manufacture and delivery of smaller, more frequent, 'on demand' batches of products, and stratified or niche medicines.

- Design and construction of smaller/reduced footprint modular facilities using standardised facility layouts and process configurations e.g. National Center for Therapeutics Manufacturing vaccine facility, Texas US; Caliber Biotherapeutics, Texas, US.
- Evolving incorporation/integration of single use (disposable) upstream and downstream process systems e.g. DSM biologics plant in Brisbane, Australia; the Shire cell processing facility in Lexington, US; XCellerex Flexfactory biomanufacturing platform (Boston, US).
- Closed systems with facilities moving towards non-classified (e.g. Grade D environmental control) operation and more open facility layouts e.g. 'GMP in a box'; 'vaccine factory in a box' (GE Healthcare, UK and G-Con, US lead providers).
- Simulation tools for factory layout/bioprocess modelling/technology transfer e.g. Medimmune biopharma' facility (Maryland, US) and vaccine facility (Speke, UK).
- Continuous processing and automation: Process Analytical Technology (PAT), robotics and platforms for mechanical manipulation e.g. Novartis-MIT Centre in US/Novartis pilot plant in Switzerland.
- Increasing complexity of global supply/value chains – local, demand-led, reconfigurable for new business models and linked to more agile, responsive manufacturing operations and improved connectivity/ integration of whole value chain (including the regulator).
- Distributed manufacturing: construction of 'vital organs' with local responsiveness in geographically diverse locations and emerging markets e.g. for vaccine production.
- Multi-function/multi-product processing suites: intensification in smaller footprint, scalable/phased modular build.
- Global rationalisation of duplicated 'big pharma' plants/supply chains with move towards global centres/hubs of manufacturing excellence and local supply chains.
- Bioprocess sustainability focussed on green construction, green chemistry and reduction in consumption of water, energy and cleaning chemicals e.g. Centocor Biologics and Pfizer biotech plants in Cork, Ireland.

Figure 9: XCellerex Flexfactory
(Photograph reproduced with kind permission XCellerex, Marlborough, MA)

Integration of product design and manufacture – designed in quality & 'manufacturability'

These involve:

- Alternative sustainable/renewable sources of material inputs, exploiting naturally occurring materials and the processes they are derived from ('factory in a cell'): for renewable feedstock's, serum substitutes, and synthesis of functional biomaterials and biopolymers e.g. Fraunhofer CMI factory in US - first GMP factory for plant-based protein production.
- Synthetic biology approaches to create new biocompatible material sources, novel expression systems, and new biological production systems.
- Nanotechnology enablers.
- Improved formulation design and understanding to increase stability, eliminate cold chain storage/transport, and eliminate use of serum.
- Simulation/predictive tools for molecular modelling, formulation and product design.

Smarter Operations - Lean manufacturing/facility layouts and Operational Excellence for high quality products, zero defects and waste and Novel delivery systems for therapeutics.

These involve:

- Converging technologies to make 'smarter' and/or miniaturised devices e.g. to monitor/feedback patient health/compliance, control release, prevent counterfeiting and enable responsive manufacturing (client & supplier feedback).

Analytics and Characterisation Metrology

These involve:

- Product & process life cycle management tools enabling human centred operational and facility design; serving as knowledge repositories (in preparation for live-licensing?).
- Metrology method validation, data standardisation and reference materials.
- Non-destructive PAT for process feedback control, automated quality control, real time monitoring and product release.
- Increase analytical power for harvesting large data sets (diagnostic, genomic).
- High throughput systems and micro-bioreactors for rapid process development and better process understanding.

Regulatory Science

Emerging regulatory uncertainties/challenges for the FoF include: quality standardisation/use of single use equipment and (re-biocompatibility; leachables/extractables); manufacture and standardisation of synthetic biology derived material; implementation of continuous manufacturing and multiproduct; metrology standardisation and validation; specific issues related to manufacture and supply of personalised/stratified/lifestyle medicines, convergent technologies, biosimilars/biobetters, including arising conflicts between biosafety (containment), and GMP, validation of comparability to allow process change and manufacturing and supply economies. The balance of product and process innovation and patient benefit and safety is debatable.

4. Conclusions and recommendations

The study was based on a review of published material and structured interviews with senior executives from large companies and SMEs in Europe, USA and Japan, along with international experts in the area.

From this review it is clear that to be competitive, the UK needs a national strategy and it is important to maintain focus on manufacturing policy, including technology demonstrators and procurement. In this respect the High Value Manufacturing Catapult (which is represented by one of the authors) is a valuable initiative, and one which supports the direction of travel indicated in this report. The concept of the Factory of the Future (Factory 2050) provides a focus for manufacturing research roadmaps and will support further initiatives in other industrial sectors.

One integrating perspective emerged during our interviews and discussions. In this view the Factory of the Future is a complex system, itself embedded in an extended enterprise involving suppliers, customers and other partners who have the potential to add value (such as local Universities and schools). This perspective is summarised in figure 10 below.

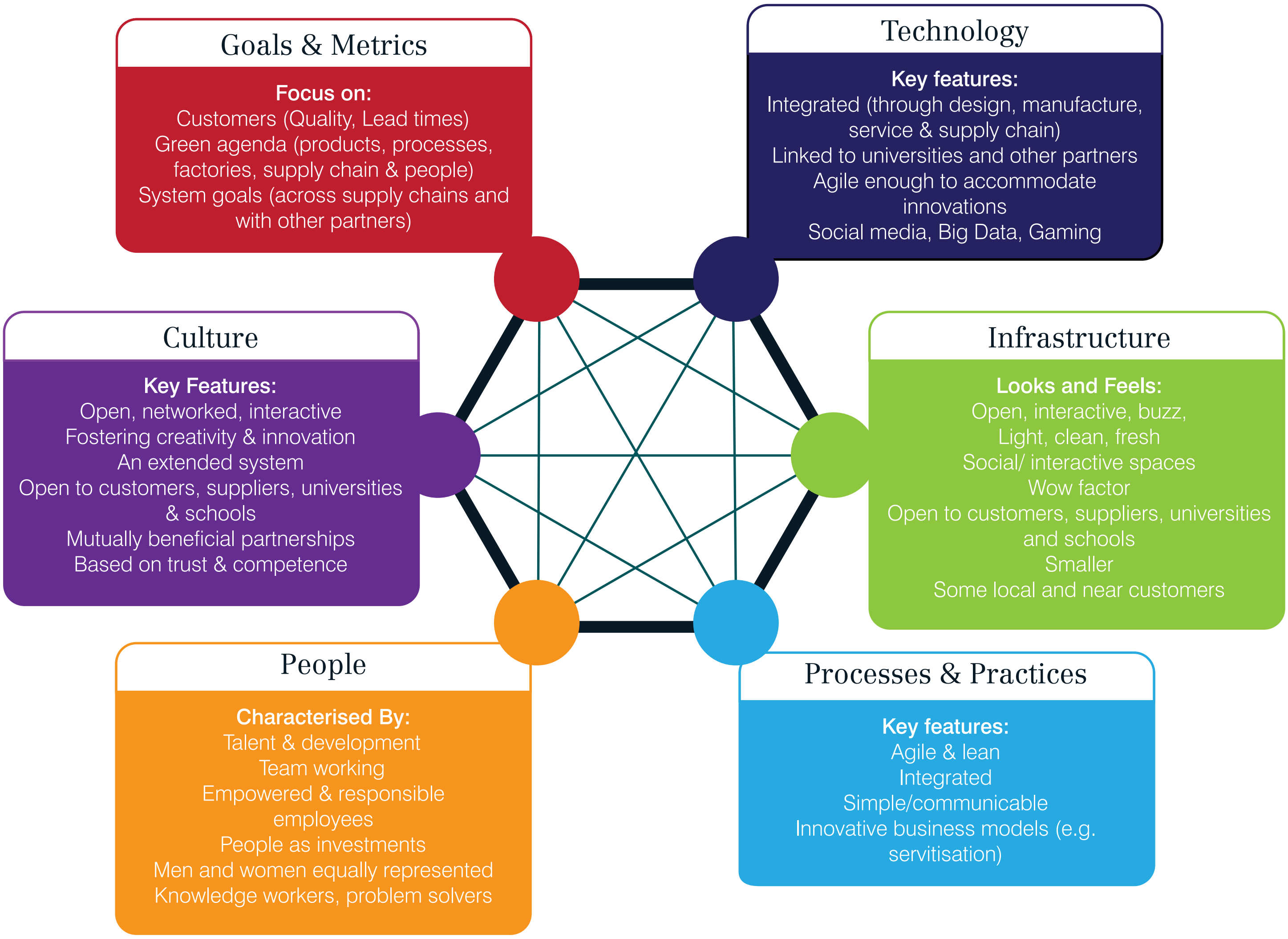

Figure 10: Characteristics of the Factory of the Future

In this view the Factory of the Future has sets of goals and metrics focussed on meeting the needs of customers and a wider green agenda. The factory works closely within the supply chain and has partnership agreements with local universities and schools, between which there is a sustained flow of people, projects and ideas. This represents the open culture which emphasises creativity and innovation, rather than command and control.

All this is supported by the physical environment, which is open and welcoming. It is clean and fresh. It has a 'wow' factor that attracts people to join. In general, these factories are small and near their customers.

The technologies support the above. They are integrated through design, manufacture, service and supply, promoting and enabling interaction between the various partners. Social media and big data are used routinely. The organisation and culture are agile enough to accommodate disruptive technologies as and when they become available.

The people are talented and have continuing opportunities for development, working in integrated teams that are empowered and responsible. These are knowledge-workers and problem-solvers. People may start apprenticeships when they are in their 40s and 50s with plenty to offer and plenty to learn. Men and women are equally represented at all levels.

The processes and practices are agile, cutting through internal and external silos. The systems are simple to communicate and understand. The factory and wider system employ innovative business models (such as servitisation).

For the operator of the factory this delivers a responsive enterprise that is key to their business model and value, delivery to the market and consequently long-term profitability. This remains economically sustainable by continually addressing the manufacturing touchstones – "better, faster, cheaper, cleaner" - and by its critical place in local innovation eco-system.

It is important to note that this perspective is not offered as a universally applicable template for the design of the Factory of the Future. Clearly there will be variations and some of the key factors influencing such variability are described below. However, this perspective represents a template for wide and serious consideration.

The table below takes a sectoral view of the FoF and some of the individual factors that influence the design of the FoF. For instance, in aerospace the desire for localised supply parks needs to be considered against the desire to meet offset and international trading requirements.

Table 2: Factors influencing the design of the Factory of the Future

	Automotive	Civil, aero-engines and airframe	Life Sciences	Fabricated Metal and Plastics	Generic drivers
Social	Continued demand for personal transport More people Large emerging middle class in BRIC	Continued demand for inexpensive international travel Huge growth internationally	Population growth and ageing in old economies Individuals must bear more of cost of health care	Reputation of manufacturing Skills exit	Large population growth Growing global middle class
Technical	Electrification of power train Electronics content Battery development	Composites and new materials	Personalised medicines Biologics	Commoditisation of manufacturing technology	Continuous change and uncertainty Automation Social media Big data
Economic	New entrant countries dramatically lowering cost EU high end Emergence of niche luxury players	New developments need a continental scale investment Embraer like niche players	Pharma business model not sustainable	Cash flow Cost of capital Competition in Europe (Swiss, German, Czech, Sweden)	Education and skills Strengthening BRIC Distributed manufacturing Regional specialisation
Environmental	Greening of product Sustainable manufacturing	Greening of product Sustainable manufacturing	Environmental second order driver	Carbon/Energy surcharge Sustainable manufacturing	Sustainability Environmental driven taxation
Political	Greening Impact of taxation	Offset obligations Greening Fuel duty	Governments unable to sustain cost Regulatory rebalancing	SMEs Regulation/ Bureaucracy (Leaning)	

It appears that there are few major, shorter-term (before 2030) game-changing manufacturing technologies that have the potential to revolutionise manufacturing or lead us to completely rethink the concept of the FoF. The technologies required in the FoF are largely already available. The FoF will make better use of the technologies - developing a better understanding of how to get the best from the technologies available, and improve levels of integration. This will require more effective organisation and processes, operated by talented and highly skilled individuals. Supporting software and systems will make the technologies easier to access, monitor and control. Moreover, adaptive control will tend towards self-learning and there will be emphasis on fast ramp up and the transition from manual manufacture of first prototypes, through semi-automation to fully automated systems.

The potential exception is Advanced Multi Material Additive Layer Manufacture (ALM a.k.a.3D printing) which could be very significant. It is inevitable in the timeframe that complex (combined metallic and synthetic/macro and nano) structures and systems will be created. There is considerable potential to produce rapidly customised high value products. ALM was cited as having potential to meet the requirements of manufacturing a batch size of one in a reconfigurable factory. Indeed linking large-scale additive manufacturing and robotics was identified as one form of a FoF. ALM offers the potential for consumer driven personalisation, producing customised prosthetics and made to measure implants produced direct from MRI scans.

The Urbee car[1] is the result of collaboration between Winnipeg engineering group, Kor Ecologic, which designed the vehicle, and Stratasys (additive manufacturing machine). Stratasys[2] is responsible for printing all the vehicle's exterior components using fused deposition modelling (FDM), which allowed the elimination of tooling, machining & handiwork and improved efficiency when a design change is needed. (Automotive X prize 2010)

There are many initiatives in more mainstream manufacturing, which are looking to utilise and qualify many materials. The combination of the above will become very potent for an industrial revolution in the 2050 timeframe.

The challenge with 3D printing is seen as the speed of build and the weakness in the direction of build (z direction). The speed could be addressed using mass parallel printing to produce complex structures and volume parts. Red Eye[3] from the USA has invested in sets of deposition machines which can currently produce around 5000 parts from an initial request in about 2 weeks – and each part can be different. Their business has a growth rate forecast of 30% year-on-year due to increased demand. They produce parts that have started in the low risk prototype and tooling and now also produce some qualified parts that have gone into products such as the ICON A5, which is in low rate production.

The meetings with high level stakeholders, senior industrialists and academics suggested that the concept of the Reconfigurable Factory needed a more detailed explanation. It is fair to say that the concept and implications of the 'Reconfigurable Factory' are not fully appreciated and it is worthwhile expanding this concept in more detail. The Reconfigurable Factory will have the ability to switch instantaneously between products being manufactured, for example, from an automotive component to an aerospace component.

This will not require the instantaneous changeover of programmes, tooling, sub-assemblies and raw materials. This cannot happen without a step change in the design and operation of manufacturing systems and technologies.

The highly desirable 'Reconfigurable Factory' requires major advances in, and integration of, many of the technologies we are currently familiar with. For instance advanced robotics, internal GPS systems, adaptive control, adaptive learning, modelling and simulation of the working environment, systems and processes, virtual reality modelling, simplified ITC systems, plug-and-play machine tools and robots, flexible and intelligent fixtures and integrated tooling systems all linked to the human aspects that will make the system operable.

The extensive use of co-operating robotics will support flexible manufacturing. Co-operation allows speed and flexibility in a -dimensional space and is way beyond the traditional use of robotics in the automotive industry. This will offer western factories a revolution that dramatically reduces their workforce cost base (by significant automation and manning reduction). This would shift the skill base of the workforce increasingly towards the higher level skills associated with the technologies listed above. By 2050 a large proportion of those roles may also have migrated to a more artificial intelligent based computing based environment. This clearly generates questions around the volume of employment in the FoF 2050.

The drive for flexibility and multi role capabilities of robots will produce robots with increasing faculties, sensors (vision, touch etc.) accuracy of implementation, and speed. The flexibility will be greater enhanced by the use of multi role heads and complex multi robot interactions. Multi role heads will include very accurate drilling, metallic spray, sanding and potentially cutting guided by internal GPS / positioner technology.

It is clear that 'design for manufacturing' will be a recognised differentiator with new methods being a key part of the intellectual property. The automated sequencing of complex manufacturing activity will also become a differentiating science in its own right. By 2050 the flexibility of operating for the interacting robotic heads will have created a complexity of operation that will move the FoF into a toolset driven engineering / manufacturing interface. The ultimate benefit of this integrated environment could be the design and manufacture of quite diverse products using the same manufacturing and assembly environment. This is clearly an attractive option for the manufacture of low volume, high value products and components.

The 'big idea' is that the extended enterprise (incorporating the factories, integrated value chains, and stakeholders such as local Universities and schools) is re-configurable to meet changing demands and needs in order to respond to customers.

Interestingly, the concept of cloud computing or cloud manufacturing was not mentioned by any of the interviewees, but the idea of localised supply parks and 'resource pools' alludes to there being potential for some form of cloud or distributed manufacturing. These could be important enablers in the reconfigurable enterprise, which is the natural extension to the reconfigurable factory. The reconfigurable enterprise will have the ability to manufacture a range of products. This will involve rapid changeover within the reconfigurable factory aided by increasing use of distributed manufacture where components are made locally within the supply park.

[1] *www.urbee.ne*
[2] *www.stratasys.com/resources/case-studies/automotive/urbee*
[3] *http://www.redeyeondemand.com*

Themes previously promoted such as 'Factory on skids', 'Micro Factory Retail Centres' and the '5-day car' do not appear on the radar for the FoF. The general trend is towards smaller, manageable, clean, well-organised, highly flexible factories that contain updated but traditional technologies that can be quickly ramped up to meet volume and changing market requirements. Customer focus and personalisation of product is recognised as being of increasing importance and it is clear that in the longer term there will be a need for centralised mass production facilities and localised facilities to personalise the product.

Future factories will tend towards flatter management structures with a more highly skilled and IT literate work force focussing more on optimisation, monitoring and controlling processes. This will lead to de-skilling of traditional skills such as machining and welding and reskilling in the new advanced technologies, the soft skills in managing operations effectively, and understanding & working with the customer.

One striking factor in this survey has been the emphasis of interviews on the importance of the value chain. The ability to create and operate a value chain that collectively delivers a unique value proposition to the user market is seen as the most significant source of future competitive advantage.

Businesses need this understanding and the skills and capabilities to both create the value chain as an integrated system – the key step – and to operate it. Materials management and resource conservation is also critical in the design and operation of the supply chain as reflected in the Japanese concept of 'Monozukuri'.

A further opportunity arises through capitalising on the largely untapped potential for collaboration between manufacturing companies and UK universities. In this view, manufacturing companies have need for the latest thinking, for new ideas and for innovation (and not just in engineering and technology). Universities are perpetually refreshing their skills and capabilities through young talent with aspirations, and have thousands of talented people potentially looking for R&D opportunities. Whilst there are some excellent role models who manage these relationships well, there are opportunities to bring these communities together in real and substantial long term relationships that benefit all parties and the UK.

Potential game changers include advances in materials enabled by materials science. This includes graphene and nano-materials, new surface coatings, new composite materials and resins including bio-composites, and biologically derived and natural, living materials. Perhaps just as important however, are game changers in our vision for the Factory of the Future and its organisational arrangements. This study is clear – the FoF will require world-class organisation, people and technology working to find creative and innovative ways of adding value.

Put another way, the potential game changers are not seen as purely technological in origin. Some are contextual and reflect the growth of the BRIC economies which will mean that we have to radically improve our factories of the future. This will require the attraction and development of more talent at the very time we are squeezed by an ageing workforce and one that currently employs too few women.

The emerging mental model for the FoF is of centres of creativity and innovation, embedded in effective networks of relationships (for example with suppliers and universities) where capable and talented people use world-class technologies and processes to create new ways of adding value. This is a world of challenge, interest and excitement.

The authors of this report were asked to include some recommendations for a UK response to the findings emerging from this study. At this stage we wish to make recommendations in eight inter-related areas concerned with the development of:

- More integrated and optimised supply/value chains and the standards that will enable them.
- Stronger long term collaborations between manufacturing companies and UK universities to improve innovative thinking and the rate and uptake of R&D.
- A focus on both organisational and technical innovation, each feeding off each other.
- A systems view of the FoF, integrating people, organisation and technology.
- The design of agile, reconfigurable factories and extended enterprises.
- A rebalancing of the regulatory framework to enable the rapid construction of the next generation of factories in Europe and to permit manufacturing innovation, in particular for life sciences.
- A clear and sustainable UK vision that factories of the future are centres of creativity and innovation, embedded in effective networks of relationships, where talented people use the latest technologies and processes to create new ways of adding value.
- Recognition that this will require a significant cultural shift both in how manufacturing organisations operate and in how they are perceived.

Some might argue that this list is probably not particularly surprising. However, we take a different view. Thus, if manufacturing companies in the UK were able to deliver the changes listed above, then that would represent a major cultural shift, with the potential for improved innovation and competitiveness. Such changes would make people want to work in manufacturing, thereby attracting, developing and retaining the talent that is needed.

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Appendix 1: Interview schedule

Foresight Future of Manufacturing project

Introductory remarks

This study is being undertaken by researchers from the Universities of Sheffield, Loughborough and Leeds, on behalf of the UK Government Office for Science (GO-Science).

The aim is to identify the main trends shaping the factory of the future, seeking to provide a timely and fresh look at the long term picture for the UK manufacturing sector out to 2050. This study is part of a wider project, due to report in autumn 2013, which will inform thinking on industrial policy.

We are interviewing experts in manufacturing about its long term future. The interview should last around one hour, and, with your permission, we would like to record it.

We will write up this interview and send you a copy of the notes for your verification.

When we have a draft of our report, we will send you a copy for comment. Quotes may be used in the final report. If we wish to use a quote from you, we will seek your explicit permission. With your permission, we would also like to include your name in the report as a participant in this work.
We aim to submit a draft report for further discussion by 16 January 2013
You will receive a copy of the final version of the report.

If we may, we may get in touch to discuss future work arising from this project.

For further details of the project, please visit the Foresight website: http://www.bis.gov.uk/foresight/our-work/projects/current-projects/future-of manufacturing

Thank you for your time and participation. We hope you find this work both interesting and useful. We will keep you informed on the next stages of this study.

Please note, throughout this interview, we would like you to try to answer each question using a 'bullet-point' format – in other words we are seeking a few short key points under each question.

Interview questions

Background information

- What is your current role? And for whom do you currently work?
- What are your major areas of expertise in the field of manufacturing?
- In which sectors/industries have you worked?
- In what countries have you worked? And/or held responsibilities?
- For how many years have you worked in the area of manufacturing?
- Have you previously worked in other areas/sectors? If so, in which?

What are the main trends shaping the Factory of the Future?
In your answers please consider the medium term, i.e., as far out as 2020/ 2030

1. Are you aware of where there is work underway to examine the likely nature of the Factory of the Future?
(this might be research, development, practice, consultancy)
What are the main findings of this work?

2. Which factories are currently regarded, internationally, as examples of best practice and why?
(for example, the VW transparent factory in Dresden, and the Nissan factory in Sunderland).
Please cite particular examples you think we should know about.

3. In which sectors are the traditional views of a factory most likely to be challenged (for example in pharmaceuticals - factory in a cell/body in a cell[1], or chemicals - additive layer manufacturing of a customised factory[2])?

4. What lessons can be learnt from examining cross-sector issues, e.g. would the Factory of the Future in the bioscience/pharma sector benefit from thinking in the aerospace/automobile sector or vice versa?
In what ways might they benefit?

5. What developments can be expected in the physical arrangements of the Factory of the Future, i.e. would it be centralised, distributed, or reconfigurable?
Have you witnessed such arrangements being effective?
How does this differ by sector?

6. Will demand for personalisation of products affect the viability of the current model of a centralised factory relying on economies of scale (e.g. the rise of 'single use' disposable or multi-use factories)?

7. Which technological trends (including robotics and new design methodologies) or emerging technologies (including nano-technologies) are most likely to have a significant impact on the Factory of the Future?
In what ways will they have an impact?

8. What role will the workforce play in the factory of the future?
How will this be optimised?
For example will the trend be towards up-skilling staff?
Or deskilling?
Or some combination of both?

[1] Human body on a chip: DARPA – MIT collaboration (http://web.mit.edu/newsoffice/2012/human-body-on-a-chip-research-funding-0724.html)
[2] Chemical Engineering: 3-D printer produces custom vessels for chemical synthesis (http://cen.acs.org/articles/90/i16/Chemical-Reactors-Demand.html)

Interview questions cont...

9. For example, are these likely to get more global? Or more local? Are they likely to get leaner? Or to build in redundancy to cover threats to resilience?

10. How important is process and product innovation in shaping the factory of the future? Can you provide examples of such innovation?

11. What will be the impact of 'servitisation'? Is this likely to increase?

12. What will be the impact of other changes in underlying business models and emerging standards in this area?

13. What are the other trends shaping the factory of the future, for example including (NB some of these may already have been touched upon earlier in the interview)

a. The green agenda (reducing energy, water, waste)
b. Changes in management practices and processes
c. Changes in communications practices and social networks/ social media
d. Changes in demands for proximity to customers
e. Changes in the costs of resources
f. Changes in the costs of transportation
g. Changes in performance metrics – e.g., increased emphasis on quality, lead times and customer satisfaction, as opposed to machine utilisation and efficiencies
h. Changes in regulatory frameworks – e.g., in health and pharma?
i. Changes in the speed at which research and development innovations get translated into use and get widely deployed? (e.g., will such lead times get shortened?)

14. What do you think are the potential 'game changers' for manufacturing? i.e., things that will lead to radical shifts in the factory of the future

15. How do views on the factory of the future vary between nations? In particular comparing: China, US, Germany, South Korea, Japan and Singapore. What do you think is causing these differences?

16. How should the UK respond to any suggestions of what the factory of the future would look like? Can the UK benefit by being ahead of the game?

17. Do you have any views on trends affecting the factory of the future as far out as 2050?

Summary questions

In summary then, what do you think are the main trends shaping the factory of the future?

Is there anything else you wish to add that we haven't covered in this interview? What next?

Just to summarise:

We will write up this interview and send you a copy of the notes for your verification
We will draft our report and send you a copy for comment
We aim to submit our final report by (relevant date)
You will receive a copy of the final version of the report.
If we may, we may get in touch to discuss future work arising from this project

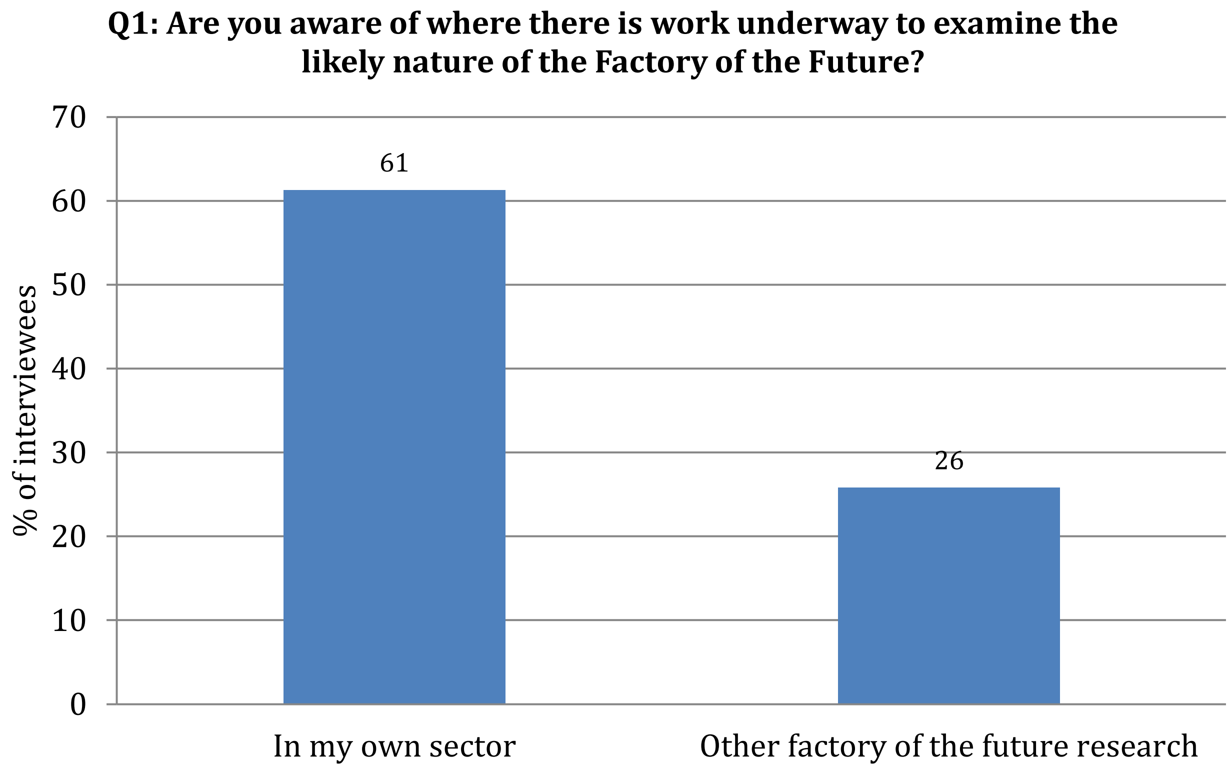
Thank you

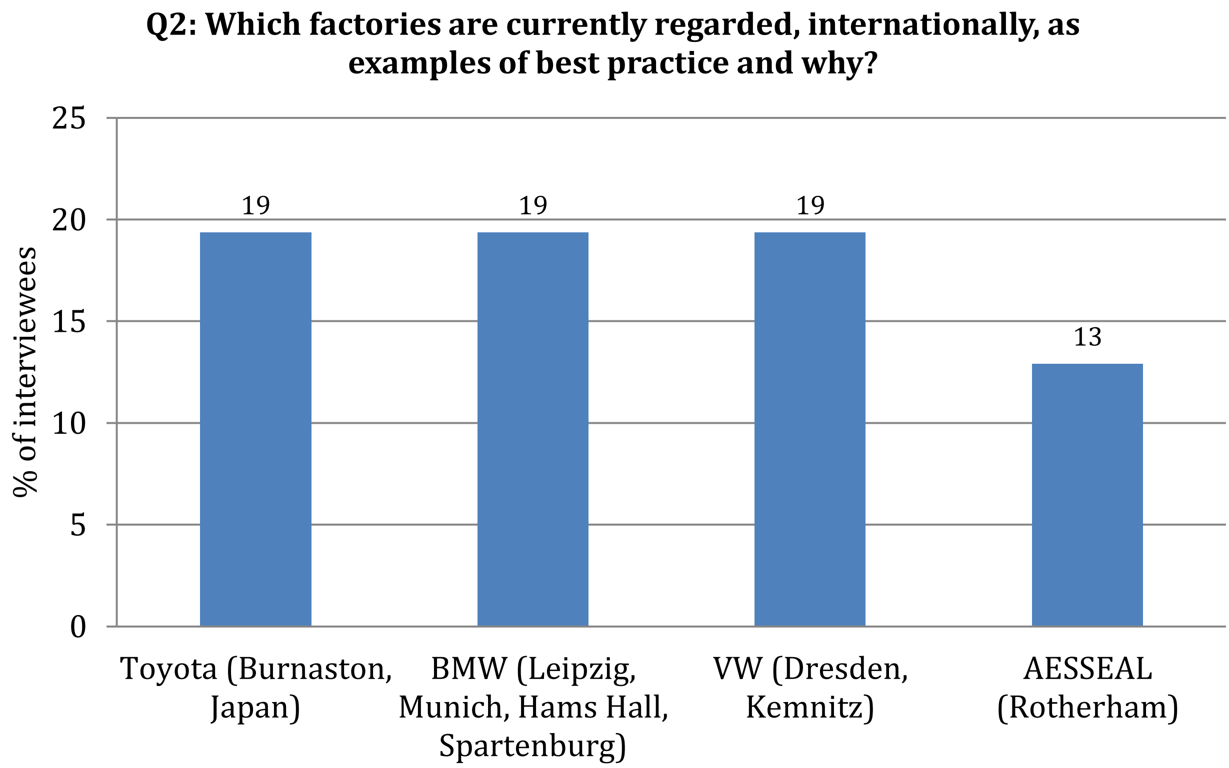
Footnote

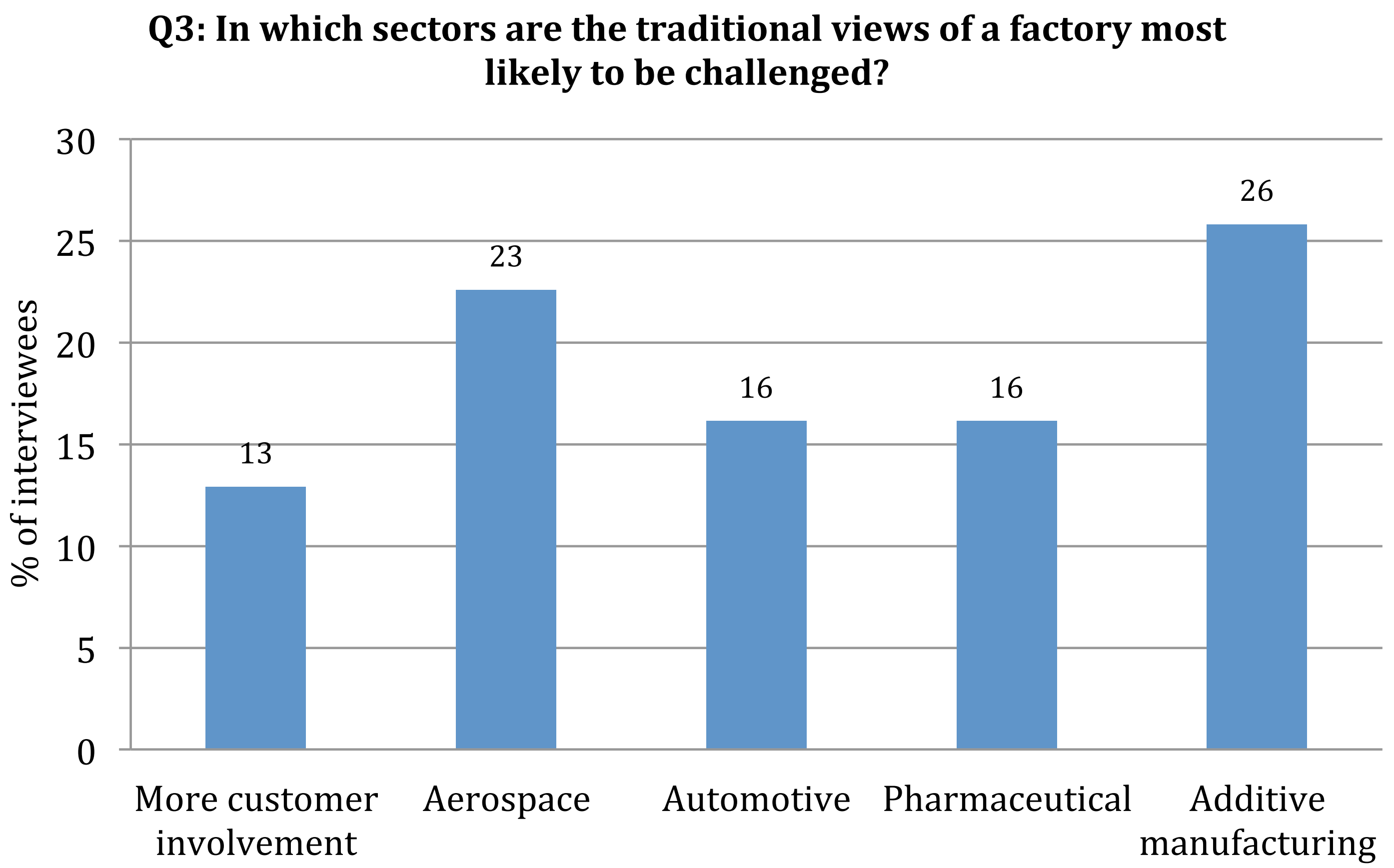
If a participant requested a definition of manufacturing, the following was provided: "Manufacturing is a system of value creating activities required to develop, produce and deliver goods and services to customers. Activities may stretch from R&D at one end to recycling at the other."

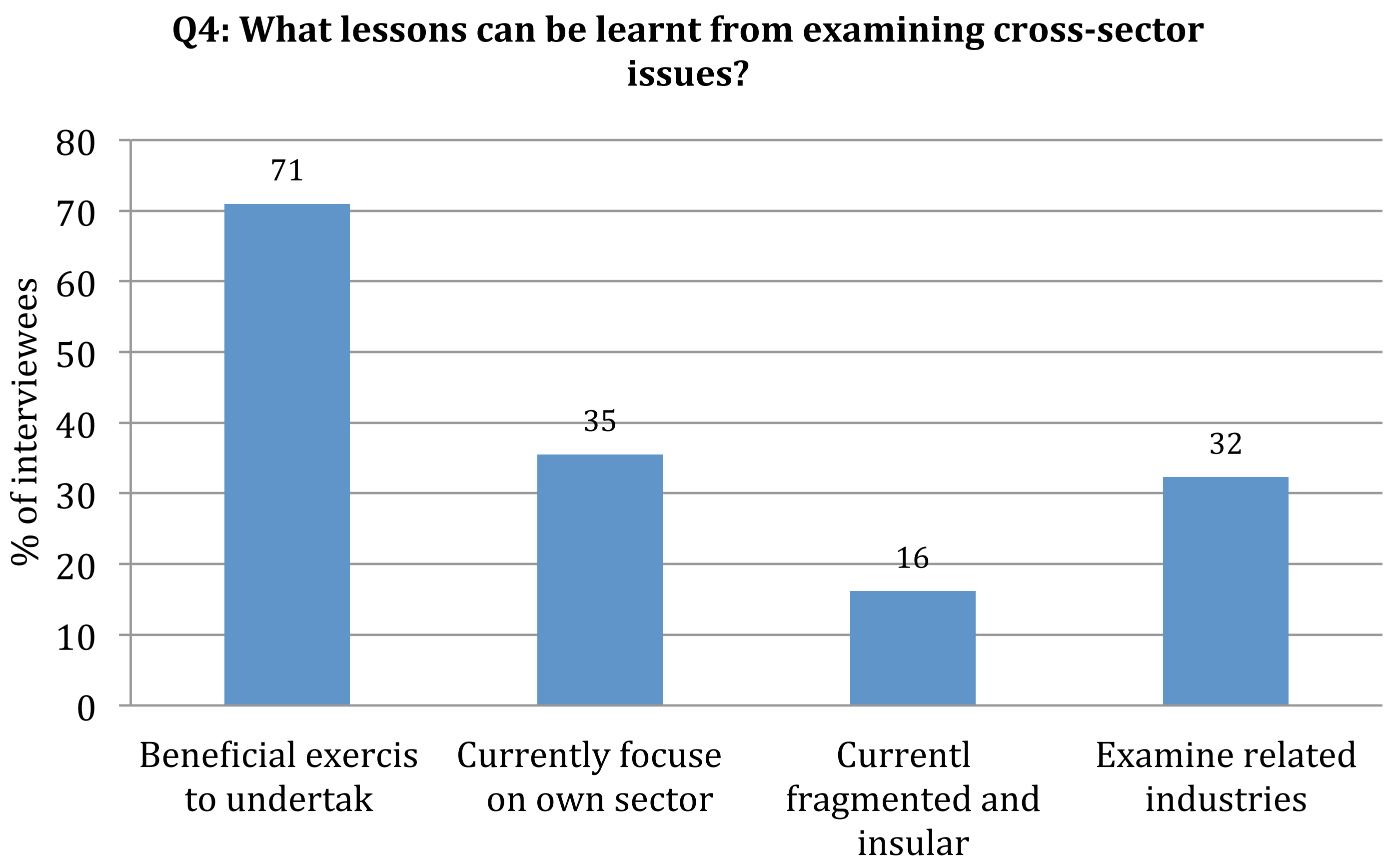
Appendix 2: Summary of responses to interview questions

The following graphs summarise interviewees' responses to each question. Only themes mentioned by over 10% of interviewees are shown, except in question 17 where only one theme reached this threshold and the most frequent themes are shown. We acknowledge the work of Helen Baker (University of Leeds) in undertaking the underlying content analysis of the interview data.

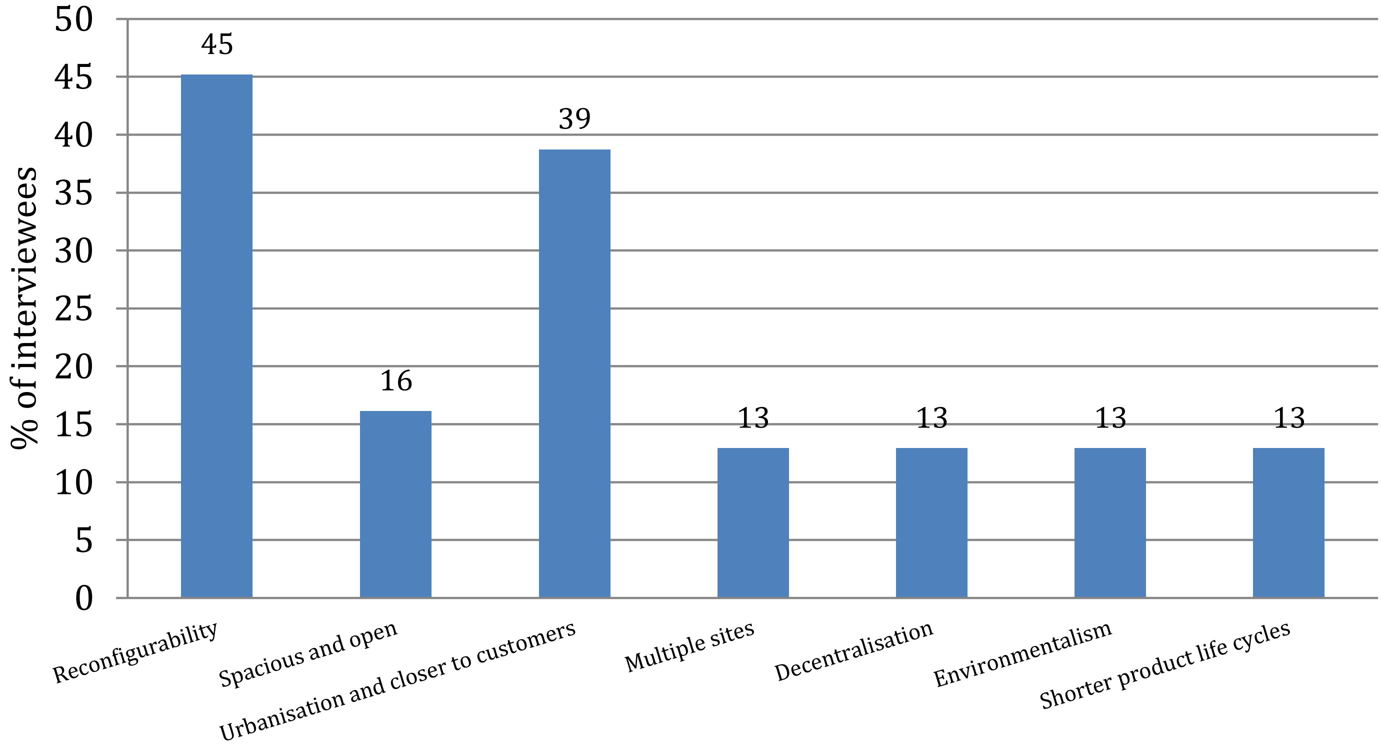




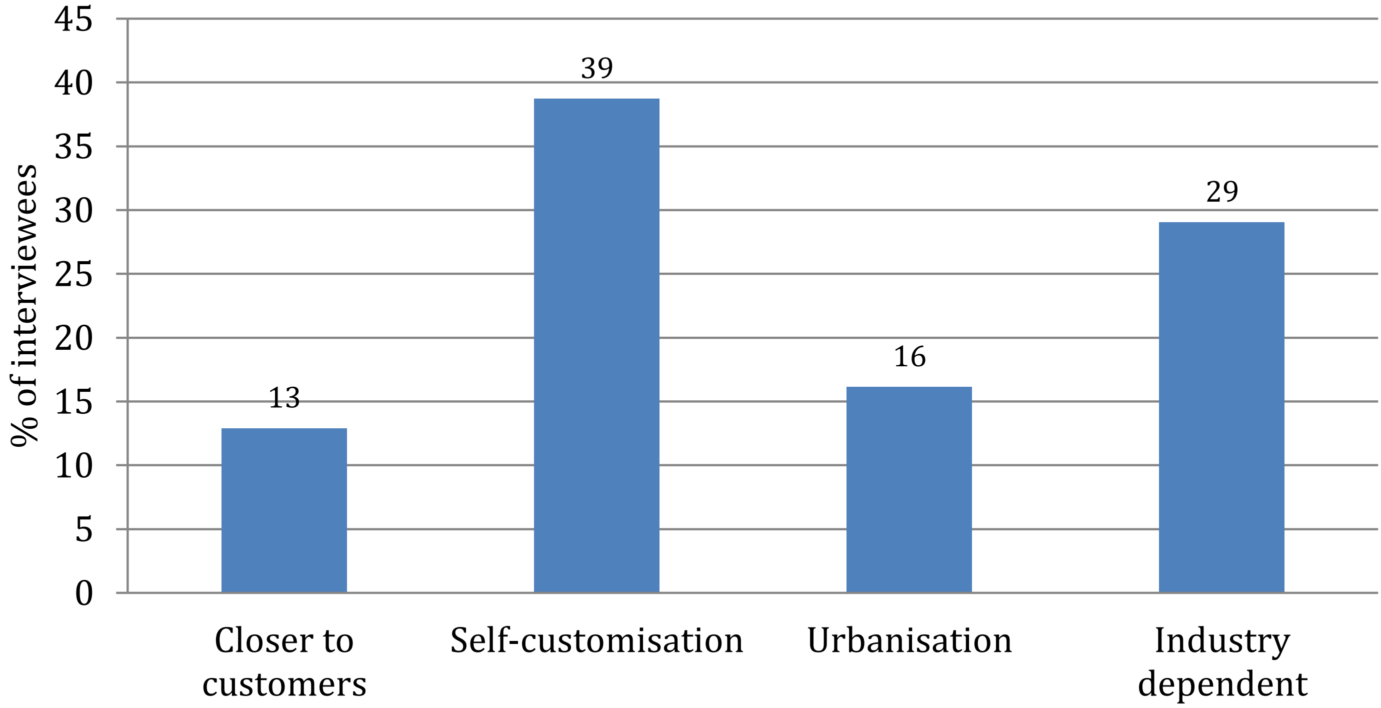

Q3: In which sectors are the traditional views of a factory most likely to be challenged?
% of interviewees
30
25
20
15
10
5
0
13
23
16
16
26
More customer involvement
Aerospace
Automotive
Pharmaceutical
Additive manufacturing

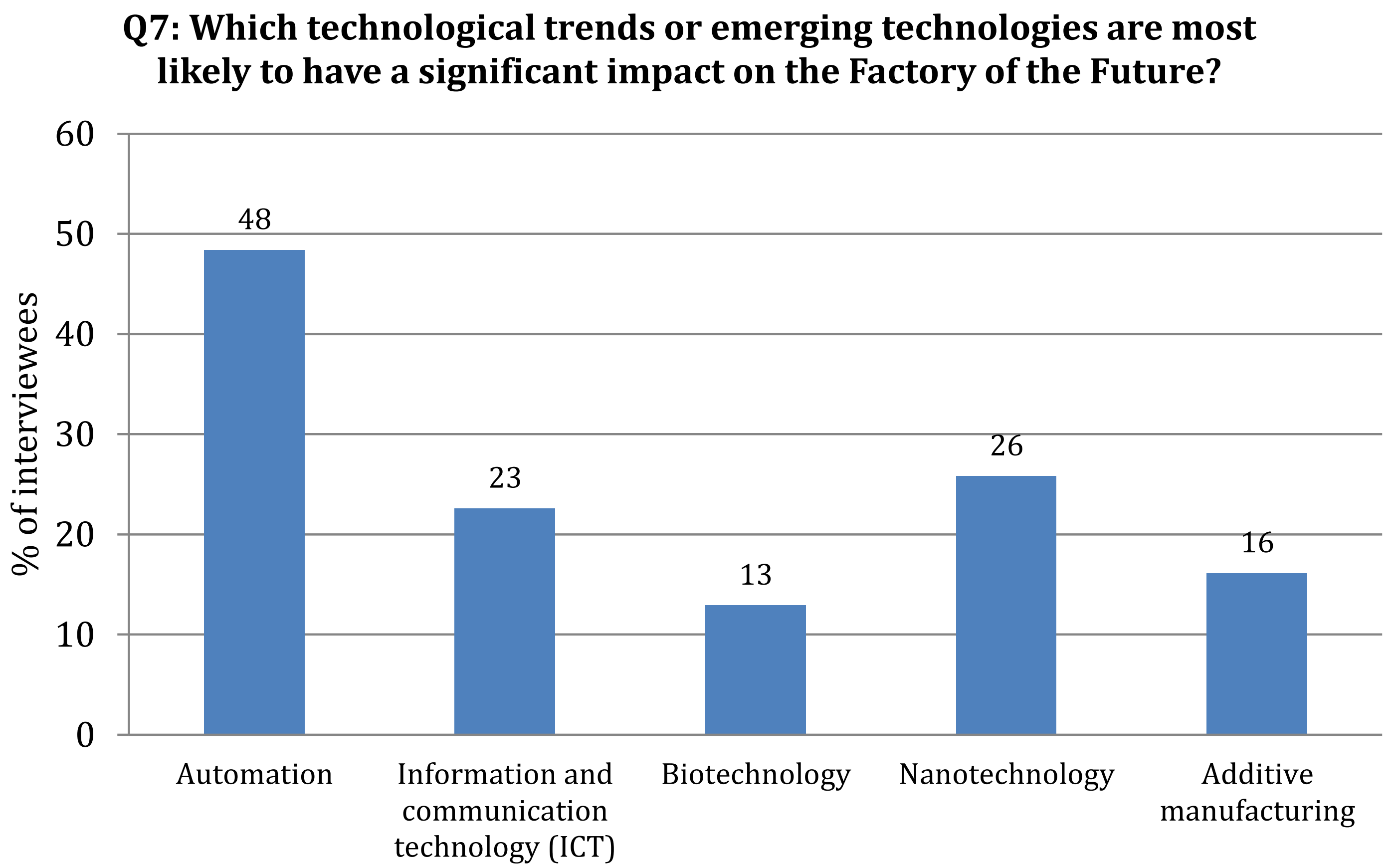

Q4: What lessons can be learnt from examining cross-sector issues?
% of interviewees
80
70
60
50
40
30
20
10
0
71
35
16
32
Beneficial exercis to undertak
Currently focuse on own sector
Currentl fragmented and insular
Examine related industries

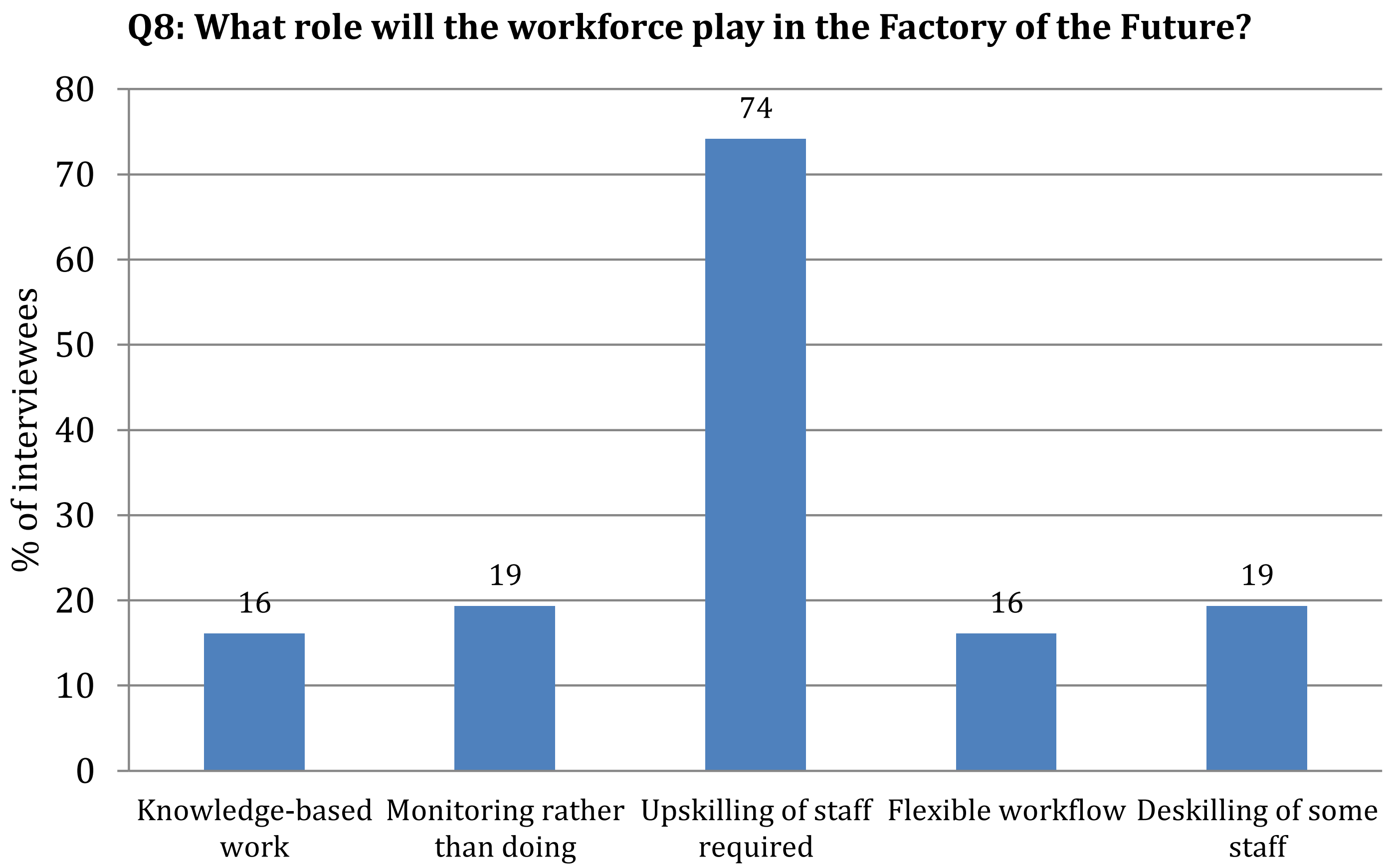
Q5: What developments can be expected in the physical arrangements of the Factory of the Future?



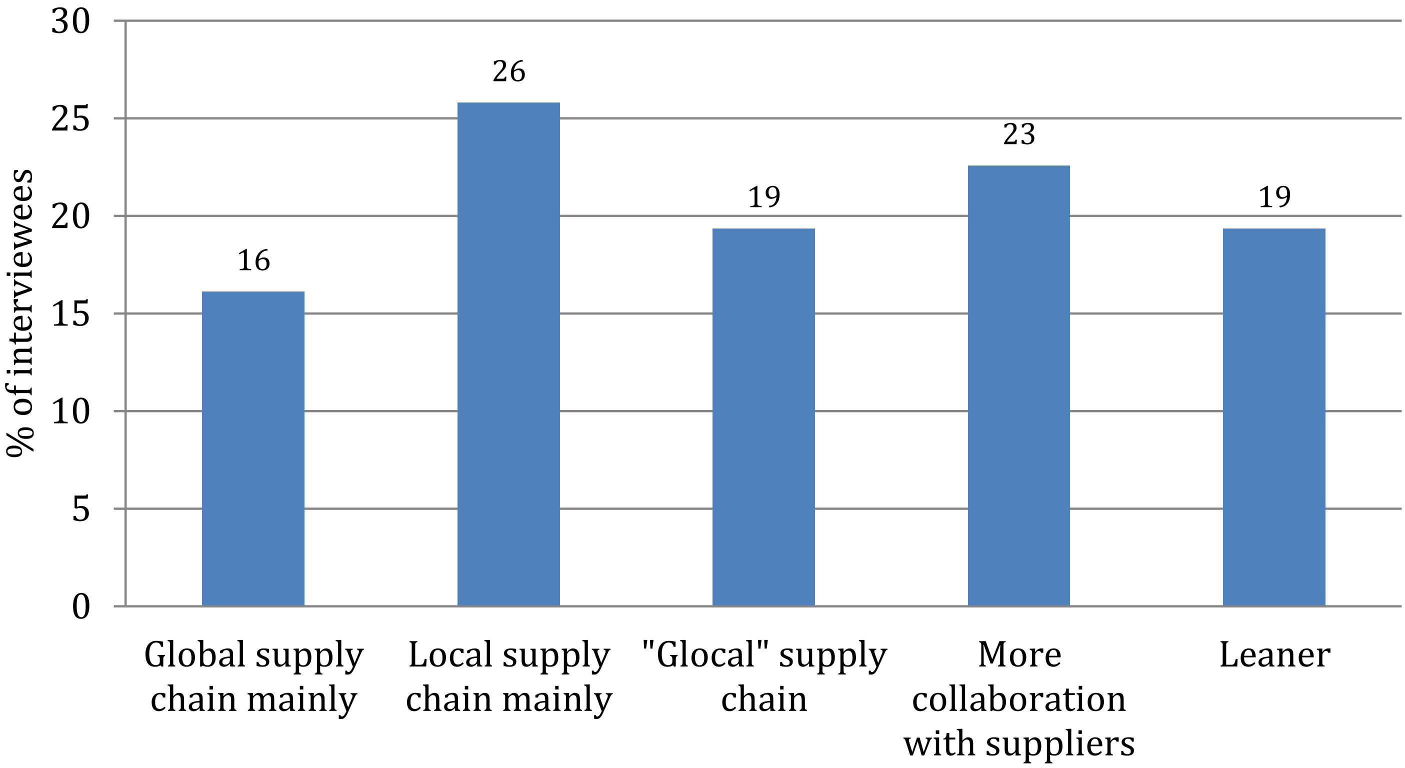
Q6: Will demand for personalisation of products affect the viability of the current model of a centralised factory relying on economies of scale?



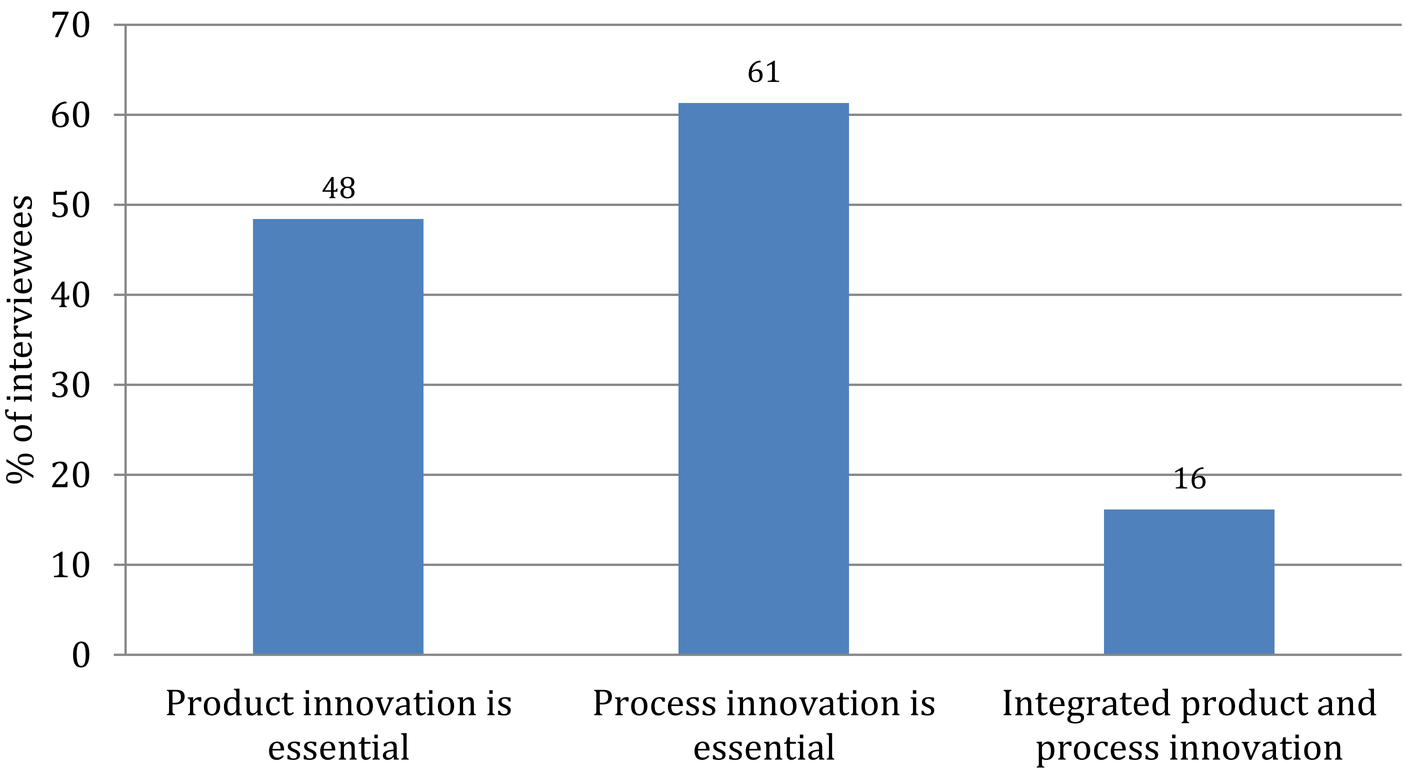

Q7: Which technological trends or emerging technologies are most likely to have a significant impact on the Factory of the Future?
% of interviewees
60
50
40
30
20
10
0
48
23
13
26
16
Automation
Information and communication technology (ICT)
Biotechnology
Nanotechnology
Additive manufacturing


Q8: What role will the workforce play in the Factory of the Future?
% of interviewees
80
70
60
50
40
30
20
10
0
16
19
74
16
19
Knowledge-based work
Monitoring rather than doing
Upskilling of staff required
Flexible workflow
Deskilling of some staff

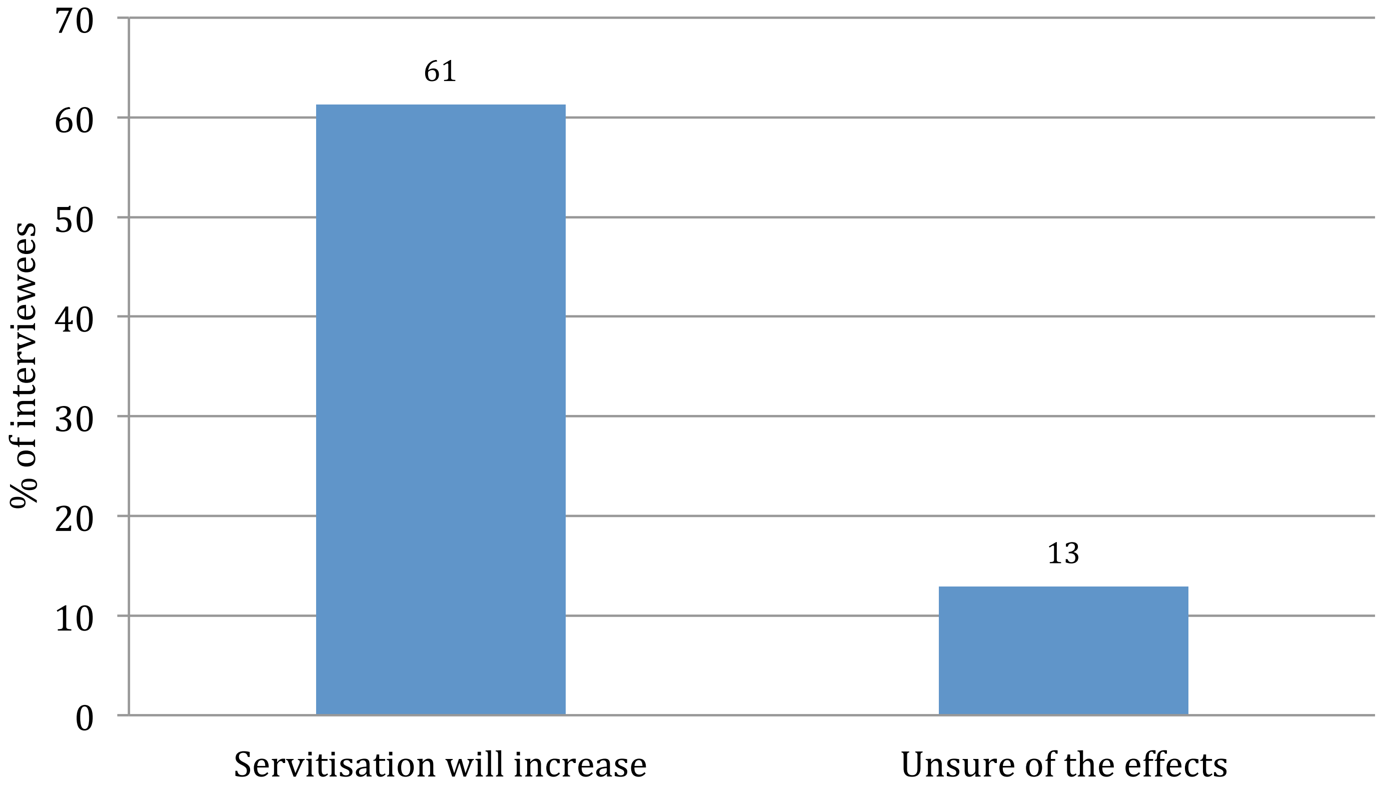
Q9: What role could the supply chain play in the Factory of the Future?



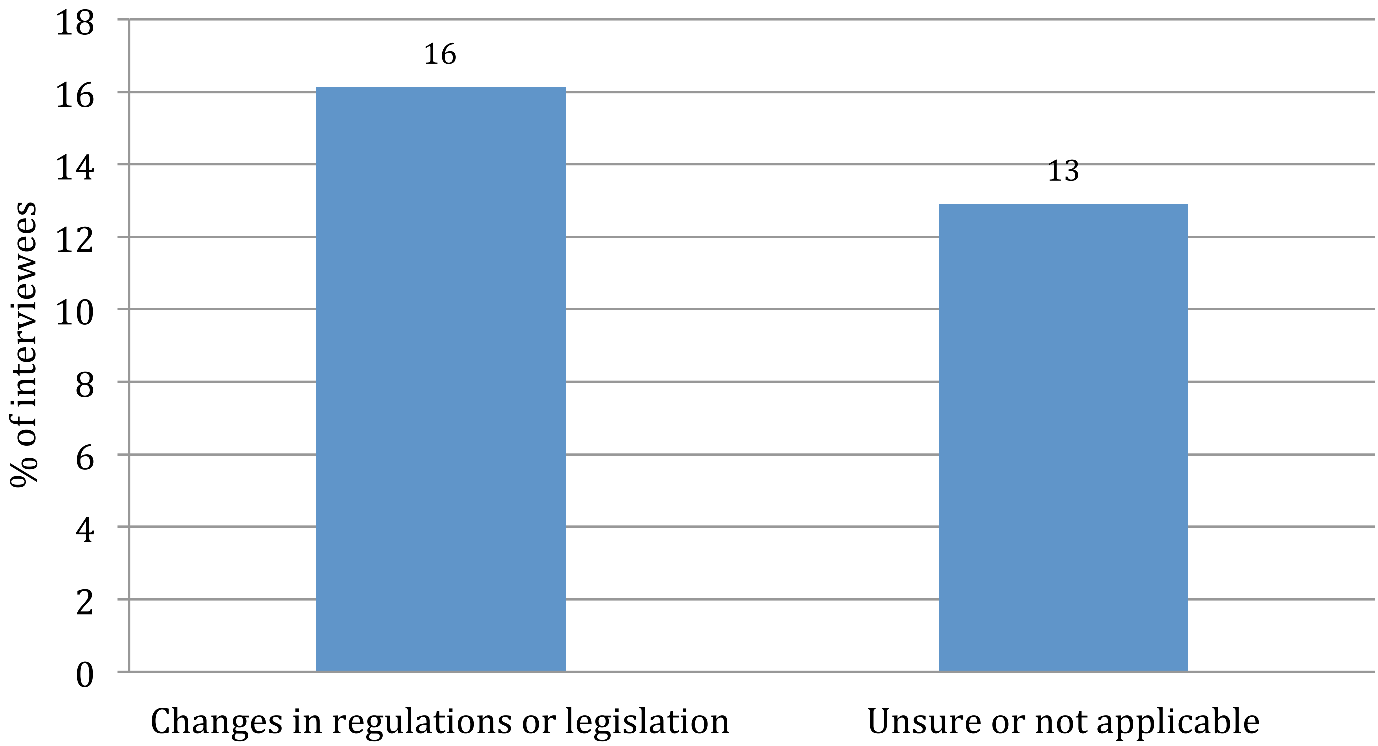
Q10: How important is process and product innovation in shaping the Factory of the Future?



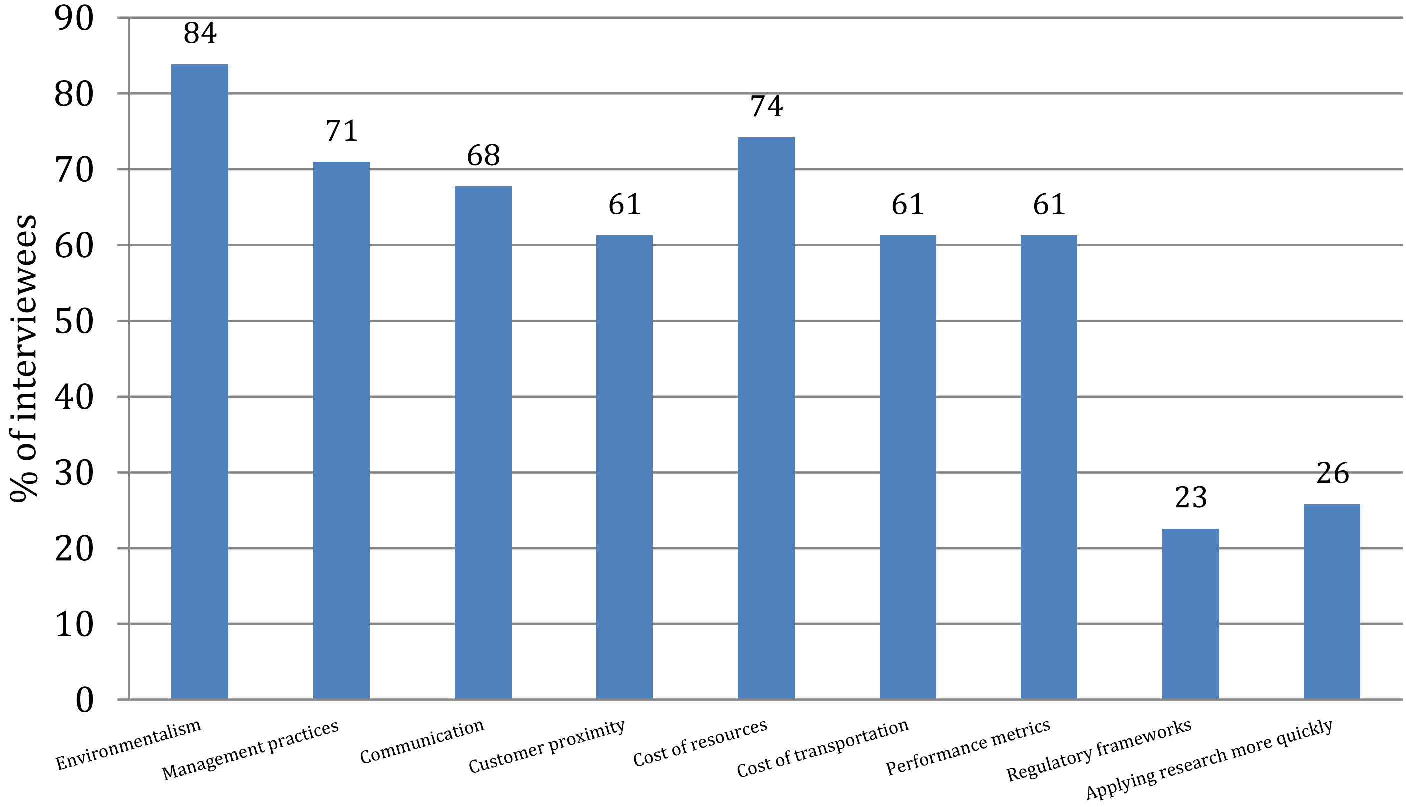
Q11: What will be the impact of 'servitisation'?



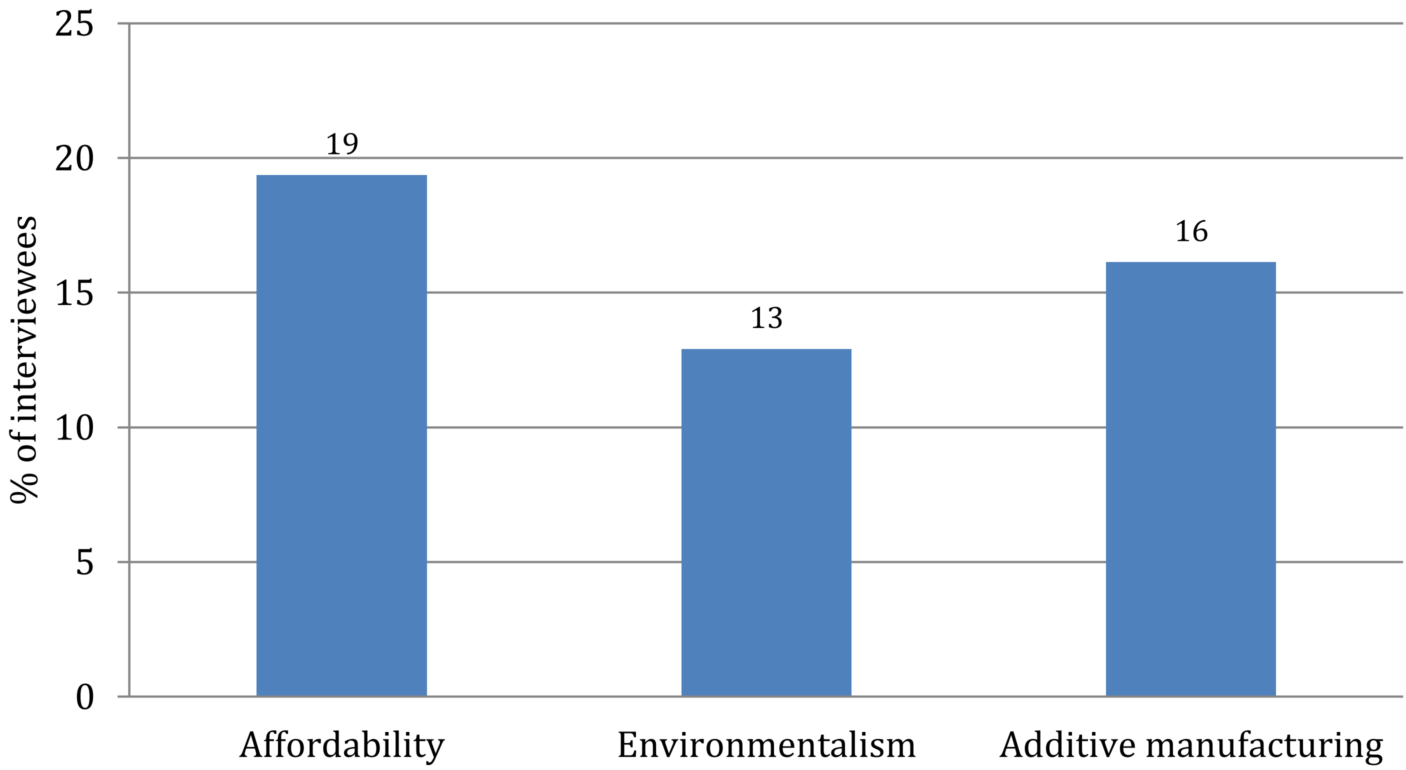
Q12: What will be the impact of other changes in underlying business models and emerging standards in this area?



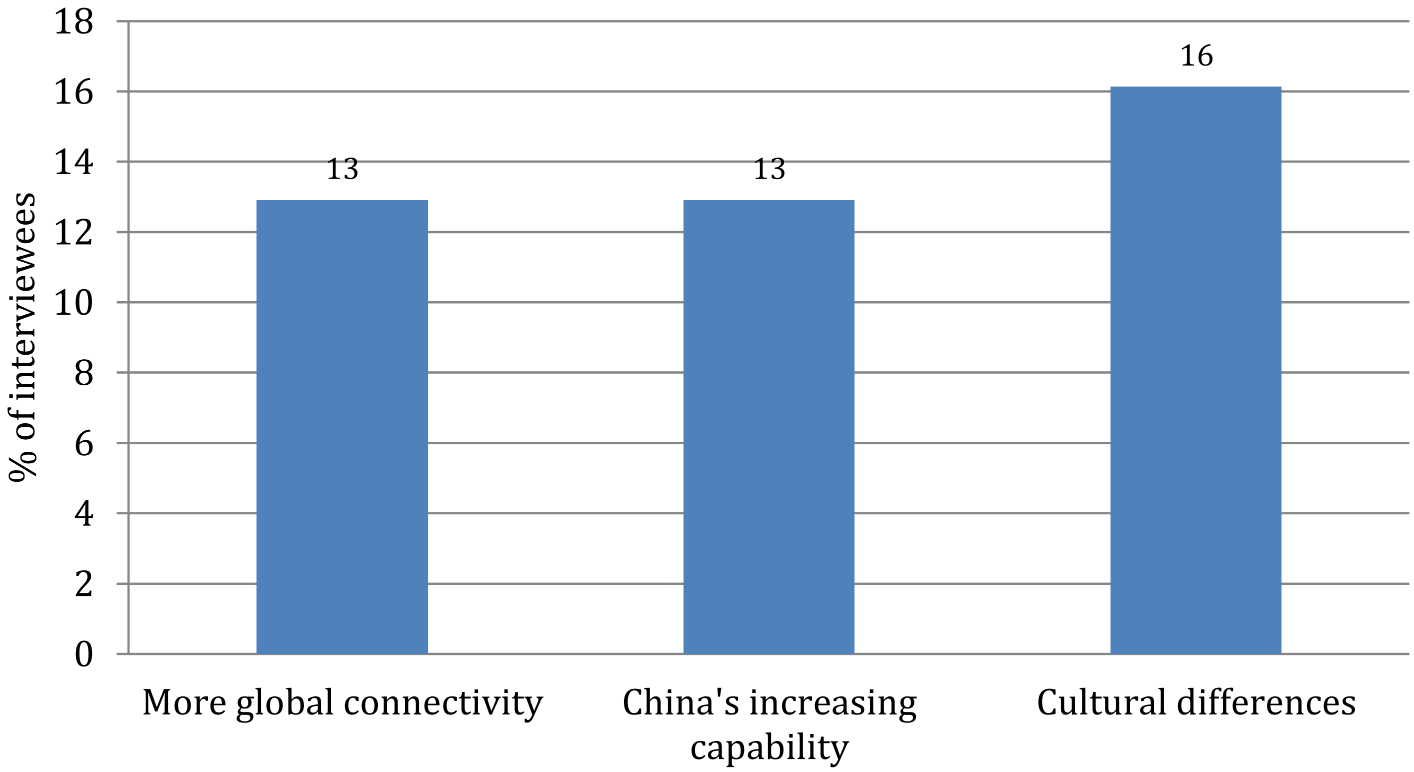
Q13: What are the other trends shaping the Factory of the Future?



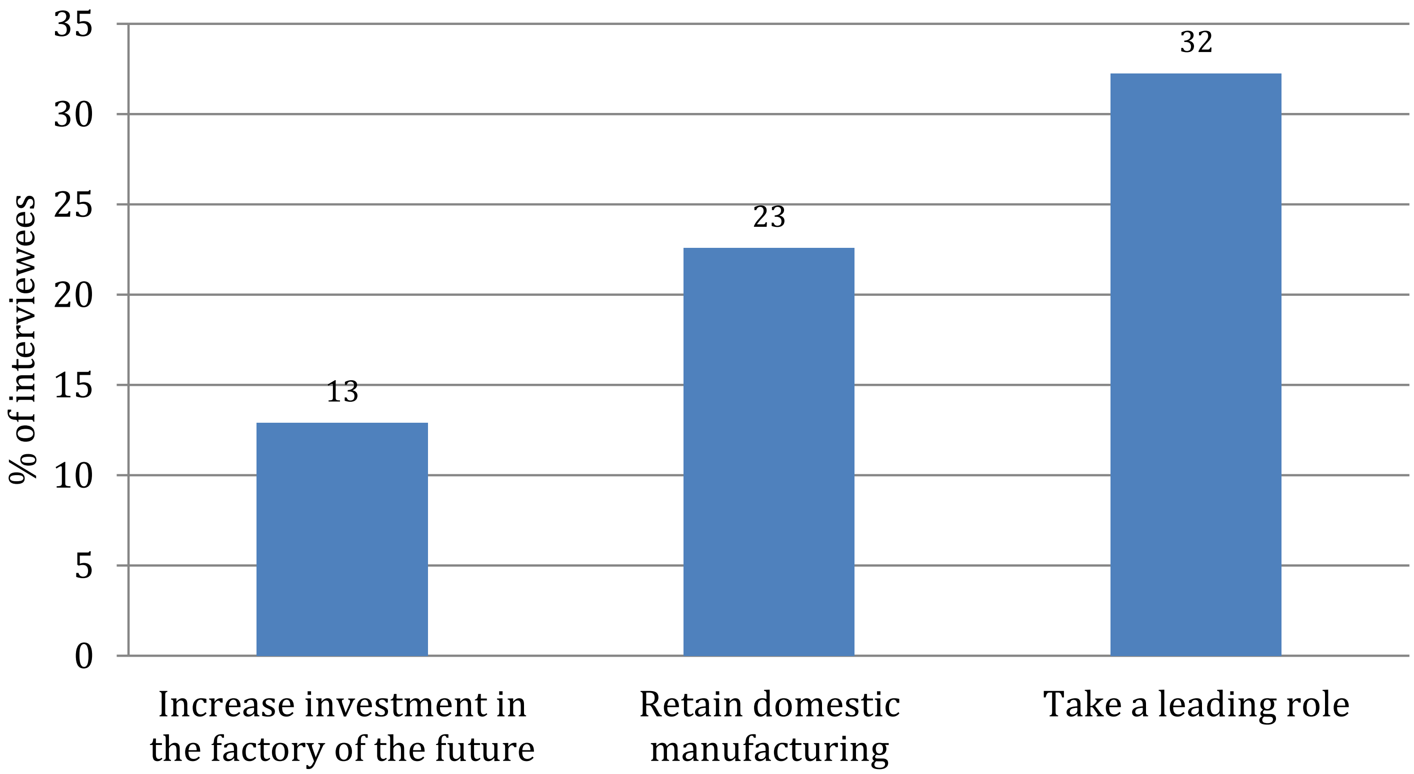
Q14: What do you think are the potential 'game changers' for manufacturing?



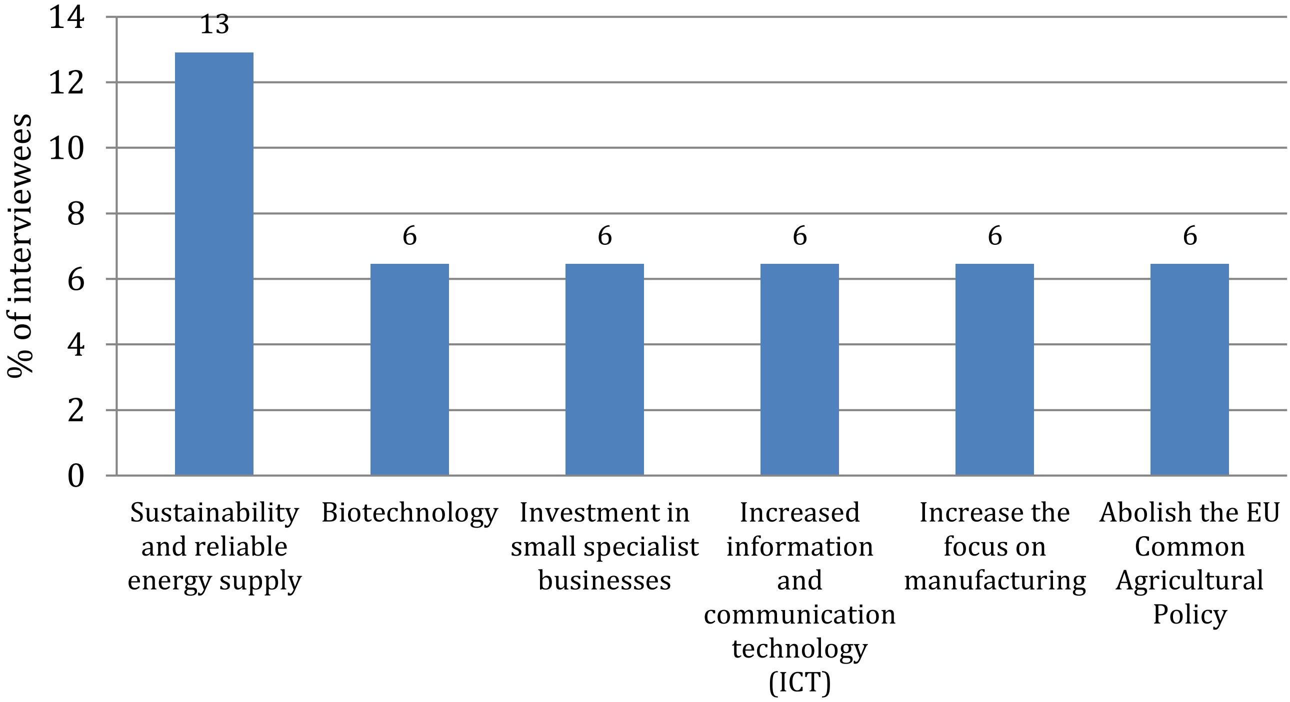
Q15: How do views on the Factory of the Future vary between nations?



Q16: How should the UK respond to any suggestions of what the Factory of the Future would look like?



Q17: Do you have any views on trends affecting the Factory of the Future as far out as 2050?



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