THE OPPORTUNITY FOR LEARNING FACTORIES IN THE UK

A report to the Gatsby Foundation

STUART EDWARDS

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Setting the UK opportunity in a broader theoretical, historical and international context has involved reading a wide range research papers, in particular those published in the Proceedings of the Annual Conference on Learning Factories, an international conference held annually over the past decade. I would also like to acknowledge the extent to which I have been helped by and drawn on a single publication*, Learning Factories: Concepts, Guidelines, Best Practice Examples,* authored by Eberhard Abele, Joachim Metternich, and Michael Tisch, which provides a comprehensive overview of the topic.

None of those named should be held responsible for any errors and infelicities in what follows.

Stuart Edwards, Edwardstowe Advisory

HYPERLINKS

Hyperlinks accessed January 2021. In this fast-moving environment, it may be necessary to search for up-to-date website references.

INTRODUCTION

At its simplest, the concept of a 'learning factory' refers to a facility with aspects of an authentic production environment designed and used primarily for the purpose of learning. There is a growing international trend to establish and operate these facilities. This trend has accelerated in recent years and become closely associated with strategies to support the digitalisation of manufacturing, otherwise known as 'Industry 4.0'.

The growth and strategic positioning of learning factories was observed in other countries during an international study of manufacturing workforce development and its link to innovation, led by the High Value Manufacturing Catapult with support from the Gatsby Foundation. The findings from this international study were presented in the *Manufacturing the Future Workforce* report published in January 2020. The report draws on international good practice to make recommendations for how innovation, education and training could be linked more systematically and effectively in the UK. It emphasises the importance of making faster progress on developing and aligning workforce skills to anchor the benefits of innovation, particularly in the context of industrial digitalisation.

The overarching recommendation is to use the concept of a 'skills value chain' as an organising principle to make improved connections between innovation, education and training initiatives. Within this approach, an enhanced role is proposed for Centres of Innovation (COIs) such as the Catapults in aligning manufacturing workforce development with emerging technologies. Specific recommendations to support the development of a more coherent and joined-up skills value chain, include to 'promote Learning Factories as an education model to enable industrial digitalisation'.

The purpose of this follow-on report is to lay the groundwork for implementing that recommendation to promote learning factories in the UK. The suggested approach in the original report is to examine the opportunities closely and to build systematically on existing assets, strengths and initiatives with COIs working with the Made Smarter Commission, Institutes of Technology (IoTs) supported by their FE and HE partners and DfE. This is with a view to an outcome in which Catapults and other COIs make more of the potential of learning factories to enable workforce development, working with FE and HE, and aligning developments with Made Smarter technology investments so that they become part of the network supporting a more systematic and strategic approach to industrial digitalisation skills.

Work undertaken for this report has involved:

- desk research on the concept of learning factories, their different forms, purposes and applications, and their current state of development internationally and in the UK
- review of relevant case study material from the original international study, supplemented by online discussions with leading international experts on learning factories
- a series of online and telephone interviews and mini-workshops with key UK stakeholders, including COIs, FE and HE and the network of IoTs, Made Smarter, employers, technology and equipment suppliers, professional bodies, commissions and consultancies, and government departments and agencies

- analysis of the foundations that already exist and the potential for learning factories to contribute to a more systematic skills value chain approach to manufacturing workforce development, identifying opportunities and challenges in a UK context
- examining more practical considerations with regard to planning and commissioning, learning approach and content, staffing and trainer training, and digital models
- gathering case studies of existing and planned learning factory facilities in the UK to illustrate key points about what can be achieved and how they can contribute to a broader skills value chain approach
- developing recommendations for a set practical steps to promote learning factories as a model to enable industrial digitalisation in the UK.

The majority of the work for this report was undertaken between late April and October 2020 during the COVID-19 pandemic crisis with various states of lockdown and social distancing. As well as placing practical constraints on how the research could be conducted, without site visits or face-to-face meetings, there has been a significant impact on the thinking and analysis within the report. This has involved assessing the contribution that learning factories could make to the skills and innovation aspects of a post-COVID economic recovery plan.

Finally, while the research has focused on a learning factory concept which is primarily relevant to a manufacturing context, it should be noted that this is one manifestation of broader concept of a 'complex simulated workplace environment'. Most of the analysis in this report can therefore be applied more widely, particularly as digitalisation is ubiquitous and blurs the distinction between sectors.

EXECUTIVE SUMMARY AND RECOMMENDATIONS

The pace of change of industrial digitalisation is accelerating. If UK manufacturing industry is to take advantage of this opportunity to improve productivity and be competitive in a post COVID, post Brexit world, two closely linked issues need be addressed: diffusion and adoption of innovation, and higher-level technical skills. Following on from the analysis of international good practice in the *Manufacturing the Future Workforce* report, and looking at trends and examples of the deployment of learning factories in other countries, this report sets out the potential for learning factories in the UK to help address these issues and how that potential can be realised most effectively.

The learning factory concept is not particularly familiar or well-understood in the UK, though the principles that underlie it in terms of experiential learning in an authentic workplace environment with access to industry-standard equipment are widely recognised and were endorsed as key features of excellent vocational teaching and learning by the influential 2013 *Commission on Adult Vocational Teaching and Learning* (CAVTL).

In terms of current deployment of learning factories, the UK appears to be behind many of its international competitors, but perhaps not as far behind as might be thought at first sight. The term 'learning factory' may rarely be used, but there are developments that have evolved over the years that have many of the features of learning factories, and in the past five years there has been an acceleration of interest and activity that reflects the global trend.

The scope for learning factories to make a bigger contribution needs to be seen in a systems context, not just in terms of the capacity and capability of individual facilities and institutions. Applying the concept of a 'skills value chain', learning factories have the potential to help join up the skills and innovation systems, acting as a physical or virtual manifestation of that linkage. This includes a core role in the direct delivery of the practical skills and awareness needed for adoption of innovation, but also how they can act as centres of expertise for scaling up delivery across the wider skills system and how they can make direct links with research and innovation processes in industry and academia.

The opportunity now exists – made more urgent in the context of COVID-19 – for a more concerted development and deployment of learning factory facilities (and other similar complex simulated workplace environments), with the potential to make a significant impact on longstanding weaknesses in UK manufacturing productivity and beyond. This is not just about encouraging more facilities to be built and equipped; a more co-ordinated, collaborative approach is also needed to maximise the contribution of existing assets, avoid waste and duplication, and focus on where gaps most need to be filled, whether nationally or locally. To make the most of this potential, it is proposed that three existing foundations need to be built on: Catapults and other Centres of Innovation (COIs), Institutes of Technology (IoTs) and similar centres of skills expertise, and the Made Smarter initiative on industrial digitalisation (Industry 4.0).

As illustrated by the *Manufacturing the Future Workforce* report, there is a growing recognition that, in order to anchor emerging technologies in the UK, Catapults and COIs need to take more active responsibility for ensuring that workforce capability is developed for innovation adoption, with a particular challenge being to achieve scale and accessibility of education and training provision. Learning factories are clearly relevant in this respect for the High Value Manufacturing Catapult network and already some of the individual centres have learning factory facilities or are developing them, though primarily for research and innovation purposes rather than education and training. Discussions undertaken during this study have also indicated that the learning factory concept could be relevant for other Catapults and COIs, particularly if considered more generically as a complex simulated workplace environment.

In terms of a more concerted approach, there are three main roles that Catapults and COIs could play.

(1) Identifying the need for learning factories. Catapults and COIs, working with industry, are well-placed to convene skills foresighting and to identify gaps in existing provision related to their areas of specialism. This kind of analysis should underpin the commissioning of learning factory facilities, their overall design, and more specific curriculum and content design. It could also suggest where new investment in learning factory facilities is unwarranted.

(2) Developing and extending the reach of their own facilities. Catapults and COIs represent a very significant investment in leading edge technology and facilities. It should be considered whether existing assets or those being commissioned in future could be leveraged more systematically for learning purposes through taking a learning factory approach. This includes, where learning factory facilities already exist but are focused primarily on research and innovation, considering whether they could play a broader role in skills development. This may not always be practical where there is high demand for specialist facilities, but there may be other approaches to broaden access such as use of digital twins.

(3) Supporting learning factory developments elsewhere. Beyond how they utilise their own facilities, Catapults and COIs can use their expertise to shape and support facilities located elsewhere, working in partnership with centres of skills expertise. This could involve planning and procurement, curriculum design, learning resources, shared staff, secondments, trainer training, CPD, master classes etc. The IoT network being established in England provides a significant opportunity for this mode of partnership working.

The remit of Institutes of Technology and the expectations now being set for them fit well with the concept of learning factories. Department for Education guidance emphasises the importance of industry standard facilities and simulated workplace environments, and working with university, innovation centre and employer partners to access their applied research base and prepare the workforce for changes in technology. Many of the Wave 1 IoTs currently establishing themselves are already developing or incorporating learning factory type facilities within a variety of delivery models which include co-ordinated regional approaches. A national network of IoTs with learning factory capabilities has the potential to be a critical link in creating a more coherent skills value chain, joining up innovation with the skills development needed for adoption at scale, particularly the technician skills needed at levels 4 and 5.

In Northern Ireland, Scotland and Wales, although there is no direct equivalent of the IoT programme, there are other foundations that can be built on in terms of centres of skills expertise. College networks already have a relatively coherent regional geographic focus. There also tends to be a more established college role in supporting businesses with innovation adoption, particularly in Northern Ireland. In Scotland, the new National Manufacturing Institute for Scotland (NMIS) is envisaged to be at the heart of a wider national network of skills and innovation provision.

Made Smarter, as a UK wide industry/government initiative, has the ambition to create a much more visible and effective digital ecosystem to accelerate the innovation and diffusion of Industrial Digital Technologies, and to upskill a million industrial workers to enable digital technologies to be successfully exploited. A pilot for a national adoption programme with advisory services for SMEs is currently underway in North West England, a digital delivery platform for skills content has been launched, and a national network of digital innovation hubs is to be commissioned. Looking at international practice, learning factory facilities could play a significant part in the national digital ecosystem envisaged by Made Smarter. This includes learning factories being incorporated within digital innovation hubs, acting as demonstrators and technology trialling facilities for adoption programmes, and enabling the delivery of upskilling in digital technologies. This would not necessarily require wholesale new investment in facilities, as much could be achieved by utilising and enhancing the range of services offered through facilities that already exist or are planned through the Catapult and IoT networks and such-like.

Alongside these national initiatives, the need and opportunity for learning factories should be looked at through a regional and local economic lens. Much of the practical planning, co-ordination and networking will be driven by factors like local geography and employer clusters. Examples already exist where strategic regional partnerships involving employers, providers and local authorities are commissioning learning factory facilities with IoT funding to fit within an integrated regional approach to innovation and skills.

To make the most of these opportunities and investments, and to "promote Learning Factories as an education model to enable industrial digitalisation", this report makes 10 recommendations.

1. **Co-ordinated government support.** The development, utilisation and networking of learning factories and other complex simulated workplace environments should be supported in a co-ordinated way across Catapults and Centres of Innovation, Institutes of Technology and other centres of skills expertise, and the Made Smarter initiative on industrial digitalisation. Opportunities should be sought wherever practical to utilise the same assets and expertise for multiple purposes, whether directly or through partnership and networking arrangements. At a national level, BEIS, DfE and their equivalents in the devolved administrations should encourage a co-ordinated, collaborative approach, including through funding alignment and incentives. Authorities at regional and local level should look similarly at how learning factory type developments can be positioned strategically in the context of local industrial clusters, and how they can be networked to maximise reach and accessibility.

2. **Mapping.** A systematic mapping exercise should be undertaken of existing and planned learning factory facilities across the UK and used to inform planning and investment at both national and regional levels, as well as networking and sharing of expertise. The mapping should be based on the key features used to categorise learning factories internationally, supplemented with any additional information of particular relevance to the UK. The work could be overseen by a core group drawn from the Catapults, Institutes of Technology, Made Smarter, the Devolved Administrations and LEPs, and it should draw on lessons from work already initiated for Made Smarter and international examples such as the Industrie 4.0 Map created in Germany. The resulting analysis should be used both to identify gaps and to avoid duplication and risk of under-utilisation.

3. **Catapults and COIs**. As part of a broader role in ensuring the workforce skills and awareness needed for innovation adoption, Catapults and COIs within their fields of specialist expertise should look to: (a) identify where there is need for learning factories and similar complex simulated workplace environments, using their understanding of future capability and competency requirements; (b) develop and extend the reach of their own such facilities for skills development and innovation adoption; (c) use their expertise to support the development and operation of learning factories elsewhere.

4. **Institutes of Technology and other centres of skills expertise.** The IoT programme should continue to encourage and support the development of learning factory facilities based on co-ordinated local partnerships where there is strong engagement from anchor employers and a sound business case. Lessons should be captured as quickly as possible from Wave 1 projects that are commissioning or incorporating learning factories and, where appropriate, additional expert advice made available to those making proposals for learning factories in future rounds, for example on the procurement of equipment. Consideration should also be given to whether a more aggregated approach to procuring learning factory equipment would have advantages as the IoT network is rolled out. Beyond the IoT programme in England, the devolved administrations should consider supporting the development of more learning factory capacity through their regional centres of skills expertise as part of a more integrated approach to skills and innovation.

5. **Made Smarter**. National roll-out of the Made Smarter initiative on industrial digitalisation should seek to utilise and provide additional support for existing and planned learning factory facilities: (a) within digital innovation hubs; (b) as demonstration and trialling facilities for adoption programmes; and (c) to enable upskilling. It should also be possible to utilise learning factory facilities for the training and professional development of those acting as advisers for the adoption programme.

6. **Trainer expertise.** More attention should be given to building the specialist staff expertise needed to operate learning factory facilities and maximise return on capital investment made. The majority of funding currently being made available, for example through the IoT programme, is for capital expenditure on buildings and equipment. This contrasts with the much greater emphasis on staffing and trainer training observed in programmes internationally, particularly in Germany, and there is a risk that new learning factory facilities are poorly utilised because of a lack of staff expertise. Wave 1 IoTs are looking imaginatively at addressing this issue, but more support is likely to be needed

to build a networked cadre of expert trainers who can combine (a) up to date knowledge and experience of how technology is being used in industry; (b) coaching and facilitation skills to make the most of specialist Learning Factory equipment and scenarios for experiential learning; (c) innovation and applied research skills with an understanding of emerging technology trends. Catapults, the IoT programme, the Education and Training Foundation, World Skills and the Professional Bodies could all potentially have a role to play in this, but clear shape and form will need to be given. Creating this cadre of expertise is also essential if learning factories are to play a broader role in the professional and specialist development of the teaching and training workforce, for example to support the national roll-out of T-levels.

7. **Shared learning and assessment resources.** A co-ordinated approach should be taken to developing and sharing learning resources across learning factory networks. Learning factories commonly facilitate experiential learning through use of 'scenarios' designed to promote the acquisition of competencies and their assessment. These can be used to support modular learning and adapted to fit within broader curricula. Their design requires expertise and resource. Where sufficient commonality of need exists, for example in respect of digitalisation or energy efficiency, it makes sense to pool efforts and share these specialised learning resources across a wider network. Examples of this type of approach already being taken include the Blended Learning Consortium of FE colleges, the Siemens Connected Curriculum developed with a group of universities using Festo Didactic learning factory equipment, the Engage Platform developed for Made Smarter, and the resources shared across the McKinsey global network of Digital Capability Centres. These approaches need to be learnt from and applied particularly across the IoT network and for technician-level training. Further work also needs to be initiated with Professional Bodies and Awarding Organisations on the use of such shared learning resources for assessment purposes and how this can recognised for modular accreditation.

8. **Interoperability.** A review should be undertaken to establish what, if any, common technical standards and platform infrastructure may be required for networks of learning factories to be able to exchange data and learning resources effectively. This could influence, for example, future guidance on procurement of learning factory equipment and software where public financial support is sought. The High Value Manufacturing Catapult and Jisc (the digital services body that serves the HE, FE and Skills sector) could both contribute their technical expertise to such a review.

9. **Virtual learning factories, digital simulations, and twins.** A concerted effort should be made to use digital technologies to extend the reach of what can be done through physical learning factory facilities. The convergence of learning and industrial technologies as both take on digitalisation creates a huge opportunity for skilling and upskilling at scale. Digital approaches also mitigate the risk that costly physical facilities quickly become out of date as the pace of technological change accelerates. The capabilities that exist in the UK and the potential impact has been illustrated during the COVID-19 crisis by how the UK Ventilator Challenge Consortium led by the High Value Manufacturing Catapult was able to ramp up production of ventilator systems very rapidly by designing, creating and simulating new production lines virtually

before anyone went on the shop floor, and training up some 3000 individuals in advance to carry out the assembly and testing. Consideration should now be given to where else virtual learning factories/complex simulated workplace environments could be used to meet large scale skilling and reskilling challenges, such as for example the need identified by the Energy Systems Catapult to skill/reskill a one-million strong workforce to transform the energy efficiency of the existing UK property stock.

10. **Exchange of knowledge and good practice.** Those developing and operating learning factory type facilities in the UK should be more effectively networked to exchange knowledge and good practice, more UK-based research should be undertaken, and there should be more international engagement. Developments to date in the UK have tended to be isolated and ad hoc, and there has been almost no engagement with international communities of practice and the associated research and academic literature. The IoT programme and the Catapults both provide foundations that could be built on to facilitate this networking, and international associations and conferences would welcome more engagement from the UK.

Undertaking this study during the COVID-19 pandemic has thrown into relief both the need and opportunity to think differently about how skills challenges are addressed. The case made by this report is for one element of reform to be the more widespread and systematic adoption of a learning factory approach, which can be conceived more broadly in terms of using complex simulated workplace environments for learning purposes, and developing them virtually as well as physically. The foundations to do so are in place. If not now, when?

CONCEPT, HISTORY AND INTERNATIONAL DEVELOPMENTS

THE CONCEPT

At its simplest, the concept of a 'learning factory' refers to a facility with aspects of an authentic production environment designed and used primarily for the purpose of learning. (1) It is not a simple duplicate of an industrial factory but designed to best suit and serve an intended experiential learning process. (2) The facility may be physical or virtual, or a blended combination. It generally involves more than one machine or operation, and can extend to include supply chains and customer services. Facilities may be primarily education-based or industry-based, or part of a hybrid institute. They are usually supported by some form of education/industry partnership.

The learning undertaken is primarily experiential, often based on scenarios, projects and collaborative problem solving. This is commonly facilitated by the factory environment being changeable and able to respond to the learners' ideas (3). There can be a range of different learning purposes: to enhance academic education through offering more realistic hands-on practical experience; to enable the acquisition of technical and vocational skills and the associated workplace behavioural and social competencies; to raise awareness and understanding of technological developments and their implications for innovation transfer; to facilitate experimentation for research, innovation or process improvement, and the acquisition of the skills and understanding that these activities require. The learners may be university students or researchers, college students or apprentices, industry personnel from large or small companies, including senior managers, designers and shop floor operatives, trainers or teachers, or school pupils learning about STEM careers and modern manufacturing.

A comprehensive, technical definition has been adopted in the international academic literature, distinguishing between learning factories in a narrow and broader sense:

> "A learning factory in a narrow sense is a learning environment specified by *processes* that are authentic, include multiple stations, and comprise technical as well as organisational aspects, a *setting* that is changeable and resembles a real value chain, a physical product being manufactured, and a *didactical concept* that comprises formal, informal and non-formal learning, enabled by own actions of the trainees in an on-site learning approach. Depending on the *purpose* of the learning factory, learning takes place through teaching, training and/or research. Consequently, learning outcomes may be competency development and/or innovation. An operating model ensuring the sustained operation of the learning factory is desirable. In a broader sense, learning environments meeting the definition above but with a setting that resembles a virtual instead of a physical value chain, or a service product instead of a physical product, or a didactical concept based on remote learning instead of on-site learning can also be considered as learning factories." (4)

This definition has been used to categorise the variety of learning factories describing their key features under seven main dimensions:

- **Operational model** – what type of organisation is the operator and how does it achieve sustainability in terms of income and financial viability, content development and renewal, and attracting and retaining professional staff with the required skills and expertise?
- **Targets and purpose** – what main purposes are being served in terms of education, vocational training, research; what secondary purposes in terms of technology testing, industrial production, innovation transfer, demonstration and publicity; who are the intended learners; what industrial sector is being targeted; and to achieve what forms of improvement e.g lean management, resource and energy efficiency, digitalisation and Industry 4.0?
- **Process** – which production processes and life cycles are depicted by the learning factory, what are the boundaries of the system and which parts are being focused on?
- **Setting** – is the learning factory purely physical, purely virtual or some form of blended 'cyber-physical' combination; is it full-size or scaled down; how much of the factory does it cover; how changeable is it; how is the digital technology integrated?
- **Product** – what is the product, is it physical or a service, is it a real functional product or one that has been developed or simplified specifically for learning purposes, how complex is it, how many components and variations does it have, and what happens to it, is it dismantled (so components can be reused), displayed, sold, or destroyed?
- **Didactics** – what is being learned in terms of competencies and learning objectives; how is it being learned in terms of the format and design of the learning, the use of learning scenarios and the role played by the trainer?
- **Metrics** – what is the size and capacity of the learning factory and the volume of activity that it undertakes – numbers of courses, numbers of learners, staffing, square metreage?

This list is a simplified version of a comprehensive technical 'morphology' which can be used as a checklist for planning and designing a new learning factory, as well as categorising those that already exist.

ORIGINS AND SPREAD OF INTERNATIONAL APPLICATIONS

The origins of the concept are generally recognised as dating from 1994, when the National Science Foundation (NSF) in the USA awarded a consortium led by Penn State University a grant to develop a 'Learning Factory'. (1) In this context, the purpose was to facilitate interdisciplinary hands-on engineering design projects with strong links and interactions with industry. A college-wide infrastructure and a large facility were equipped with machines, materials and tools that could be used to support industry-sponsored design projects. The *Penn State Learning Factory* has continued to operate ever since, and by 2020 had completed more than 2750 projects for more than 600 different sponsors, with some 13,000 students participating in such a project.

Since the 1990s the concept has spread beyond the USA, with increasing use of learning factories, particularly in Europe. An example of an early learning factory in Europe was the Institute of Production Management, Technology and Machine Tools, now known as the *Centre for Industrial Productivity,* at Darmstadt Technical University in Germany which was established in 2007. Its learning purpose is to impart knowledge of the most important methods for designing efficient production processes, which is done through producing real products in a complete value stream from raw materials to the shipped products. Over the past decade it has trained more than 4000 students and 2000 industrial employees.

A further indication of the uptake of the concept of learning factories in Europe was the founding of the Initiative on European Learning Factories at Darmstadt in 2011, with eight founder members drawn from Austria, Croatia, Germany, Greece, Hungary, and Sweden. In 2017 the European Initiative was renamed as the *International Association of Learning Factories,* with members joining from Israel and South Africa, though its membership is still predominantly European, with the majority either German or Austrian.

The main focus of academic research on learning factories, certainly in Europe, is an organisation called *CIRP* (College International pour la Recherche en Productique) or the International Academy for Production Engineering. CIRP describes itself as "the world leading organisation in production engineering research and is at the forefront of design, optimisation, control and management of processes, machines and systems". Working in partnership with the International Association of Learning Factories, it has sponsored an annual conference on learning factories since 2011, the 10th and most recent of which took place virtually in April 2020 (having originally been scheduled to take place at Graz in Austria) on the theme of *'Learning Factories across the value chain – from innovation to service'.* Research papers presented at these conferences have provided a very useful resource for this study.

The greatest growth of learning factories in an individual country appears to be in Germany. A study of learning factories at German universities conducted in 2018/19 identified 51 examples (5). There are also at least five run by the network of Fraunhofers (applied research and innovation centres similar to the UK Catapults) and another five in private industry (6). Strategic initiatives exist at both national and federal state levels to create and utilise networks of learning factory facilities to support digitalisation in small to medium size businesses (SMEs) and enhance the capabilities of vocational schools.

The German Federal Ministry for Economic Affairs and Energy has incorporated a number of university and Fraunhofer learning factory facilities into a national network of 'Mittelstand 4.0 Competence Centres' which has been operating since 2015 to support SMEs with digitalisation (7). The network has grown to 26 centres in total, a combination of regional centres of excellence and more specialised thematic centres. Each centre is run by a consortium including a university/research partner and a business association/chamber. The learning factory facilities are used to deliver two key practical aspects of the support package for SMEs, demonstrating how digital technologies can transform businesses and enabling them to test out their own technical solutions. Each Competence Centre receives €1.5 – €2.0m annually from a federal budget (€36m in total) to deliver a nationally specified set of services; the money is for staffing to deliver the services, as infrastructure and facilities are already expected to be in place.

At individual federal state level, where responsibility lies for the publicly funded vocational schools which deliver the 'dual training system' in co-operation with local companies, co-ordinated developments have been underway since 2016. The leading example is Baden-Wurttemberg, the federal state where 30% of all German machinery and 25% of its cars are produced, and where Festo Didactic a major supplier of learning factory equipment is headquartered. Influenced by the University of Stuttgart's Learning Factory of Advanced Industrial Engineering, the state government has supported a programme to install more than 40 'Smart Factories' in its state vocational schools catering for both apprentices and diploma students. These Smart Factories are in effect Industry 4.0 simulators which share learning scenarios that can be tailored to local industry while remaining common across similar colleges (8). Smaller scale initiatives to upgrade vocational schools with learning factory installations (sometimes branded as 'lighthouses') exist in Bavaria and Lower Saxony which are also centres of car manufacturing.

Beyond Europe, the development of learning factories has continued in North America. Canada now has at least two university-based learning factories and another in development. What is described as the first 'iFactory' in North America (based on a 'Factory-in-a-Lab' model developed by the University of Stuttgart) was established in 2011 at the *Intelligent Manufacturing Systems (IMS) Centre* at the University of Windsor, Ontario. This is a highly modular and reconfigurable assembly factory, which is used to focus on systems learning. In 2018, the *School of Engineering Practice and Technology at McMaster University in Toronto* launched a learning factory designed to simulate an Industry 4.0 factory of the future. The University of British Columbia is establishing an *Advanced Composites Learning Factory* in partnership with the Composites Research Network, as part of a new Innovation Precinct. This will be based on a physical factory with a core capability which is designed to be immensely data rich, with multiple layers of sensors and data analysis, and highly reconfigurable The physical factory will be linked to a digital twin in the cloud, where a virtual factory based on simulation and data from the physical factory will be used to understand, manage, and improve advanced composites manufacturing processes.

In the US a body called 'Manufacturing USA' co-ordinates a network of 14 regional manufacturing innovation institutes using a public/private partnership model. The network hosts multiple learning factory applications, including a *Digital Capability Centre (DCC)* at the Digital Manufacturing and Design Innovation Institute MxD (previously known as DMDII) in Chicago. The DCC is an innovative experiential learning facility founded in partnership with McKinsey, and is one of a global network of five DCCs established by McKinsey with local partners.

In addition to Chicago, the other four DCC locations in the McKinsey network are Aachen, Beijing, Singapore and Venice. All of these have been put in place since April 2017, working with a major US technology provider called PTC and local partners. Essentially a DCC is a learning factory focused on Industry 4.0 manufacturing, designed to demonstrate what various aspects of digital transformation can achieve and how this can be done. Each DCC learning factory models the production of a different real world product (e.g refrigerator compressors at Chicago, textiles at Aachen), but they are digitally connected and the main learning purposes are the same. They are used primarily to facilitate immersive workshops for managers and technicians, though there are offerings for the whole workforce, addressing culture change as well as technology, and there are 20+ experiential learning modules.

The DCC network is one part of McKinsey's wider global network of capability centres based on learning factory principles. Other centres focus for example on lean production, energy productivity and design to value. There is also a portable McKinsey 'Model factory in a box' (MFIB) based on lemonade factory which is used to deliver experiential workshops and training modules on site.

Large manufacturing companies have developed their own learning factories. Examples include the Chrysler World Class Manufacturing Academy in Michigan, USA; the BMW VPS (Value-Oriented Production System) Centre, the Karcher Learning Factory and the Schaffler MOVE academy (Schaffler manufactures automotive, industrial and aerospace components). (9)

There are also now equipment and service providers that tailor bespoke learning factory systems for specific industrial sectors. (10) PTC's 'ThingWorx' Industrial Internet of Things platform underpins McKinsey's DCCs. Festo Didactic, a global provider of equipment and solutions for technical education with German origins, has produced a modular 'iFactory' which can be tailored to specific end user requirements allowing for simulation of multiple assembly scenarios and training in areas such as automation, pneumatics, computer interface and camera inspection. Other suppliers include Siemens, which works closely with Festo Didactic and provides the 'Mindsphere' Internet of Things platform, Bosch Rexroth which specialises in drive and control technology, and the Didactic Division of SMC, a Japanese company which is a major global supplier of automation and pneumatic components.

MOTIVATION, AIMS AND ENABLERS

An interesting question is what may have motivated this spread in the uptake of the learning factory concept over the past two decades. Looking at the wider context of learning theory and practice, and at trends in manufacturing, a number of drivers can be identified both in terms of what learning factories aim to achieve and what has enabled their development. Six of these appear to have been particularly significant:

- ***Learning by doing and collaborative problem solving.*** Over the past 20 years, particularly in Higher Education and subjects such as engineering and medicine, there has been significant and growing interest in approaches which can broadly be described as 'learning by doing', and theoretical models such a 'constructivism' and 'constructionism'. There has also been a growth in teaching and learning practices designed to facilitate this type of learning, such as 'collaborative problem-solving' which brings out the social and team dimensions of practical activities. For example, a key finding from a 2013-14 large-scale survey of US undergraduate teaching faculties was the move away from lectures and the increased use of student-centred teaching practices over the past 25 years, with all-time highs reported in faculties' reliance upon group projects (45.5%) and co-operative learning (60.7%). (11) The original NSF learning factory project at Penn State University can be seen as a way of facilitating this type of collaborative problem solving in an authentic environment so that engineering students could tackle real-world problems sponsored by clients. It is also probably no accident that McMaster University in Canada, which is the associated with the origins of 'problem-based learning' (PBL) in medical education, has now developed a learning factory for engineering students. The connections are also apparent in the academic literature and promotional materials explaining the rationale for learning factories, which often have a strong emphasis on the benefits of experiential and team-based learning and refer to research findings to indicate how learning by doing improves retention. Some of the academic literature explains in some detail the underlying learning theory and how this can be applied in the design of learning factories and their didactic approaches, and how their effectiveness is evaluated. For example, McKinsey's website states: "Cognitive research has consistently shown that 'learning by doing' is the best method for teaching adults—it accelerates learning and enhances retention. … Unlike traditional corporate training programmes, McKinsey Capabilities Centres create opportunities for experiential learning—people actively practising skills, rather than sitting in a classroom. Participants spend more than 80 per cent of their time in realistic work settings that mimic factories, offices, and even call centres. They collaborate to solve problems and tackle real-time challenges, sometimes implementing multiple strategies. And by creating a 'safe' environment for experimentation, the training atmosphere encourages teams to propose and test bold, innovative solutions that might appear too risky in the field."

- ***Digital learning technologies and the enhanced capability for simulation and analysis.*** The other key trend in learning practices has been the adoption of digital technologies and in particular the increasing practicality of using Virtual and Augmented Reality (VR and AR) to simulate real world environments and processes, and the hugely enhanced ability to capture and analyse learning data. This has made possible the creation of virtual learning factories and digital twins, which can be considered as learning technology applications. These can be less costly to develop, easier to adapt and re-program, and are not constrained by a single physical location.

- ***Lean production and resource efficiency.*** The objective behind most of the earlier learning factories was to provide a real world setting to convey knowledge about lean management, process improvement, resource efficiency and associated management and organisational skills (12). A major advantage of the learning factory approach, particularly in an industrial context, is the ability to gain the benefits of experiential learning using real conditions without costly disruption to production. (13) The Centre for Industrial Productivity (CiP) at Darmstadt, which was the first European learning factory has focused from the outset on what it describes as "lean production experiential training". Four of the capability centres in the McKinsey network offer lean manufacturing training, as do others outside the McKinsey network, such as the Lean Learning Factory at the University of Split in Croatia. Examples of learning factories focusing specifically on energy and resource efficiency include the Learning Factories for Energy Productivity at Darmstadt and Munich (each of which has learning factories focused on both lean and resource efficiency) and the Green Factories network in Bavaria. A major impetus for these has been Germany's withdrawal from nuclear power. The project in Bavaria was given a budget of 12 million euros and has created a distributed network of 12 learning factories based either at universities or Fraunhoffers. (14)

- ***Digital manufacturing and Industry 4.0.*** A major feature of the development of learning factories in recent years has been their alignment with the digital transformation of manufacturing and the confluence of technologies such as data analytics, artificial intelligence, advanced robotics and the internet of things, commonly referred to as Industry 4.0. As well as McKinsey's network of five Digital Capability Centres, other examples with a strong focus on Industry 4.0 include: the University of Bolzano Smart Mini Factory lab in Italy; the Industry 4.0 Learning Factory at Bochum University of Applied Sciences in Germany; and the University College Dublin Learning Factory in Smart Precision Manufacturing in the Republic of Ireland. A common theme of many of these Industry 4.0 focused learning factories is the role they play in exposing SMEs to the potential for digital transformation. For example, the Learning Factory at Bochum University, as well as being used for student education and research projects, provides training for a regional association of small lock and key manufacturers supplying the German auto and building industries. (15) As referred to earlier, the German Federal Government has sought to encourage and systematise this role for learning factories in supporting the uptake of Industry 4.0 through its substantial financial support for the network of '*Mittelstand 4.0 Competence Centres*'.

- ***Pace of change and shortened product cycle.*** Closely related to digitalisation, another factor mentioned in the literature is the need for manufacturing to be increasingly flexible both to enable greater customisation of products and to cope with shorter product cycles driven by the increasing pace of innovation and competition to bring new products to the market more quickly. (16) Learning factories can be used to support the modelling and experimentation needed for this type of adaptive manufacturing, acting for example as prototypes for changeable and reconfigurable manufacturing systems. Some learning factories have been designed specifically to support these requirements of changeability. These include the Learning Factory for Advanced Industrial Engineering at the University of Stuttgart and the iFactory in the Intelligent Manufacturing Systems Centre at the University of Windsor, Canada, both of which are based on Festo's transformable manufacturing platform.

- ***Global production and reshoring.*** Trends in globalisation and the need to facilitate strategies for responding to them can be seen as another driver for the development and spread of learning factories. A Learning Factory on Global Production at Karlsruhe Institute of Technology in Germany has been developed in partnership with Bosch specifically to help build knowledge and skills for planning and managing globally distributed production networks. The model network consists of a lead factory in a high-wage economy and two assembly plants in low-wage economies. The assembly plants are physically realised as part of the learning factory, but the lead factory is only virtual. Learners undertake exercises to learn how to optimise what is produced where, responding to different scenarios as key factors are varied. (17) Individual company learning factories, such as those of BMW and Karcher, have been rolled out globally across all their production sites. There are also references to learning factories supporting the reshoring of manufacturing jobs in higher-wage economies as the lower-skilled assembly tasks that could previously have been off-shored more easily are automated and new skills are required to work in factories of the future.

All these factors appear to have built on each other so that in recent years the rate of growth of learning factories has accelerated, as well as the level of interest in them. The combination of digital learning technologies with the digital transformation of manufacturing seems to have been particularly important in the past five years or so. One gauge of the sharp growth in interest is the number of indexed research publications relating to learning factories. A recent analysis showed a tenfold increase between 2012 and 2019. (18).

DEVELOPING LEARNING FACTORIES IN THE UK

THE CASE FOR LEARNING FACTORIES IN THE UK

Before looking at the current state of play with learning factories in the UK and their potential for further development, it is worth considering why they may have particular relevance in current UK circumstances. The trends that have encouraged the global growth of learning factories in other countries such as Germany, the USA and Singapore, apply equally to the UK, though manufacturing represents a smaller proportion of our economy. In addition, there are longstanding, systemic weaknesses in our approach to skills development and the adoption of innovation which are widely recognised to have undermined growth in productivity. On top of that, with this study being undertaken in 2020, new and unprecedented challenges have forced their way onto the agenda in the wake of the COVID-19 pandemic and Brexit.

Addressing long-standing productivity issues

Learning factories are fundamentally a vehicle to raise levels of skills and awareness to enable improvements in productivity. The UK's problem with sluggish growth in productivity, particularly since the 2008 financial crisis, is well documented. It is the core weakness in the economy (pre-COVID) that the Government's Industrial Strategy (19) and related Post-16 Skills Plan (20) sought to address. Moreover, it is evident that the manufacturing sector has been a major component of that problem.

A 2018 McKinsey report entitled *Solving the United Kingdom's productivity puzzle in a digital age* highlights manufacturing alongside finance as having had an outsize impact on the slowdown in productivity growth relative to their share of the economy. "Despite making up less than 20 per cent of UK value added and employment, the decline in productivity growth in these sectors combined accounted for nearly half of the productivity-growth slowdown." (21) Looking at the reasons for this, the McKinsey report highlights weak equipment investment as playing a key role in declining productivity growth in manufacturing, particularly because of equipment's role in automation. It also points to the fact that, although the UK ranks overall among the top digitising nations, there are relative gaps in areas that are significant for productivity growth in manufacturing such as supply-chain management, robotics adoption, and investment in next generation technologies like the Internet of Things and advanced artificial intelligence (AI). Looking at solutions to promote productivity growth, two of the three areas highlighted are skills and the closing the adoption gaps in digital and next-generation technologies. Moreover, these two are seen as closely connected: lack of skills and awareness are identified as key barriers to technology adoption.

The 2017 Made Smarter Review led by Jurgen Maier presents a very similar analysis, but also sets out the extent of the opportunity if action can be taken successfully to transform UK manufacturing through the adoption of industrial digital technology (IDT). It is argued that the UK has the potential to differentiate itself in the digital industrial revolution and become a world leader in IDT, stimulating a leap forward in productivity: "Overall, from the data and evidence collated, we are confident that industrial productivity can be improved by more than 25 per cent by 2025." (22) The main barriers to be overcome include low levels of adoption particularly amongst SMEs, lack of skills particularly at higher technical levels (i.e. levels 4/5) and lack of co-ordination for the effective diffusion of technologies from the UK's world class research centres and the Catapult network.

Low levels of adoption and the need to accelerate the rate of technological diffusion to the UK's long tail of lower productivity firms were also major themes of a speech delivered in 2018 by Andrew Haldane, the Chief Economist at the Bank of England, entitled *The UK's Productivity Problem: Hub No Spokes* (23). HIs analysis identifies that the productivity gap between top and bottom performing companies in the UK is significantly larger than that in France, Germany and the US, and that the long and growing tail of firms in which productivity growth has effectively stalled accounts for the UK's inferior productivity as a national economy. Considering the determinants of effective technology diffusion, Haldane identifies UK weaknesses in technology transfer, human capital and institutional infrastructure. The UK is very strong on top-end innovation, but has fewer institutional spokes supporting technological trickle down. The formation of the Catapult network since 2011 is a positive, but compared with the Fraunhofer network in Germany on which it was modelled it is still much smaller and more limited in scope, serving "more as an innovation than a diffusion engine, leaving largely untouched the long tail of UK companies".

Focusing on the skills issue, both the Report of the Independent Panel on Technical Education chaired by David Sainsbury in 2016 (24) and the Government's response in the Post-16 Skills Plan highlight that the UK performs poorly on intermediate technical skills and is forecast to fall from 22nd to 28th out of 33 OECD countries for intermediate skills. (25) The Skills Plan is also clear that one of the things wrong with the current system is that "we have too little dedicated technical education at higher levels to meet our need for technician-level skills, and programmes are not always designed to deliver what is needed to move to skilled employment". The Independent Panel's report also identified weaknesses in the provider base, calling for a rationalisation of specialist technical education facilities, and recommending that funding should be restricted to "colleges and training providers which meet clear criteria for quality, stability and an ability to maintain up-to-date equipment and infrastructure".

Making the connection back to an innovation perspective, or more specifically an innovation systems perspective, Gatsby commissioned a report in 2019 on *Technicians and Innovation* from Professor Paul Lewis of King's College London (26). This highlights the contribution of technicians not just to the innovation process itself but to the absorptive capacity of firms and their ability to apply new technologies. Considering the UK's provision of technical education, the report identifies a systemic failure whereby employers struggle to find up to date practical training for technician apprentices to learn how to use new methods of production associated with emerging technologies, and local colleges and training providers have little incentive to provide what they need. Often the numbers are too small to justify the investment required and without other incentives or means of aggregating demand there is a 'skills valley of death' in which training providers struggle to develop commercially viable programmes for emerging technologies.

The *Manufacturing the Future Workforce Report* similarly highlights the disconnect between the skills and innovation systems, which means that the UK's real strength in both its research base and capacity for technology innovation is undermined by the difficulty its manufacturers face in accessing the skilled workforce they need to turn such innovation into profit and maintain their competitiveness taking advantage of latest technologies. Both reports recommend a response that connects institutions more systematically, and based on observation of international good practice, this has been developed into the concept of a 'skills value chain'.

Addressing the immediate context

Arguably the UK has managed until now to get by without properly addressing these issues. Current circumstances remove the option of continuing to do so. In a post-Brexit trading environment, the UK cannot afford to ignore barriers to translating its world leading R&D capability into industrial productivity and commercial profit, or to be reliant on importing the technical skills it needs for innovation adoption. In a post-COVID world, a skills system lacking the capability to address the nation's growing shortage in technical skills can no longer be tolerated alongside the prospect of a new generation of mass unemployment.

In this context, particularly given the impact of the COVID pandemic which is addressed further in a final section of this report, there is now a widespread recognition of the urgent need to reform the FE and Skills system, including taking on lessons from international practice. The case made in this report is that more widespread adoption of a learning factory approach could be an important component of the wider systemic reform required. However, it should also be recognised that it is not necessarily straightforward to import a model that is working in Germany and elsewhere, and isolated initiatives are not necessarily going to succeed in a different manufacturing culture with a very different technical and vocational education system. It is important therefore to consider what foundations already exist in the UK, how learning factory developments could go with the grain of wider initiatives and reforms, and what obstacles may need to be removed to realise their potential contribution.

CURRENT STATE OF PLAY AND FOUNDATIONS FOR FUTURE DEVELOPMENT

The initial impression is of a lack of facilities calling themselves 'learning factories'. Examples from the UK do not feature in the international literature and nor are any of the McKinsey Capability/Digital Capability Centres located in the UK. Similarly, there is an absence of UK-based authors writing about learning factories. However, this is to some extent an issue of terminology. The term 'learning factory' is not commonly used and is sometimes misunderstood, for example conjuring up the negative image of a school that is a rote learning production line for exams. When the concept is correctly understood, it is possible to find developments which demonstrate the main features of a learning factory or that are moving in that direction. There is also a more positive reaction when the experiential style of learning which learning factories facilitate is understood.

Back in 2013 the *Commission on Adult Vocational Teaching and Learning (CAVTL)* (27) effectively endorsed a learning factory type approach, though it did not mention the concept by name. When setting out the main characteristics of excellent vocational teaching and learning programmes it included "a clear line of sight to work" and "access to industry-standard facilities and resources reflecting the ways in which technology is transforming work". CAVTL also highlighted the centrality of "practical problem solving and critical reflection on experience, including learning from mistakes in real and simulated settings".

Within university engineering and manufacturing related departments it is relatively commonplace to have workshop-type facilities that can support students working on projects, often with industry sponsors. Many FE colleges offer their students and apprentices training in real working environments which can be run as mini businesses with paying customers. Common examples include auto repair and maintenance, hairdressers, beauty salons, florists and restaurants. Larger scale and more technologically sophisticated examples tend to involve industry partners or to be industry-led, and some of these display many of the features of learning factories without being badged as such.

Amongst the examples identified that go furthest in replicating full production line, factory-like facilities for learning purposes are:

- *Nissan* in partnership with Sunderland College back in 2000 established a training centre for car workers with a simulated production line, in response to its need to expand its local workforce;
- the *Toyota and Lexus Academy in Derbyshire* opened in 2016 to train apprentices and other staff which mirrors the Toyota working environment, with a replica production line, vehicle showrooms and workshops;
- the *JCB Dove Engineering Centre in Staffordshire* opened in 2017 to train apprentices which includes a mechatronics suite with a hi-tech rig that replicates an entire manufacturing system along with hydraulic and pneumatic equipment and a related area where students undertake projects using computer-aided design;
- *Middlesex University's Cyber Factory training facility* which was opened for its Department of Design Engineering in 2017 and is installed with Festo Didactic equipment and Siemens wireless technology;
- *Coventry University's Institute for Advanced Manufacturing and Engineering (AME)* which in partnership with the Unipart Manufacturing Group opened in 2014 a purpose-built manufacturing and teaching space on a Unipart site, described as the UK's first 'Faculty on the Factory Floor' (see Case Study 4);
- *Make UK's Technology Hub* which was opened at their Aston Campus in Birmingham in 2017 and has been designed and equipped to replicate modern engineering and manufacturing workplaces for the training of engineering apprentices and managers;
- *Dudley College of Technology's Advance II, Centre for Advanced Building Technologies* opened in 2017 which includes a four-storey factory hangar where off-site manufacture of 'pods' or elements of buildings can be undertaken, led through live projects with off-site construction companies. There is also use of immersive technologies (AR/VR) in both training for future technologies such Building Information Modelling and for simulation of construction skills such as welding;
- the *College of West Anglia's Training Factory* which provides hands on training and assessment for line operators, single and multi-skilled electrical and mechanical engineers, in a realistic factory environment;
- Kirklees College's *Process Manufacturing Centre* which opened in 2016 and has a fully operational batch manufacturing plant using equipment supplied by industry partners;
- the *Fashion Technology Academy (FTA)* opened in 2017 which is a collaboration between Fashion Enter Ltd, Haringey Council, DWP and the e-retailer ASOS.com, and integrates training in industry practices with a live factory producing garments, and also offers educational visits for HE, FE and secondary school level students;

- *London Design and Engineering University Technical College (UTC)* which opened in 2016 and is an industry sponsored college catering for students aged 13 upwards, and has a range of labs with specialist mechatronics, pneumatics and visualisation equipment, including an Amazon factory line, which can be flexibly reconfigured for student projects and learning scenarios;
- *University of Lincoln's National Centre for Food Manufacturing* which serves in one place the needs of the industry for further education, higher education (levels 2 to 6), including degree apprenticeships), research and innovation, and has a purpose-built food factory for teaching and research (see Case Study 5).

Looking more widely, there are plenty of other examples, which while not factories, make use of sophisticated technology to simulate authentic working conditions for training purposes. Some illustrative examples are:

- aircraft, vehicle and ship simulators used for training in the armed forces, such as the Royal Navy's immersive bridge trainers which have been deployed at training establishments like HMS Collingwood since 2000. The Navy's simulation software can now mimic 21 different ship models in different geographical locations, under different weather conditions, day or night. Bridge and engine room simulators are also used in civilian nautical training establishments such as the Warsash Maritime Academy, part of Solent University, which opened in the UK in 2019;
- the *National Training Academy for Rail (NTAR)* opened in 2015 with joint funding from government and industry has facilities to support the digitalisation of rail engineering including the digital signalling equipment, a de-constructed train and a virtual reality and 3D simulation room;
- *Bridgewater and Taunton College's nuclear training facility* opened in 2018 as part of the National College for Nuclear includes the PRACTICE activity centre which uses VR to replicate a nuclear plant in microcosm where highly technical operations can be rehearsed and appropriate industry behaviours learnt in a safe environment.

Beyond individual examples, it is important to consider the wider strategic landscape when assessing the potential for learning factories to contribute to a more coherent and effective UK skills and innovation system. This study has therefore, as recommended by the *Manufacturing the Future Workforce* report, focused on three potential foundations which could play a key role in supporting and aligning future learning factory developments: the Catapults and other Centres of Innovation (COIs) which have UK-wide distribution; the emergent network of Institutes of Technology in England; and the Made Smarter programme, which is currently being piloted in the North West with a view to future UK wide roll-out. In addition, developments have been looked at in Scotland, Wales and Northern Ireland particularly in respect of their devolved skills systems and centres of skills expertise. An account is given here of the current state of play.

Catapults and Centres of Innovation (COIs)

Catapults are specialist technology and innovation centres providing access to cutting-edge R&D infrastructure. The network consists of nine different Catapults which have been established by Innovate UK since 2011. Between them they have a presence at 30 different physical locations spread across the UK, with over £1 billion of research and demonstration facilities under their management. Each Catapult focuses on a key sector of industry where the UK has strengths and there is potential for new technologies to generate economic growth. Their main aim is to bring together UK businesses, scientists, technical specialists and engineers to work side by side on late-stage research and development, and thereby accelerate the development, deployment and adoption of new technologies.

Beyond the Catapult network, there are other facilities that perform similar functions, such as the National Physical Laboratory (NPL), The Welding Institute (TWI) and some of the applied science institutes within universities. Scotland has also created its own network of eight innovation centres which specialise in key sectors and share some of the features of catapults on a smaller scale. The *Manufacturing the Future Workforce* report uses the more generic description of 'Centres of Innovation' to encompass these other facilities, defined as "organisations that undertake technology translation, provide related services and transfer knowledge to support industrial success". Although this study has focused mainly on the Catapults, its analysis is equally applicable to other COIs.

In terms of the potential for the assets and expertise of Catapults and COIs to be harnessed as foundations for a more strategic development of learning factory capabilities in the UK, there are some positive indicators and gathering momentum.

- Internationally, similar organisations like the Fraunhofer Institutes in Germany on which the Catapults were originally modelled have played as significant role in the development of learning factories, and in Singapore the newly launched Advanced Manufacturing Training Academy is being positioned as the hub for the national advanced manufacturing training ecosystem, foresighting future skillsets, identifying gaps in existing training provision and working with training providers to fill them.
- In the UK, as illustrated by the *Manufacturing the Future Workforce* report, there is a growing recognition that, in order to anchor emerging technologies, Catapults and COIs need to take more active responsibility for ensuring that workforce capability is developed for innovation adoption, with a particular challenge being to achieve scale and accessibility of provision.
- There are also now examples of learning factory facilities established or being developed at UK Catapults and COIs, and although these tend to be primarily for research and innovation purposes there is some broader use for education and training.

The main developments, as would be expected, are associated with the High Value Manufacturing Catapult (HVMC) and its network of seven centres. Specific examples include:

- at the Manufacturing Technology Centre (MTC) in Coventry, the Advanced Manufacturing Training Centre built in 2015 and the DRAMA (Digital Reconfigurable Additive Manufacturing facilities for Aerospace) project which began in 2017 and is developing a digital learning factory to help build a stronger additive manufacturing supply chain for UK aerospace;
- at the Advanced Research Manufacturing Centre (ARMC) in Sheffield, the *Factory 2050* which was opened in 2015 (see Case Study 1);
- at the Warwick Manufacturing Group (WMG), the Digital Skills Factory (see Case Study 2); and

- the incorporation of the Advanced Forming Research Centre (AFRC) in Renfrewshire into the National Manufacturing Institute Scotland (NMIS).

Discussions undertaken during this study have also indicated that the learning factory concept could be relevant for other Catapults and COIs, particularly if considered more generically as a complex simulated workplace environment. Examples are given here that illustrate this potential elsewhere in the Catapult network beyond the HVMC.

- The Cell and Gene Therapy (CGT) Catapult has established a large-scale Manufacturing Centre at Stevenage which is specifically dedicated to cell and gene therapy manufacture with facilities such as adaptable production clean rooms which companies can tailor to their specific needs. It has also developed a skills strategy based on a survey of companies to gauge the need to scale up the quality and quantity of the workforce as the industry grows. The model now being adopted by the CGT Catapult to address these skills needs, and to provide a talent pipeline for the innovative SMEs it works with, involves acting as a hub for a geographically distributed national network of licensed training providers. The Catapult supports a blended learning approach with a virtual learning centre and e-learning modules and immersive content co-created with employers. This enables most of the training content to be delivered by local training providers and employers, with the capacity to use the specialist facilities at the Catapult Manufacturing Centre for short enriched experiences: for example, apprentices from companies which have joined the Advanced Therapies Apprenticeship Community come in from across the country for 2 or 3 days intensive training twice a year as part of their programme.

  In the context of the UK national response to COVID-19 and preparedness for future possible pandemics, this approach has recently been given a major boost through funding announced both to establish a further national Manufacturing Innovation Centre at Braintree in Essex and to strengthen the capabilities of the training and skills network. The latter will involve the development of *national Centres for Advanced Therapies Training and Skills (nCATTS)* with facilities to provide industry-standard skills and experience, as well as further development of the virtual Centre for Advanced Therapies Training and Skills (vCATTS) to provide online training programmes for advanced therapy and vaccine manufacturing.

- The Energy Systems Catapult based in Birmingham has developed a national asset called the 'Living Lab' – a 150-home (and growing) test and demonstration environment for businesses to trial new energy products and services in homes retrofitted with room-by-room sensors, smart-heating controls and other smart home technologies, such as electric vehicle charging. Consideration is now being given to whether this type of facility could be developed further to take a 'learning building' approach to the need identified to skill/reskill a one million strong workforce to transform the energy efficiency of the existing UK property stock.

- The Compound Semi-Conductor Applications Catapult based in Newport, South Wales is the newest addition to the Catapult network. The facilities at its new Innovation Centre are for laboratory-based research rather than training or production, and its skills strategy is still in development. The breadth of range of applications across different industries means that it is unlikely to be appropriate to develop learning factory facilities that are specific to its remit, but it could have a role to play in supporting learning factories in industry sectors using compound semi-conductors, for example advising on technology and developing curriculum content and learning scenarios.

Institutes of Technology and centres of skills expertise

Institutes of Technology (IoTs) are the flagship programme in England designed to spearhead the delivery of higher technical education in STEM subjects and address the barriers that have held back delivery of high-quality provision on the scale needed to avert serious skills shortages. They are intended to bring together employers with FE colleges and universities into a new type of prestigious institution. Their remit and the expectations now being set for them fit well with the concept of learning factories. The Government's plan to create a comprehensive national network of employer-led IoTs throughout England means that they have the potential to play a key role in the future development of learning factory facilities and supporting a more coherent and effective skills and innovation system.

The first 12 IoTs were announced in April 2019 and have since been establishing themselves. A competition prospectus has also been published by the Department for Education (DfE) for a second wave of eight new IoTs (28). The success criteria set by the DfE for new proposals highlight features that are consistent with and could encourage a learning factory model.

- Learners have access to industry standard facilities, simulated workplace environments and dual industry/teaching professionals, who can provide real applied expertise, training in the latest techniques alongside current business and employment skills.
- Being able to anticipate and innovate in response to current and future industrial change such as industrial digitalisation or automated manufacturing, accessing the applied research base of their university partners, innovation centres and employer partners to prepare the workforce for changes in technology, working practices and business models.
- Working collaboratively, adding value and driving innovation by harnessing each partner's strengths, ranging from assets such as facilities and equipment to relationships and resources, so that the overall delivery model is greater than the sum of its individual parts.

Many of the Wave 1 IoTs currently establishing themselves are already developing or incorporating learning factory type facilities within a variety of delivery models which include co-ordinated regional approaches. Examples identified during discussions for this study include:

- East London IoT is installing learning factory equipment as part of a new, purpose-built facility for advanced technologies at Barking and Dagenham College;
- Greater Birmingham and Solihull IoT is installing a large 'Cyber-Physical Factory' at Aston University to form part of the hub of a regional 'hub and spoke' model, networked with smaller facilities at each of the spokes (see Case Study 3);

- Lincolnshire IoT has incorporated the National Centre for Food Manufacturing (NCFM) at Lincoln University and envisages that the learning factory type approach pioneered at NCFM could be applied more extensively across a widely distributed geographical network of centres with each major town having its own centre of expertise (see Case Study 5);
- West of England IoT is commissioning a learning factory facility at the University of the West of England as part of the skills strand of a broader initiative called DETI (the Centre for Digital Engineering and Innovation) which is designed to align research, innovation and skills more closely as part of a wider sectoral and regional industrial strategy;
- Yorkshire and Humberside IoT is installing learning factory equipment at two of its partner FE colleges, York and Selby.

Thus in England, there is the prospect that a national network of IoTs with learning factory capabilities will eventually cover all regions and be a critical link in creating a more coherent skills value chain, joining up innovation with the skills development needed for adoption at scale, particularly for the technician skills needed at levels 4 and 5 which are the focus of the government's policy on *Higher technical education reforms* (29).

In Northern Ireland, Scotland and Wales, although there is no direct equivalent of the IoT programme, there are other foundations that can be built on in terms of centres of skills expertise. College networks already have a relatively coherent regional geographic focus (which is not always the case in England despite the Area Review process). There also tends to be a more established college role in supporting businesses with innovation adoption, particularly in Northern Ireland (30). Specific features and proposals which could provide foundations for learning factory type developments were identified in each of the devolved administrations.

- Northern Ireland's rationalised network of six FE colleges (down from 16 in 2007) enables each college to have a clear regional focus and the scale needed to give critical mass. Particular features are: (a) the extent to which their business support role extends beyond vocational and technical training to include business development and innovation processes; (b) the intent to take a more collaborative and co-ordinated approach to business engagement across the college network based on subject specialisms; (c) the extent to which the colleges are involved in developing and delivering Higher Education and Higher Level Apprenticeship Programmes. The Department for the Economy has encouraged FE colleges through a range of funded initiatives to provide innovation support services for SMEs and to work with universities to meet the knowledge exchange needs of businesses in a co-ordinated fashion (31). In some instances colleges take the lead on larger innovation projects, for example Belfast Metropolitan College led a successful consortium bid for Horizon 2020 funding to support digitalisation in the construction industry and on a transnational INTERREG bid to develop pilot approaches to hydrogen energy generation and utilisation. Colleges have also agreed a model of curriculum hubs where one college has been selected on behalf of the FE sector regionally to have a lead role in horizon scanning, curriculum development and employer engagement for developing new apprenticeship solutions, and is recognised for their expertise and specialisation (32).

- Scotland has similarly reshaped the structure of its college sector through a major programme of regionalisation, reducing the number of colleges from 43 to 26 in 13 regions (Glasgow, Lanarkshire and Highlands and Islands remain as multi-college regions, with 10 colleges within the University of the Highlands and Islands region). Particular features in Scotland are: (a) the extent to which there is a managed system across FE, HE, skills and enterprise; (b) the opportunity created by the new National Manufacturing Institute for Scotland (NMIS). As well as there being a single Scottish Funding Council for Further and Higher Education, its work is co-ordinated with Skills Development Scotland and the economic development agencies by an Enterprise and Skills Strategic Board established in 2018 to promote alignment and a common agenda. NMIS exemplifies this approach in respect of manufacturing and at the heart of its plans for the future is the building of a major new facility in Renfrewshire which will house a fully digitalised factory of the future, skills academy and collaboration hub for manufacturers. This is envisaged will support a wider national network of skills and innovation provision. In addition, there are already examples of colleges working in partnership with innovation centres located in their region, such as Edinburgh College's relationship, facilitated through a City Region Deal, with the Data Lab which is Scotland's innovation centre for data and AI.
- Wales too has undergone a significant rationalisation of its college network reducing the number from 25 to 13 with regional alignment reinforced by the existence of three over-arching Regional Skills Partnerships. There are some examples of a co-ordinated approach being taken to strategic skills issues, such as the Construction Wales Innovation Centre (CWIC) which is a pan-Wales enterprise operating on a hub and spoke model led by University of Wales Trinity Saint David (UWTSD) Group and involving Coleg Sir Gar and Coleg Ceredigion, Coleg y Cymoedd and Coleg Cambria. Further proposals exist to reform and bring greater co-ordination to the wider system in which colleges operate, reflecting some of the features already seen in Scotland and Northern Ireland. A single commission is proposed to be responsible for further and higher education, skills, and all Welsh Government funded research and innovation. Proposals made in the 2018 Reid Review of Government Funded Research and Innovation in Wales (33) recommend giving FE colleges access to Welsh innovation funding and encouraging them to work together with universities and research and technology organisations in new innovation hubs across Wales. Similar proposals are made in the 2019 Brown Review of Digital Innovation for the Economy and Future of Work in Wales (34) for the creation of industrial innovation clusters and the integration of existing business, skills and innovation support to form a single business diagnostic and transformation process.

While the skills systems may have diverged across the UK, the same technological and economic forces are propelling the need to create institutions and partnerships with specialist facilities and capabilities for skills acquisition to take place alongside innovation, particularly in the context of digitalisation. The potential for colleges to play a greater role in innovation and knowledge transfer has recently been highlighted both by a Gatsby Foundation report on *Further Education Colleges and Innovation* (35) and by the *Commission on the College of the Future* (36).

Made Smarter

The 2017 Made Smarter Review of the opportunity to transform UK manufacturing through the adoption of industrial digital technologies (IDT) made a series of recommendations that received UK Government support and have led to the establishment of Made Smarter as a UK wide industry/government initiative or 'movement'. The two key recommendations in this context were:

- To create a much more visible and effective digital ecosystem to accelerate the innovation and diffusion of Industrial Digital Technologies, including
  - a National Adoption Programme with advisory services through LEPs
  - a network of Digital Innovation Hubs supporting a national innovation programme
  - Digital Transformational Demonstrator programmes
  - a network of Digital Research Centres
- To upskill a million industrial workers to enable digital technologies to be successfully exploited, by means of:
  - a National Skills Strategy and Implementation Group under Made Smarter
  - a modern digital delivery platform providing digestible content for upskilling and reskilling
  - an incentivised programme of personal training and reskilling allowances.

These recommendations are now being taken forward under the aegis of the Made Smarter Commission. A pilot for the national adoption programme with advisory services for SMEs is currently underway in North West England and is due to be completed and evaluated in March 2021. The pilot programme contains four elements of support, integrated into a single programme:

- strengthened regional SME advisory services
- financial support for investment
- mentoring support and improved university links
- support for change management

The advisory services include workforce advisers on skills and organisational development issues related to technology adoption, and there is a leadership programme offered by the Lancaster University Management School. A digital engineering skills platform – *Engage* – has been launched in partnership with Enginuity, a specialist provider, to make available online content from leading edge companies and centres of innovation like Rolls Royce and the High Value Manufacturing Catapult. The UK Research and Innovation Challenge Fund is also being directed to support the innovation strand through a Manufacturing Made Smarter Challenge, with £147m government funding to be matched by industry over five years. This will deliver related innovation themes through collaborative R&D opportunities, research centres, technology accelerators, test beds, demonstrators and networks, including the commissioning of a national network of digital innovation hubs.

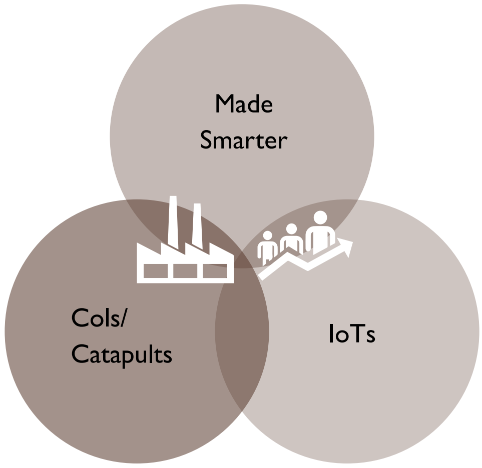
A challenge going forward for Made Smarter will be how any national roll-out of the adoption programme (which would currently be England only), and the skills strand which currently does not have any significant dedicated budget, can be most effectively brought together with the innovation strand to create the skills value chains needed for adoption at scale in every region of the UK. Looking at international practice, and in particular the way in which the German national network of Mittelstand 4.0 Competence Centres has incorporated a number of university and Fraunhofer facilities (see above), learning factory facilities could play a significant part in the national digital ecosystem envisaged by Made Smarter. This includes learning factories being incorporated within digital innovation hubs, acting as demonstrators and technology trialling facilities for adoption programmes, and enabling the delivery of upskilling in digital technologies. This would not necessarily require wholesale new investment in facilities, as much could be achieved by utilising and enhancing the range of services offered through facilities that already exist or are planned through the Catapult and IoT networks and such like. The Manufacturing Made Smarter Innovation Hub - Smart Factory competition launched in November 2020 presents an opportunity to take forward such an approach.

Where learning factories fit

The graphic below (figure 1) sums up in a simple form where the opportunity to further develop learning factory capabilities could fit in the context of UK national initiatives.

Learning Factory fit

- Made Smarter - needs a national ecosystem of facilities to support digitalisation
- IoTs need industry-standard equipment and access to expertise to anticipate and address future workforce needs
- Catapults/COIs need skills transmitters for scale and accessilbility
- All need strong industry partnerships

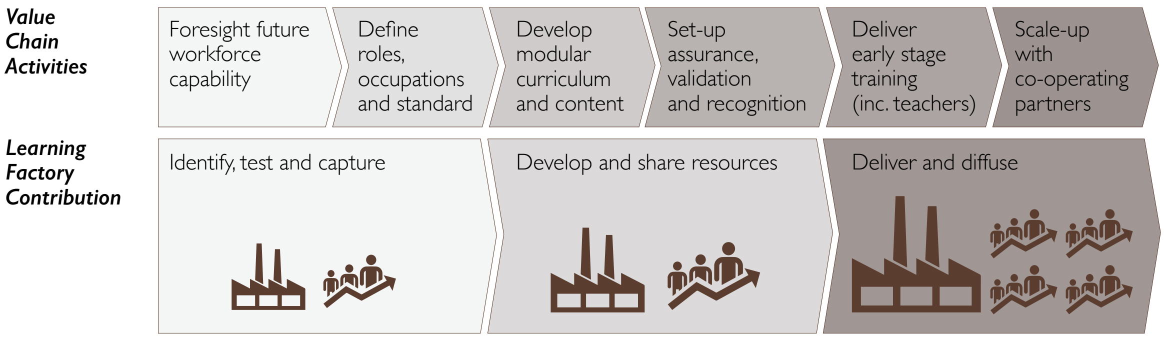


Alongside these national initiatives, the need and opportunity for learning factories should be looked at through a regional and local economic lens. Much of the practical planning, co-ordination and networking will be driven by factors like local geography and employer clusters. Examples already exist, such as in the West of England and Greater Birmingham and Solihull (Case Study 3), where strategic regional partnerships involving employers, providers and local authorities are commissioning learning factory facilities with IoT funding to fit within an integrated regional approach to innovation and skills, and the regionalisation of skills provision in the Northern Ireland, Scotland and Wales offers similar potential. Make UK, the manufacturers' organisation, has also made clear the importance of regional co-ordination in its recommendations for the roll-out of Made Smarter (37).

The challenge now is how to build on these foundations so the potential of learning factories and similar approaches in other sectors is harnessed more strategically to help address systemic problems holding back productivity and levelling up, including technical skill shortages at levels 4/5, diffusing innovation, and smaller companies struggling to know where to start with digital transformation. The remainder of this section first takes a more systematic look at how learning factories can be positioned to contribute to the skills value chain and then makes recommendations for how that potential can be more effectively realised.

POSITIONING LEARNING FACTORIES IN THE CONTEXT OF THE SKILLS VALUE CHAIN

Learning factories take a range of forms and can serve different main purposes in terms of innovation, education, and training. The contribution that a learning factory can make and where it is positioned within a skills value chain will vary depending on individual characteristics and wider context. Nevertheless, it can be considered where the scope lies for learning factories to contribute. Figure 2 below sets out the flow of value chain activities with a high-level view of learning factory contributions.



The graphic is intended to show that there is a role for learning factories to contribute and make links across all stages of the skills value chain, though the biggest contribution is likely to be at the righthand end where the delivery of training starts and capacity building is required across the wider skills system to achieve scale and accessibility. The potential learning factory contribution at each stage of activity is now considered in more detail.

Foresight future workforce capability/Define roles, occupations and standards
The first step of the skills value chain approach involves foresighting future workforce capability by identifying the 'future state' skills necessary to exploit emerging technologies, such as those associated with industrial digitalisation. There is a particular need to understand how as the digital transformation of manufacturing takes hold, and in particular the impact of Artificial Intelligence (AI), how this changes the role of humans working alongside machines rather than necessarily replacing them. (38) This involves first identifying what organisational capability is needed to address future challenges associated with emerging technologies and then deriving from that the workforce competencies needed to enable such organisational capability. Systematic processes are used to gather and evaluate expert opinions, and the development of theoretical future scenarios can also be involved. Following its international study for the Manufacturing the Future Workforce report, the HVMC has trialled a step by step process using groups of specialist technologists, expert educators and employer evaluators to foresight future skills needed for industrial digitalisation.

Learning factories' primary interest in the foresighting process is in the outcome, knowing what competencies are likely to be required in future and who within future organisations and teams will need them. This understanding of future competencies and associated roles is crucial for the overall design of a learning factory, and for developing the programmes and scenarios that are to be delivered through its facilities. However, there is scope also for learning factories to contribute to the foresighting process, at least in a supporting role.

A controlled environment for testing the application of emerging technologies and bringing together students and trainees to tackle real world projects and problem-solving exercises can provide valuable insight into the future competencies needed for the successful adoption of those technologies. Such insights can be fed into expert group discussions, or the outcomes of expert discussions can be tested and validated in a learning factory environment. By way of example, the Institute for Advanced Manufacturing and Engineering at Coventry University (see Case Study 4) found that when industrial partners undertook projects using their learning factory facilities, skills gaps were revealed that had previously been hidden and companies would not have articulated for themselves as future needs. These have been captured and fed back into the curriculum for the future workforce.

There can also be a valuable feedback loop. As learners undertake experiential learning and problem-solving that have been designed to develop a certain set of competencies, they may adopt new techniques and ways of working that alter or refine the understanding of what the key competencies are. A striking example of this type of feedback loop comes from a naval training simulation rather than an actual learning factory. When crew were being trained on a sophisticated bridge simulator to manoeuvre the Queen Elizabeth aircraft carrier, they worked out new techniques that were more effective with the new technologies being used. These techniques were then successfully applied in the real world and became part of the future training.

Develop modular curriculum and content / Set up assurance, validation and recognition
A learning factory is a sophisticated set of learning resources built using implicit as well as explicit knowledge and know-how. The design of a learning factory can be considered at three levels: the overall learning factory environment that is to be built and equipped; the learning modules or programmes that are to be delivered through the learning factory; and the specific scenarios or learning situations that are created using the learning factory's capability to facilitate experiential learning (39). At each of these levels, a key design component should be an understanding of the range of competencies that the learning factory is intended to develop and the anticipated nature of learners who will acquire them. This design approach is consistent with the skills value chain concept, and learning factories should be able to make a substantial contribution at this stage, particularly if the modules and scenarios can be shared across a network as is happening with some of the initiatives in Germany and across the McKinsey global network of Digital Capability Centres. Such sharing of resources can also encourage other forms of collaboration.

An interesting recent development in the UK is the 'Connected Curriculum' sponsored by Siemens. This involves collaborative development of a set of Industry 4.0 curriculum resources that can be tailored to the needs of individual institutions and uses the Siemens industrial software portfolio and the Mindsphere platform, working in partnership with Festo Didactic's learning factory hardware. The Connected Curriculum was launched in 2019 with a group of six university partners (The University of Sheffield, Liverpool John Moores, Middlesex University, Newcastle University and Manchester Metropolitan University) and is aimed initially at undergraduate and postgraduate courses though the approach has scope to be extended more widely.

In terms of assurance, validation and recognition, there is clearly potential for learning factories to play a significant role in assessment, and for this to be linked to modular qualifications and micro-credentials. Competencies can be difficult to measure as they are not directly observable; however, characteristics associated with competencies can be observed in the performance of tasks, and questions can be asked about required knowledge elements. The advantage of a learning factory is that it can bring these two aspects together in a fully interactive, yet controlled learning environment, in particular enabling the observation of how action-oriented tasks are performed. This is done through designing problem-based scenarios that require trainees to act in a new situation which demands the intended competencies, alongside more conventional knowledge-based tests which can assess whether they know why a practical approach has been successful (40). Structured observation of the performance elements is generally undertaken by human observers, whether live or on video. Going beyond that, the data-rich environment of a digitalised learning factory operating on Industry 4.0 principles ought to open up new opportunities for the collection and analysis of data for both formative and summative assessment of how practical tasks are performed.

Although this potential is clear, and there is a growing interest in assessment and evaluation methodologies in the academic literature on learning factories (41), the study has struggled to identify strong examples in practice. This appears to be an area where more needs to be done to realise the potential of a learning factory approach, particularly in the context of UK qualification and recognition regimes. (A recommendation on shared learning and assessment resources in the next section of the report seeks to address this point.)

Deliver early stage training (inc. teachers) / Scale up with co-operating partners

It is here that learning factories have the greatest potential to link the innovation and skills systems together, acting as centres of expertise and transmitting the requirements of new technologies into the wider skills system. This can be done both through direct delivery of training and through support and capacity building across wider networks to enable greater scale and accessibility.

The particular added value of a learning factory is that it can set the delivery of training in an authentic industrial environment that is designed to demonstrate new and emerging technologies. This link can be further enhanced when staff actively involved in research and innovation projects use the same facility and can share their expertise. This might happen where a learning factory run by a COI is also used for education and training purposes, or where one is run by a college working in close partnership with a COI or industry partner with R&D capability, as may be the case for example with an Institute of Technology.

In terms of scaling up it is unlikely to be sensible or economic to envisage large numbers of full-scale physical learning factory facilities being established to give local coverage for each main technology specialism. The challenge therefore is to make best use of a limited number of well-equipped and expertly staffed specialist facilities to support wider geographically distributed networks of provision whether at national or regional level. There is scope for learning factories to do this in three ways.

First, learning factories can act as centres of expertise for teacher/trainer training. It is often difficult for staff in more generalist local providers to keep up to date with new technologies and to get hands-on experience of using leading edge equipment. Learning factories could run modules and demonstrations to support teacher training and CPD in relevant specialisms. For example, learning factory facilities could be used to support teacher training for the roll-out of T-levels in certain subject areas. A similar role could be played in respect of small business advisers being deployed to support the national roll-out of Made Smarter.

Secondly, learning factories can act as hubs for networks of distance learning. In this model most of the learning takes place at physical locations away from the learning factory, but learners travel in to use its facilities for specific modules and projects, and the learning factory may also provide learning content that can be accessed remotely. The National Centre for Food Manufacturing at Lincoln University uses this model for its apprenticeship programme. Apprentices are spread across the country at other food manufacturing locations. They spend most of their time with their employer or their local college/training provider, but distance learning materials are available to support their off-the-job learning and they spend three weeks a year at the National Centre using the learning factory facilities (see Case Study 5). Without necessarily having a formal learning factory set up, some of the Catapults, such as the Gene and Cell Therapy Catapult (see above), have begun to use a similar model to support distributed delivery of apprenticeships through local providers, including 'summer school' type blocks of access to their specialist facilities.

Thirdly, a hub and spoke model can be taken significantly further if Industry 4.0 principles are applied to create fully integrated cyber-physical networks. Digital twins and simulations of a learning factory can be used for remote facilitation of learning, using shared data and digital learning resources. This can be done in conjunction with physical equipment and facilities, so for example local providers could have smaller and cheaper learning factory installations that are enhanced through integration with more complex digital twins. This type of approach is beginning to be seen in some of the German state-level initiatives with vocational schools, including use of digital twins of learning factories to provide more inter-disciplinary content for economics and business management provision.

While all of the above is technically possible, it should be recognised that each approach assumes increasing levels of collaboration and inter-operability.

Conclusion and Recommendations

A more concerted approach will be needed to position learning factories in this way to strengthen the skills value chain in the UK. There are three main roles that Catapults and COIs could play.

(1) Identifying the need for learning factories. Catapults and COIs, working with industry, are well-placed to convene skills foresighting and identify gaps in existing provision related to their areas of specialism. This kind of analysis should underpin the commissioning of learning factory facilities, their overall design, and more specific curriculum and content design. It could also suggest where new investment in learning factory facilities is unwarranted.

(2) Developing and extending the reach of their own facilities. Catapults and COIs represent a very significant investment in leading edge technology and facilities. It should be considered whether existing assets or those being commissioned in future could be leveraged more systematically for learning purposes through taking a learning factory approach. This includes, where learning factory facilities already exist but are focused primarily on research and innovation, considering whether they could play a broader role in skills development. This may not always be practical where there is high demand for specialist facilities, but there may be other approaches to broaden access such as use of digital twins.

(3) Supporting learning factory developments elsewhere. Beyond how they utilise their own facilities, Catapults and COIs can use their expertise to shape and support facilities located elsewhere, working in partnership with centres of skills expertise. This could involve planning and procurement, curriculum design, learning resources, shared staff, secondments, trainer training, CPD, master classes etc. The IoT network being established in England provides a significant opportunity for this mode of partnership working.

Catapults and COIs cannot play these roles in isolation. The five recommendations which follow set out what is needed to make the most each of the foundations identified to "promote Learning Factories as an education model to enable industrial digitalisation".

Recommendation 1. Co-ordinated government support. The development, utilisation and networking of learning factories and other complex simulated workplace environments should be supported in a co-ordinated way across Catapults and Centres of Innovation, Institutes of Technology and other centres of skills expertise, and the Made Smarter initiative on industrial digitalisation. Opportunities should be sought wherever practical to utilise the same assets and expertise for multiple purposes, whether directly or through partnership and networking arrangements. At a national level, BEIS, DfE and their equivalents in the devolved administrations should encourage a co-ordinated, collaborative approach, including through funding alignment and incentives. Authorities at regional and local level should look similarly at how learning factory type developments can be positioned strategically in the context of local industrial clusters, and how they can be networked to maximise reach and accessibility.

Recommendation 2. Mapping. A systematic mapping exercise should be undertaken of existing and planned learning factory facilities across the UK and used to inform planning and investment at both national and regional levels, as well as networking and sharing of expertise. The mapping should be based on the key features used to categorise learning factories internationally, supplemented with any additional information of particular relevance to the UK. The work could be overseen by a core group drawn from the Catapults, Institutes of Technology, Made Smarter, the Devolved Administrations and LEPs, and it should draw on lessons from work already initiated for Made Smarter and international examples such as the Industrie 4.0 Map created in Germany. The resulting analysis should be used both to identify gaps and to avoid duplication and risk of under-utilisation.

Recommendation 3. Catapults and COIs. As part of a broader role in ensuring the workforce skills and awareness needed for innovation adoption, Catapults and COIs within their fields of specialist expertise should look to: (a) identify where there is need for learning factories and similar complex simulated workplace environments, using their understanding of future capability and competency requirements; (b) develop and extend the reach of their own such facilities for skills development and innovation adoption; (c) use their expertise to support the development and operation of learning factories elsewhere.

Recommendation 4. Institutes of Technology and other centres of skills expertise. The IoT programme should continue to encourage and support the development of learning factory facilities based on co-ordinated local partnerships where there is strong engagement from anchor employers and a sound business case. Lessons should be captured as quickly as possible from Wave 1 projects that are commissioning or incorporating learning factories and, where appropriate, additional expert advice made available to those making proposals for learning factories in future rounds, for example on the procurement of equipment. Consideration should also be given to whether a more aggregated approach to procuring learning factory equipment would have advantages as the IoT network is rolled out. Beyond the IoT programme in England, the devolved administrations should consider supporting the development of more learning factory capacity through their regional centres of skills expertise as part of a more integrated approach to skills and innovation.

Recommendation 5. Made Smarter. National roll-out of the Made Smarter initiative on industrial digitalisation should seek to utilise and provide additional support for existing and planned learning factory facilities: (a) within digital innovation hubs; (b) as demonstration and trialling facilities for adoption programmes; and (c) to enable upskilling. It should also be possible to utilise learning factory facilities for the training and professional development of those acting as advisers for the adoption programme.

PRACTICAL CONSIDERATIONS AND GUIDANCE

This section offers pointers to some of the more practical considerations that arise when commissioning and operating a learning factory. It reflects discussions with those associated with developments already underway in the UK, a review of the international academic literature and speaking to some of the experts and specialist suppliers. In particular, it draws on the recent publication, Learning Factories: Concepts, Guidelines, Best Practice Examples (Abele, Metternich, and Tisch 2019) which seeks to provide a comprehensive overview of the current state of research and practice, and features best practice case studies of 31 existing learning factories.

This is a complex subject and there are many variations of learning factory for different purposes so it is only possible to give a flavour. Four subjects are covered:

- Planning and commissioning
- Learning approach and content
- Staffing and trainer training
- Digital models

Planning, design and commissioning

The seven dimensions used to classify the main characteristics of learning factories (set out again below) can also form a useful checklist for planning purposes.

- Operational model – what type of organisation is the operator and how does it achieve sustainability in terms of income and financial viability, content development and renewal, and attracting and retaining professional staff with the required skills and expertise?
- Targets and purpose – what main purposes are being served in terms of education, vocational training, research; what secondary purposes in terms of technology testing, industrial production, innovation transfer, demonstration and publicity; who are the intended learners; what industrial sector is being targeted; and to achieve what forms of improvement e.g lean management, resource and energy efficiency, digitalisation and Industry 4.0?
- Process – which production processes and life cycles are depicted by the learning factory, what are the boundaries of the system and which parts are being focused on?
- Setting – is the learning factory purely physical, purely virtual or some form of blended 'cyber-physical' combination; is it full-size or scaled down; how much of the factory does it cover; how changeable is it; how is the digital technology integrated?
- Product – what is the product, is it physical or a service, is it a real functional product or one that has been developed or simplified specifically for learning purposes, how complex is it, how many components and variations does it have, and what happens to it, is it dismantled (so components can be reused), displayed, sold, or destroyed?
- Didactics – what is being learned in terms of competencies and learning objectives; how is it being learned in terms of the format and design of the learning, the use of learning scenarios and the role played by the trainer?
- Metrics – what is the size and capacity of the learning factory and the volume of activity that it undertakes – numbers of courses, numbers of learners, staffing, square metreage?

The fundamental questions to be answered are about clarity of purpose and achieving operational sustainability. These will determine what form and scale of learning factory is appropriate, the level of investment that is required and can be justified, and whether indeed a learning factory is the right solution. A learning factory can represent a substantial investment in creating a complex learning environment with highly specialised equipment and expertise. The risk is that it could end up being underutilised and not properly maintained, or is little more than a shiny status symbol to be used for marketing. Equally there is no point in creating a learning environment that is larger and more sophisticated than is required, which could even be counter-productive if learners and trainers are intimidated by its complexity. If the purpose is just for individuals to acquire a limited set of technical skills, there may well be more cost-effective ways of achieving that.

There are a number of approaches to achieving operational sustainability. For an individual company primarily serving its own needs, or large organisations with a centralised training function such as the military, it is likely to be somewhat more straightforward to assess and manage the level of demand, and factor that into a business case. For organisations like catapults/COIs, universities, colleges or independent training providers, which generally rely on a mix of public and private income sources with a variety of users, it is likely to be more complex. Three approaches observed are:

- having anchor users – a small group of large employers or some form of membership subscription arrangement that can ensure a base level of utilisation;
- combining multiple uses and income streams – if a facility is used for education and training as well as research and innovation, or vice-versa, it can increase utilisation levels and gain access to multiple income streams;
- being part of a strategic network – demand can be aggregated and costs shared if a learning factory is planned to serve a collaborative network for example in a 'hub and spoke model'.

Another key consideration is the business model for commissioning a learning factory facility and the extent to which it needs to be customised or can be bought and installed off the shelf. Two main options exist with variations of approach within each of them.

- One-off bespoke. This is most likely to be appropriate either for a specialised research and innovation centre or a large company or organisation for which it makes sense to design a facility with their own equipment primarily for usage by their own staff. The development can be undertaken in-house by the commissioning/operating organisation, or external learning factory experts can be hired to undertake the detailed planning, design and installation. There are various design guidelines documenting sequential steps that can be followed, such as the 'Darmstadt Approach to Competency-Oriented Planning and Design' which is a three-level, holistic approach, starting from the targets and competencies to be achieved, and covering the overall learning factory environment, the modules to be taught and individual scenarios/situations to be used. The main advantage of a one-off, bespoke development is that it can be customised precisely to the objectives of the operating organisation and the technologies being used. The main drawbacks are that it may take longer to design and install, it requires more in-house expertise, it may be less flexible to cover a range of uses and there may be more risk. These drawbacks can be mitigated to some extent by working with external experts applying tried and tested approaches, and this appears to be an increasing trend.

- Turnkey or standardised off the shelf. This involves a ready-made solution being purchased and installed, though some degree of adaptation and customisation may still be possible. There are various ways in which this can be done. One approach is basically to make a copy of an existing learning factory and install it at a different site. This approach has used in co-operation with McKinsey to replicate versions of the Darmstadt Technical University's Process Learning Factory CiP at locations in other countries and in different industrial contexts. The other main approach involves purchasing from a range of products offered by specialist learning factory suppliers. These can vary in scale and complexity, and can often be built up in a modular fashion over time, starting from relatively modest beginnings. They also often come with support packages of training for the trainers and operators, and training materials and exercises for the learners. These ready-made approaches will most often be suitable for colleges and universities using their facilities primarily for education and training purposes, though the more complex installations can also be used for research and innovation. The main advantages of this type of approach tend to be: lower costs and quicker implementation; less expertise required in-house; networking and exchange of experience and learning resources with other operators using similar set-ups; and benefitting from the research and testing that has been undertaken by others. The main drawback is that a duplicated or standardised product may not be sufficiently adaptable to meet specialised needs.

Other variations to be considered are repurposing/incorporating existing equipment rather than purchasing just from new, mobile learning factories that can be taken out to different sites, and digital twins (see more below).

Costs can vary widely depending on scale, complexity and specialisation. The entry point for the smallest, simplest off the shelf product from a learning factory provider that might be appropriate for an individual college is about £100k. For larger and more complex, off the shelf products that might be for universities or network hubs this can rise to £2m. For one-off bespoke developments, it is more difficult to give figures because each will be individual but they are likely to be significant investments, starting from the top end of the range for standardised products and going upwards.

Learning approach and content

Learning factories embody a particular approach to learning that reflects underlying theoretical perspectives and empirical research on how adults most effectively acquire practical vocational competencies. The growing interest in 'learning by doing' and 'collaborative problem solving', underpinned by theoretical models such a 'constructivism' and 'constructionism', has already been cited above as a factor that helps explain the global growth in learning factory deployments. Furthermore, there appears to be a good fit between the added value capabilities of learning factories and the competencies increasingly being recognised as key for the adoption of digital technologies associated with Industry 4.0 – helping to further explain the rapid acceleration in learning factories being commissioned and academic papers being written about them in recent years.

A cluster of related terms are used to describe the forms of learning that learning factories are designed to facilitate:

- Learning by doing – which emphasises the importance of practical experience rather than passive receipt of knowledge (the theoretical origins of which are generally associated with the American philosopher John Dewey);
- Experiential learning – which focuses on how knowledge and competencies are built through the transformation of the learner's experience, often characterised by a four part cycle of (a) concrete experience, (b) reflective observation, (c) abstract conceptualisation, and (d) new active experimentation (as described in the work of David Kolb);
- Active learning – which concentrates on the active involvement of learners, analysing situations, intervening to test their ideas and evaluating results, and which as a concept can be further sub-divided as follows:
- Action-oriented learning – which focuses on the actions of the learner and their observations of cause and effect as they independently tackle complex problems;
- Problem-based learning – where active learning starts from the presentation of a problem and results from the process of working toward understanding or resolution of that problem (an approach that originated in medical education and has since been adopted in other fields including engineering);
- Collaborative problem solving – which combines problem-based learning with a social and team working dimension, and is about solving problems together, applying knowledge and discussing with others what will work best;
- Project-based learning – where the active learning is stimulated by a real world or authentic project which is often undertaken in a team;
- Game-based learning or gamification – which integrates elements of game play for serious learning purposes;
- Research-based learning – which organises learning in mutual dependence with research.

These forms of learning can be facilitated in a variety of ways, many of which are likely to be easier and cheaper than developing a learning factory or equivalent complex simulated workplace environment. However, a learning factory-type facility has certain inherent advantages over either a conventional classroom/academic learning environment or work-based learning, and these advantages come to the fore in certain circumstances for the development of certain types of competency. The 'sweet spot' appears to lie in being able to combine complexity, authenticity, control and safety where there is sufficient scale of demand to justify the effort and investment entailed. A conventional classroom environment cannot replicate the complexity or come close to giving an authentic experience of working in a modern manufacturing environment. A real workplace has the complexity and authenticity but it cannot be controlled for learning purposes without significant disruption or provide a low risk environment for practising and trying things out. To give a sporting analogy, one could think of the role played by a training pitch in coaching a football team: tactics and formations can be explained to a team on a white board, individuals can work alone on their technical skills and fitness, but they still need the opportunity to pull all these things together and try them out in a dynamic learning environment with team mates and an opposition before putting them into practice in a real game.

For learning factories, as dedicated learning environments designed to facilitate various forms of active and experiential learning in a manufacturing context, it is the combination of complexity and authenticity that sets them apart. The benefits commonly cited include: the range and combination of competencies that can be developed; the relevance of these competencies for the future workplace; the motivational and affective context created; and the possibilities to integrate learning with research, innovation and technology transfer. Each of these is explained briefly below.

- Range and combination of competencies. Learning factories are recognised as offering the potential for competency development in all human performance areas – cognitive, affective and psychomotor. Their capability to develop interdisciplinary competencies and softer skills such as communication, team working and creativity alongside the application of more specific technical and procedural skills is particularly important.
- Relevance for future competencies. Significant attention is currently being given to identifying the competencies required for digitalisation and Industry 4.0, and how these can be developed most effectively. While this is still work in progress, there is widespread recognition that learning factories are well-suited for this task through the unique connection they make between thinking and doing in the context of production, and how they can actively involve the learner at the intersection of manufacturing, information and communication technologies.
- Motivational and affective context. The authentic character of a learning factory and the possibility to act hands-on immediately can be important motivators to learn as well as helping to instil workplace attitudes and behaviour. Adult learning theories emphasise the importance of learning being self-directed, experiential, and having immediacy of application to practical problems. The sound, smell, touch and feel of real equipment in an authentic production environment can all help create an 'affective context' which intensifies the experience and promotes the retention of learning.
- Integration with research, innovation and technology transfer. Learning factories are well-suited to act as research enablers and to be used as laboratory environments for manufacturing systems. They can also act as demonstrators of new and emerging technologies. If these uses are integrated alongside competency development, they can provide a direct mechanism to create the workforce capabilities needed for technology transfer and adoption.

While all these potential benefits are achievable, realising them can involve a significant learning design task. It is not just a matter of having the right equipment, but how modules, tasks and scenarios are created to make use of that equipment to fulfil learning objectives based on the competencies to be acquired. This requires expertise both in the design of content and facilitating its use. It also points to the importance of being able to share content, particularly through software and digital resources that can be used with equipment in multiple physical locations.

Staffing and trainer training

When thinking about learning factories, there is a natural tendency to focus on equipment and technology, and the buildings in which they are housed. This is reinforced by the majority of funding currently being made available in the UK, for example through the IoT programme, being for capital expenditure on buildings and equipment. This contrasts with a much greater emphasis on staffing and trainer training observed in some of the programmes internationally. For example in Germany, the Federal Government's substantial financial support for 'Mittelstand 4.0 Competence Centres' has been for the staffing needed to extend the usage of existing assets and deliver additional services to SMEs, and Baden Wurttemburg's programme to install 'Smart Factories' in its state vocational schools has been accompanied by a significant package of teacher training on how to utilise the equipment and content.

The staffing requirements of any learning factory facility will depend very much on its scale and what it is being used for. Consideration needs to be given to the set-up and maintenance of equipment as well as how it is used and a key role is likely to be that of technician or lab engineer. Teaching and training staff will ideally bring a combination of expertise: (a) up to date knowledge and experience of how technology is being used in industry; (b) coaching and facilitation skills to make the most of specialist learning factory equipment and scenarios for experiential learning; (c) innovation and applied research skills with an understanding of emerging technology trends. They may also need learning design skills if content and scenarios are being developed in-house.

The study has encountered various approaches to address these staffing needs both internationally and in the UK. One model used in universities is to develop the role of research assistants as tutors and learning facilitators, typically working in pairs. The progression for the individual might start with them undertaking modules themselves as students, then working alongside a more experienced tutor and facilitator, before in due course taking on the lead role. In company-run facilities, or those with a strong company partnership, the company's own personnel may be drawn on, perhaps using internal secondments or part-time arrangements.

Discussions with Wave 1 IoTs looking to establish learning factory facilities have indicated that sourcing staff with requisite expertise could be a significant challenge for them, as it could be for IoTs more generally given the level of expertise and specialism expected. The risk is that the substantial amounts of capital funding being made available for the programme do not achieve as good a return on investment as hoped and that new facilities are poorly utilised because of a lack of staff expertise.

Many of the Wave 1 IoTs are looking imaginatively at addressing this issue, and at how their partnership arrangements with businesses and universities can be leveraged to access and pay for the expertise they need. For example, the *South Central IoT (SCIoT),* which has a digital specialism and is led by Milton Keynes College and based at Bletchley Park, has made the development of various models of 'dual professionalism' – bringing in external expertise from industry and academia – a major part of its strategy. About 40 to 60 per cent of its course content will be delivered by dual professionals, many of whom will come from their project partners which include major IT and cyber-security companies, as well as Cranfield University which is considering offering placements to their PhDs. SCIoT is also working with City & Guilds to create an educator/coach qualification for dual professionals. The National Centre for Food Manufacturing, which is a well-established learning factory facility within the Lincolnshire IoT, has developed a model of hybrid teaching staff who could be considered as 'tri-professionals' with expertise in teaching, industry and innovation. All teaching staff are expected to have relevant industry experience and to be engaged in innovation projects. This makes it possible to access multiple funding streams which in turn can enable salaries to be offered at a level to attract the expertise needed (see Case Study 5). In terms of training, those purchasing an off-the-shelf or turn-key learning factory set up will normally be able to access some form of accompanying package of training for their staff.

Nevertheless, it is doubtful whether the full potential value of the substantial capital investments being made in IoTs, Catapults and similar organisations, where this is directed to creating learning factory type facilities, can be realised without more support to build a networked cadre of expert trainers. Learning factory facilities, whether located in IoTs, Catapults or elsewhere, could also provide an ideal setting for continuous professional development of teachers and trainers to help ensure they are up to date with new and emerging technologies. For example they could make a significant contribution in some sectors to the professional development programme for the national roll-out of T-levels in England.

Digital models

The core concept of a learning factory involves a physical facility. However, as digitalisation of real world production has gathered pace and with the growing capabilities of virtual reality (VR), augmented reality (AR) and other simulation and learning technologies, there has been increasing interest in digital or virtual learning factories, as well as various forms of hybrid which blend digital and physical capabilities together. Given the increasing focus of Industry 4.0 on what are described as 'cyber-physical' production systems, learning factories are inevitably themselves becoming cyber-physical. There is a spectrum of degrees to which this is happening, and digital and physical elements are being brought together in different ways for different purposes. There are also pros and cons to be taken in account when considering how far to go with virtualisation, given the importance of authenticity. Nevertheless, it is clear this is an absolutely key area for the future development of learning factories, and that the potential for what can be achieved is only going to grow alongside the capabilities and affordability of the technologies involved.

The following list categorises and illustrates the spectrum and variety of possible digital approaches to learning factories.

- Digitally supported. This is where a physical learning factory is in some way supported or extended by digital and virtual technologies. Examples of how this can be done include:
  - using e-learning materials alongside the hands-on learning, often covering theoretical concepts that complement the practical experience;
  - using multi-media learning technologies to enhance and personalise the learning experience within the learning factory;
  - extending the scope of the physical learning factory through some form of virtual simulation, which could for example enable a complete factory to be digitally replicated around a limited configuration of physical equipment or more timely feedback to be given on processes that are time-consuming to complete in reality.
- Wholly digital. At the other end of the spectrum is where a learning factory is a completely simulated virtual model. Their development requires expertise and software tools for visualisation and analysis. Once the model has been

developed, its use only requires a computer with visualisation software and hardware such as VR glasses, and it can in principle be used in any physical location by anyone with access to such equipment. Examples include the XPRES Virtual Lab at the KTH Royal Institute of Technology in Stockholm which uses a simulated factory model for production research and the McKinsey Virtual Model Factory which operates in a 3D immersive environment

- Hybrid. This approach looks to get the best of both worlds through integration of physical and digital. As such, it implies a step further than just 'digitally supported' in that virtual representation is based on the same digital data set as the physical learning factory and is fully integrated into the design rather than being a supplementary add-on. In this sense Industry 4.0 principles are being applied to the learning factory itself.

Digital has distinct advantages and disadvantages when compared with physical.

The main pros are:

- Cost. It will usually be cheaper to create a virtual simulation than to equip and house a physical learning factory, particularly if the goal is to recreate a large factory.
- Scalability. Once created, a virtual model can be replicated freely whereas each new physical facility is likely to incur substantial new costs.
- Accessibility. In principle a virtual model can be accessed anywhere rather than being tied to one physical location.
- Adaptability. Adapting and reconfiguring is likely to be simpler and quicker within a range of programmed scenarios.
- Updatability. Updating is likely to be easier and cheaper than for a physical learning factory which carries the risk of being overtaken by the pace of change.
- Scope for learning design. A virtual simulation can designed more freely to focus on what enhances and accelerates learning, for example accentuating key learning points, enabling unlimited practice and providing instant feedback.

The main cons are:

- Loss of authenticity. Learning is inevitably less hands-on and the experience is indirect and mediated. The sound, touch, feel, smell cannot be fully replicated.
- Limited activity. The scope for active learning is reduced when a learner is engaging through a computer screen and it can be a challenge to create opportunities.
- Limited sociability. The way in which learners interact with each other is very different and it can be a challenge to bring in team-working dimensions.
- Limited self-direction. What the model can do is predefined by how it is programmed and this can reduce the scope for learners to experiment and direct their own learning.
- Complex to design. The programming and integration of all the elements to combine thinking and doing can be a massive task requiring considerable expertise.

These disadvantages need to be taken seriously as they risk undermining the essential qualities which differentiate a learning factory as a complex experiential learning environment. It is generally acknowledged that the virtual cannot totally replace the real physical experience, but hybrid models that integrate as well as combine the physical and the digital appear to be where things are heading. This is not necessarily an easy option as it involves the additional effort to have both the physical and digital and to effectively integrate them and get the best of both worlds, but it mirrors and supports where industry itself is heading.

The growing importance of this digital dimension has significant implications for how a more strategic deployment of learning factories is supported. It reinforces the need to look at systems, networks and value chains, and not just at individual facilities in specific physical locations. The effort and expertise needed to develop digital learning resources and scenarios, complex simulations and digital twins makes little sense if it just for the benefit of one physical facility and those who can access it. To get the full benefit of digital resources they need to be shared and networked in some way. Capital investment in individual institutions alone is not necessarily going to achieve the degree of networking and connectivity needed.

Examples of this approach already exist and could be built on. The Blended Learning Consortium in the FE sector has an arrangement whereby members pay a subscription and then vote on what learning resources should be developed for shared use, though this tends not to work for more specialist areas. The Gene and Cell Therapy Catapult (see above) is taking a strategic approach to put in place a skills value chain that integrates physical and virtual resources across a geographically distributed network. The Connected Curriculum (see above) is a shared set of resources using Siemens software and Festo Didactic hardware that can be tailored for the needs of partner HE institutions. The Engage Platform developed for Made Smarter gathers together digital engineering skills content from leading edge organisations. International examples showing what could be done include how resources could be shared across the Baden-Wurttemberg network of Smart Factories in Germany and the McKinsey global network of Digital Capability Centres.

A further question is that of systems interoperability. This is a complex technical subject and it is not immediately clear what needs to be done if anything. However, there is a case for undertaking a review to establish if there is a need for example to encourage greater compatibility and open standards.

Finally, it should be noted that the UK has considerable strengths in learning technologies and more broadly in immersive technologies such virtual and augmented reality. There is a large eco-system of predominantly smaller, innovative learning technology companies, and manufacturing is estimated to make up 12-15% of the UK e-learning market. (42) A 2018 report from Innovate UK on *The Immersive Economy in the UK* (43) estimated that there were then around 1,000 immersive specialist companies in the UK employing around 4,500 people and generating £660 million in sales, potentially representing as much as 9% of the global market share. There has already been a major uptake of immersive technologies in manufacturing over the past 3-5 years, with 19% of companies now making use for training and a report from the HVM Catapult identifying 'huge opportunities for the use of the technology in upskilling the existing workforce'. (44)

Conclusion and recommendations

This section has focused primarily on practical considerations which, in conjunction with the five case studies appended at the end of the report, are intended to help those working on learning factory developments in individual institutions. At the same time, it has raised broader issues which go beyond what can be tackled at individual institutional level but need to be addressed to make the most of the opportunity for learning factories in the UK.

One further point that became clear in the course of this study was that those who are working on learning factory developments in the UK, or are considering whether they should be doing so, would benefit from more opportunities to network with each other and exchange ideas, and to learn from what is happening internationally. One outcome of this report, it is hoped, will be to encourage more of that to happen.

Five additional recommendations derived from the analysis in this section are as follows.

Recommendation 6. Trainer expertise. More attention should be given to building the specialist staff expertise needed to operate learning factory facilities and maximise return on capital investment made. In particular, more support is likely to be needed to build a networked cadre of expert trainers who can combine (a) up to date knowledge and experience of how technology is being used in industry; (b) coaching and facilitation skills to make the most of specialist learning factory equipment and scenarios for experiential learning; (c) innovation and applied research skills with an understanding of emerging technology trends. Catapults, the IoT programme, the Education and Training Foundation, World Skills and the Professional Bodies could all potentially have a role to play in this, but clear shape and form will need to be given. Creating this cadre of expertise is also essential if learning factories are to play a broader role in the professional and specialist development of the teaching and training workforce, for example to support the national roll-out of T levels.

Recommendation 7. Shared learning and assessment resources. A co-ordinated approach should be taken to developing and sharing learning resources across learning factory networks. Where sufficient commonality of need exists, for example in respect of digitalisation or energy efficiency, it makes sense to pool efforts and share these specialised learning resources across a wider network. Existing shared approaches need to be learnt from and applied particularly across the IoT network and for technician level training. Further work also needs to be initiated with Professional Bodies and Awarding Organisations on the use of such shared learning resources for assessment purposes and how this can recognised for modular accreditation.

Recommendation 8. Interoperability. A review should undertaken to establish what, if any, common technical standards and platform infrastructure may be required for networks of learning factories to be able to exchange data and learning resources effectively. This could influence, for example, future guidance on procurement of learning factory equipment and software where public financial support is sought. The High Value Manufacturing Catapult and Jisc (the digital services body that serves the HE, FE and Skills sector) could both contribute their technical expertise to such a review.

Recommendation 9. Virtual learning factories, digital simulations, and twins. A concerted effort should be made to use digital technologies to extend the reach of what can be done through physical learning factory facilities. The convergence of learning and industrial technologies as both take on digitalisation creates a huge opportunity for skilling and upskilling at scale. Digital approaches also mitigate the risk that costly physical facilities quickly become out of date as the pace of technological change accelerates. The capabilities that exist in the UK and their potential impact has been illustrated during the COVID-19 crisis. Consideration should now be given to where else a virtual learning factories/complex simulated workplace environments could be used to meet large scale skilling and reskilling challenges, such as for example the need identified by the Energy Systems Catapult to skill/reskill a one-million strong workforce to transform the energy efficiency of the existing UK property stock.

Recommendation 10. Exchange of knowledge and good practice. Those developing and operating learning factory type facilities in the UK should be more effectively networked to exchange knowledge and good practice, more UK-based research should be undertaken and there should be more international engagement. Developments to date in the UK have tended to be isolated and ad hoc, and there has been almost no engagement with international communities of practice and the associated research and academic literature. The IoT programme and the Catapults both provide foundations that could be built on to facilitate this networking, and international associations and conferences would welcome more engagement from the UK.

IMPACT OF THE COVID-19 PANDEMIC

This study was undertaken between April and October 2020, during a period when the UK and many other parts of the world were under lockdown fighting the COVID-19 pandemic and trying to chart a safe course towards a 'new normal' with measures such as social distancing. These unprecedented circumstances have had a profound impact on the economic, industrial, educational and social context in which the need and opportunities for developing learning factories in the UK must be considered. That impact will take years to fully understand, but there is an immediate imperative for government, industry and education to respond, to mitigate where possible the negative effects and to seize opportunities thrown up by the dislocation to accelerate positive change and innovation. So where could learning factories fit? How can they help address new needs and opportunities?

Seven new factors have been identified.

1. **Acceleration of Industry 4.0.** Most commentators and industry insiders believe the impact of the COVID crisis will be to accelerate the digitalisation of manufacturing. The widespread suspension of production and the need to adopt social distancing protocols as it resumes have been powerful drivers to review existing processes and look to adopt new technologies (45).
2. **Shortening of manufacturing supply chains.** The pandemic has highlighted the risk of dependency on extended supply chains and many companies are looking for opportunities to 'onshore' production. This sits alongside the adoption of digital technologies which are needed to make UK-based production globally competitive.
3. **Availability of technical expertise.** Large numbers of redundancies are being experienced in some areas of advanced manufacturing, particularly aerospace. Learning factories need access to personnel with up to date technical expertise. The current circumstances may make it possible to hire staff who would not normally be available or to enter into arrangements with employers who can only deploy such staff on a part-time basis.
4. **Loss of apprenticeship opportunities.** Apprenticeship programmes have been significantly disrupted with jobs being lost, restricted opportunities for both on-the-job and off-the-job training, and many training providers facing severe financial difficulties. Given the likely depth of the mounting recession, there are questions about how much provision can sustained using the current model and what is the best use of the apprenticeship levy. A network of high-quality, authentic learning factories with the capacity to deliver more widely and at scale through technology could play some role in filling this gap.
5. **Large-scale skilling needed for jobs of the future.** Many of the jobs being lost will not return, and large numbers of young people and adults will need to be skilled and reskilled in the competencies required for jobs of the future, including those associated with Industry 4.0. Formal apprenticeships are unlikely to be an appropriate and sufficiently flexible response to meet the scale of need. Learning factories could play a wider role in delivering short upskilling and reskilling courses designed around competencies for the future, and perhaps accredited through micro-credentials.

6. **Adoption of distance and blended learning.** The delivery model of colleges and training providers of necessity changed almost overnight. Models using educational technology for distance and blended learning which were previously often marginal and supplemental became for a period of time the only option. The degree of sophistication and effectiveness with which the technology was deployed may have been variable, and the reliance on it may recede as face-to-face learning and teaching cautiously resumes, but the impact has been profound in terms of showing what could be possible and providing a new stimulus for the technology supplier market. There is an opportunity to build on what has happened by developing hybrid learning factories which combine physical resources with sophisticated use of digital twins, simulations and learning technology to maximise flexibility and reach.
7. **A new willingness to collaborate, be flexible and innovate.** Many instances exist where the COVID-19 crisis has given rise to new ways of working. A notable engineering example is the Ventilator Challenge UK consortium led by the High Value Manufacturing Catapult. This involved an unprecedented ramp-up of production facilities for two existing ventilator systems, with seven entirely new manufacturing facilities being established to produce 10 years' supply of ventilators in just 10 weeks. The team came together remotely using a virtual design tool, created and simulated the production line virtually before anyone went on the shop floor, and trained up some 3000 individuals in advance to carry out the assembly and testing using hundreds of Hololens 2 devices. The lessons learnt from such examples could be applied to other challenges faced by UK manufacturing, including upskilling to support digital transformation and zero carbon.

Each of the above tends to reinforce and make more urgent the case for promoting a learning factory approach, particularly if that is considered more broadly to include sophisticated simulations of workplace environments for learning purposes. As with the Ventilator Challenge UK consortium it is not a question of starting from scratch, but of better aligning existing resources and investments, and being prepared to flex existing rules and procedures to achieve a common purpose.

CASE STUDIES

CASE STUDY 1: ADVANCED MANUFACTURING RESEARCH CENTRE, FACTORY 2050

In 2001, the University of Sheffield established the Advanced Manufacturing Research Centre (AMRC) with Boeing. The ambition was to develop a translational research centre which built on the indigenous capabilities of the local manufacturing economy, namely metals and metal cutting, Sheffield being world renowned for its steel. Since then the AMRC has grown significantly from eight people to more than 600, and in 2011 it became part of the High Value Manufacturing (HVM) Catapult. Factory 2050 opened in 2015 and marked a new era and direction for parts of the AMRC, recognising that times and technologies were changing.

Its origins go back to 2013, when the Government called for evidence for the *'Future of Manufacturing Project'* and one of the AMRC's founders, Professor Keith Ridgway co-authored a study called *'The factory of the future'* – a study which looked at the trends which would shape and influence the future of manufacturing in the UK. In this study, the authors concluded that future manufacturing methods would be increasingly digital, and would involve technology which can be readily reconfigured. They also saw a need for new skills, making it essential to attract the right talent into the manufacturing industry. Factory 2050 exists to facilitate the transition to this new form of manufacturing.

When Factory 2050 was opened, it had two main purposes – delivery of projects around automated assembly and smart integration of digital technologies, and as a demonstration facility for these technologies. The design of the Factory 2050 building was key. The main public area is a circular edifice enclosed by glass, the aim being to show that manufacturing is no longer oily rags and spanners, but sophisticated equipment in clean environments. The building was paid for initially by a £10 million HEFCE Research Partnership Investment Fund award. Since opening in 2015, it has been funded by research income and by investment from the High Value Manufacturing Catapult and other sources.

Factory 2050's core strengths are in assembly technologies, automation, robotics, metrology, inspection, AI and informatics. To deliver against emerging needs in these areas, a new suite of equipment was commissioned. Instead of the machine tools that the AMRC was famous for, the new facility was equipped with the latest in digital manufacturing technology. This includes:

- state-of-the-art robots – capable of machining metals, composites or plastics, or of working alongside humans (co-bots);
- autonomous guided vehicles (AGVs) that can react to signals sent across the network and transport parts around the factory, navigating their own way round the facility using sensors and AI;
- vision systems which can spot part-defects that humans would have overlooked;
- systems that workers can talk to and understand and respond to.

This technology is used both for live projects and as accessible demonstrators.

The principal use of Factory 2050 is as a testbed, or a sandpit, where UK-based manufacturers can work alongside a young research-focused workforce who bring a variety of non-traditional manufacturing skills (software engineers, game designers and control and systems engineers) to develop innovative solutions based on digital technologies. Much of this activity is based on horizontal innovation which involves transitioning standard practices from one industrial sector to another where it is novel, for example from aerospace into construction. However, there is also a large amount of experimentation through the introduction of new technology to solve traditional challenges.

The secondary purpose is around education through demonstration. Visitors witness the latest Industry 4.0 technologies at Factory 2050 and for example are able to test the latest in virtual reality devices and see how VR can be used in their business, or experiment with augmented reality and see the value that this technology could provide. These demonstration activities are presented to a whole spectrum of interested parties: school children on STEM visits; graduates taking sandwich year or summer internships; shop floor operators working alongside the research engineers; middle and senior management who visit to understand what industrial digitalisation looks, feels and smells like, and the impact that this technology could have on their business. Factory 2050 also has a significant role in the education of policy makers and funding bodies.

Factory 2050's capabilities enable it to play a wider role. It can take a lead in the region as the convener of conversations and education between the layers of the digital ecosystem. Working alongside the Institutes of Technology advice and guidance can be offered on the future needs of industry in the digital manufacturing space so that their technology investment is the most appropriate for the future workforce. Working as the HVM Catapult with the other Catapults, it can ensure that investment is made in the cutting-edge technologies and skills that industry will need looking forwards. Working with government and programmes such as Made Smarter it can inform policy to fund those future skills and investment.

Looking ahead, the role of Factory 2050 will be to continue as a testbed, a sandpit and an open-access demonstrator:

- a test-bed for new products, algorithms, and ways of working to be tested in a semi-industrial environment in which people are free to fail (digitally of course);
- a sandpit for large OEMs to come and see how these novel products will interface with their systems (which will have been replicated in Factory 2050);
- a demonstrator to enthuse the imagination of the next generation of engineers, the work-force of UK manufacturing and the managers of UK industry.

Key learning points:

- Industrial pull, not academic push. Factory 2050's development has been based on understanding the needs of industry and developing a delivery model to deliver what they want, not what someone thinks they want.
- University pipeline. The fact that the AMRC and Factory 2050 are part of the University of Sheffield creates a very strong pipeline going both ways – the opportunity to take lower TRL (technology readiness level) research from the University research base and to use the learning factory facilities to expose it to industry, and also to articulate the needs of industry to the academic base.

- Multi-disciplinary staff. The move towards digitalisation has broken down the barriers of traditional careers. The AMRC employees at Factory 2050 have a diverse range of backgrounds as far as education goes, from software engineers, to control system engineers to game designers. The relative youth of the engineers in the digital space means that barriers of communication are broken down when engaging in STEM activities.
- Apprentices as innovation ambassadors. Bringing in apprentices to experience working with the latest equipment and technologies means that when they go back to their course, they can enthuse and inspire their cohort. This can be particularly important for knowledge transfer to smaller companies.

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CASE STUDY 2: DIGITAL SKILLS FACTORY AT WMG, UNIVERSITY OF WARWICK

The Warwick Manufacturing Group (WMG) is both a department of the University of Warwick and one of the seven High Value Manufacturing Catapult (HVMC) Centres in the UK. It seeks to bring together industrial research, direct industrial engagement and teaching/training activities. Its teaching and skill training programmes are derived directly from its R&D activity conducted in tight partnership with key industrial partners who are developing core digital manufacturing strategies.

WMG has developed a range of learning factory facilities to meet its needs and those of its industrial partners. These include three full-scale industrial production lines, a transportable set of kit with industrial grade equipment, and a purpose-built, self-contained and transportable teaching platform. Various funding streams have been used from industry, HVMC, other government R&D sources and WMG's own teaching funds An interesting feature is that some of these facilities were originally commissioned with industrial partners using innovation funding for R&D projects, and have then been partially repurposed to enable extended uses for teaching and training.

The teaching and training activities cover broad concepts associated with digital and smart manufacturing systems such as modelling, simulation and digital twins engineering, cyber-physical systems development, integration and lifecycle management, as well as data and information management and knowledge representation. The practical, hands-on training uses the physical systems available across the range of learning factory facilities, matched to the appropriate level of training. Three main types of learning programme are supported: undergraduate and MSc courses; generic one or two week commercial courses offered to industry on automation and Industry 4.0, typically used by the larger companies like Jaguar Land Rover, Royal Mail and Dyson; and company specific, customised training programmes. Currently there is limited SME take up of these programmes and no apprenticeship training is offered, though WMG is keen to increase its reach and accessibility particularly for SMEs, some of which already offer industrial engagements for students.

The individual learning factory facilities are as follows:

- The Integrated Manufacturing Logistics (IML) Line. This was the first full-scale production system installed in 2013, based originally on part of a Ford production line for conventional combustion engines. It has since evolved with the needs of the industry to accelerate electrification and has been remodelled as a battery module and pack assembly line. A key feature is adaptable logistics to demonstrate how Industry 4.0 methods can be applied to legacy equipment as well as new production systems within a series of advanced manufacturing scenarios.
- The AMPLIiFII Line. The AMPLiFII pilot line is part of the Energy Innovation Centre and supports the manufacture of pre-production prototype battery modules and packs, based on cylindrical cell formats. It operates at industry 4.0 standards with key objectives of ensuring in-line quality verification, a no-faults-forward policy and a fully flexible, integrated approach. AMPLiFII (Automated Module to pack Pilot Line for Industrial Innovation) started as a two-year Innovate UK funded project to create sustainable supply and manufacture of battery packs for hybrid and electric vehicles in the UK, based on a flexible, modular battery design. On completion of the original project in 2017, it became an open access facility for R&D and skills development with industry, and is now used a third of the time for skills training. The main differences from the IML line are that it is more clearly focused on future production systems and that it is set up as a real production line, producing and assembling real battery modules. As such it is very specific and highly authentic but less flexible and more limited in how it can be reconfigured.
- The MagneMotion Line. This originated as a Catapult project with the Lear Corporation, a major manufacturer of car seats with 125 factories worldwide. The aim was to redesign their production lines using intelligent conveyor systems based on independent cart technology using magnetically-controlled frictionless propulsion rather than relying on mechanical gears, chains and belts. Once the design and development phase was completed in 2019, the line was repurposed to support the training of staff operating Lear factories across the globe, enabling them to be trained in advance of the new conveyor lines being adopted at their locations. The plan now is for the line to be used more generically in future to train industry professionals from other companies on the integration and use of flexible manufacturing technologies, and on the development of advanced motion control, product/pallet tracking and scheduling.
- Training FlightCase 4.0. The project with Lear has also led to the creation of a transportable set of industrial grade equipment that can be dispatched to any site. It was recognised that for some of the training it was cheaper and more efficient for the trainers to fly out to the learners with a demonstration kit rather than bringing all the learners to the full-scale production line at WMG. The Flightcase contains a range of equipment deployed in industry: industrial PCs and PLCs (programmable logic controllers), collaborative robots, industrial RFID (radio frequency identification) systems and sensor arrays, linear drives, etc. There are also options in terms of how much is done physically and how much virtually, so for example the physical PLC can be used to control virtual machinery or it could all be virtual. WMG see the Flightcase as having many potential uses beyond the Lear project, for example being taken out for demonstrations at SME premises to show how the technologies could be used on their production lines.

- Teaching SuitCase 4.0. The Teaching Suitcase is a purpose-built, self-contained and transportable teaching platform used largely with undergraduates and MScs. It includes mainstream and low-cost equipment such as tablet-based human machine interfaces, single-board computers, ambient sensors, and simple actuators.

The facilities and equipment at WMG are set up in particular ways to teach and train students and professionals on the use, deployment and integration of digital technologies to support real-world manufacturing scenarios. The focus is placed on integrating digital systems and engineering data pipelines and workflows that allow future engineers to develop data-driven production monitoring and real-time KPI (key performance indicator) visualisation, predictive maintenance capabilities and effective product track and trace capabilities. The training content is structured around key phases of the production system lifecycle, from its engineering phases, during which engineering data is produced, to its commissioning and operational phases during which operational data is produced. The combination of industry grade physical equipment and rich digital environment provided by the learning factory facilities allows the trainee to experience the constraints of the real-world of manufacturing, and at the same time learn through experiment in a risk-free environment.

Key learning points:

- Multiple use of R&D facilities. Learning factory facilities initially designed and funded primarily for R&D projects can be opened up and given extended use for teaching and training.
- Legacy, current and future production equipment. Putting past, present and future technologies alongside each other can enable a wider and more realistic range of learning.
- Transportable facilities. Kits of equipment assembled to create mobile learning factories can enable flexible and accessible delivery, giving a range of options beyond permanently sited full-scale facilities.
- Integration of digital technologies. Industry 4.0 principles can be embedded in teaching and training through the integration of data systems with physical equipment and structuring content around the key phases of production and the data flows generated.

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CASE STUDY 3: GREATER BIRMINGHAM AND SOLIHULL INSTITUTE OF TECHNOLOGY

The Greater Birmingham and Solihull Institute of Technology (GBS IoT) is developing a regional 'hub and spoke' model focused on creating skills pathways into technical careers in local advanced manufacturing and engineering industries, particularly for under-represented and disadvantaged groups. At the core of the IoT 'hub' will be the installation of a state-of-the-art, 'Cyber-Physical Factory', which in turn will be networked with and support accessible skills delivery at each of the 'spokes'.

The IoT is based on a region-wide partnership including seven of the local further and higher education institutions, led by Solihull College and University Centre (SCUC), as well as employer and stakeholder advisers drawn from five major local businesses, the local LEP, the two local councils, the chamber of commerce and Aim Higher West Midlands. The partnership of local education and skills providers was already working together on a well-established basis prior to the IoT proposal, having been in existence since 2016.

The 'hub and spoke' model, and the networked deployment of learning factory equipment within it, came from a shared perception across the partnership that they could work together more effectively to offer employers and learners what they needed and wanted. This included: clearer progression routes and a more coherent offer across the region; better utilisation of existing equipment and keeping up to date with latest technologies; and shared access to specialist staffing and technician expertise rather than competing for it. Using the 'hub and spoke' model, the aim is to develop and deliver new education provision with a focus on flexible full and part-time level 4 and 5, including apprenticeship standards, enabling learners to progress to higher level opportunities such as higher education and degree apprenticeships: generating 1,000 plus IoT learners by 2023-4.

The 'hub' will be a prestigious new build of 440m^2 located within the grounds of Aston University and due to open in September 2021. The new building will house the IoT's 'Cyber-Physical Factory', consisting of a newly-purchased manufacturing rig and supporting software which will create a simulated working environment linked to advancing Industry 4.0 technology.

The specific themes for delivery, aligned to employer requirements, will include:

- Fundamentals of control technology
- Smart Factory techniques
- Mechatronics
- Material flow
- System networking including IT infrastructure
- Information flow in complex systems
- Process planning
- Planning assembly and dismantling
- Data processing systems.

The Cyber-Physical Factory is a substantial investment and, by installing it in the hub, the aim is to be able to maximise utilisation and ensure technician/instructor expertise is sourced for all partners. The multiple uses envisaged include:

- partners working together under the leadership of Aston University, using its expertise in applied research and pedagogy, to develop curricula and teaching resources which will be used in the teaching of all IoT provision
- CPD established to upskill those teachers and trainers who need to update their understanding of industry technologies and techniques
- high-level research activity, exploiting the connections of the partners and interconnectivity with existing assets
- demonstration and trialling of new technologies for SMEs
- demonstrations for schools, parents, teachers, careers advisers to motivate and inspire.

Another planned feature of the set-up for the hub is that the new cyber-physical rig will be linked to a suite of advanced traditional and non-traditional manufacturing assets housed at the adjacent Aston University and Birmingham City University Campuses. This will enable further exploitation of the cyber-physical rig going beyond more abstract training scenarios and reflecting a wider range of authentic situations and industrial practices. Often the reality is that new technologies have to be introduced in a more piecemeal fashion on a brownfield site and part of the challenge is to incorporate existing equipment while implementing Industry 4.0 principles.

The three college spoke campuses (BMet College, Solihull College, South & City College) are located across the region and provide local provision to ensure geographically accessible HE vocational education is available for engineering companies and their employees. Each college campus is located in an area of the region with high levels of unemployment and low HE participation; by basing the IoT spokes within these communities, local residents are more likely to participate in vocational education and training. The college spokes will link virtually to the hub through common software and remote demonstrations. In addition, college students will have regular workshops in the central hub.

The two supporting university partner spokes (University of Birmingham and University College Birmingham) will link into the applied research elements of the project, support with monitoring quality of provision and development of clear progression routes.

Key learning points:

- Provider collaboration. An established partnership including all the local FE and HE institutions has been an important foundation for planning learning factory facilities on a 'hub and spoke' model as part of a coherent regional skills offer
- 'Hub and spoke'. The hub and spoke model enables the investment in core learning factory facilities and expert staff to be better utilised, with development of curricula and learning resources and delivery of CPD co-ordinated across the network.
- Existing equipment. The authenticity of the simulated working environment being created is being enhanced by linking the new installations with existing more traditional equipment, reflecting the challenges often encountered in industry.

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CASE STUDY 4: INSTITUTE FOR ADVANCED MANUFACTURING AND ENGINEERING, COVENTRY UNIVERSITY

The Institute for Advanced Manufacturing and Engineering (AME) is one of four industry focused research centres that make up the Institute for Future Transport and Cities at Coventry University. It specialises in manufacturing research in areas such as Industry 4.0, Digital Manufacturing and Simulation, Automation and Control, Metrology and Uncertainty of Measurement, Surface Engineering, Wearables, Lasers, Welding and Joining. The centre was originally created in partnership with Unipart Manufacturing Group, a major tier 1 supplier of automotive components.

The AME is located at Unipart Manufacturing's main factory site in Coventry and describes itself as the 'UK's First Faculty on the Factory Floor'. It has developed a distinct model on that basis which brings together academia, industry and R&D directly on the factory floor, both to deliver industry-ready graduates through their manufacturing engineering degree courses that are enhanced by activity-led learning based on the real projects in the factory, and to develop new products, processes and technologies.

The AME was built and equipped by the two principal partners with additional financial support from the Higher Education Funding Council and opened in 2014 offering 2000 sq ft of purpose-built manufacturing and teaching space. The majority of this consists of AME's manufacturing hub, equipped with state-of-the-art robotic automation, forming, joining, analysis and simulation, metrology and product verification technology.

The impetus for creating the AME came from seeking a new and different approach to address three issues: the skills gap in engineering; a lack of industry-ready graduate engineers; and the need to improve return on investment on research and development. The vision was to "create a centre of engineering excellence for innovative teaching and research, in a real world manufacturing environment, that delivers engineers, manufacturing leaders and technologies to enable business growth in the UK high-value manufacturing". This was underpinned by strategic objectives to deliver in three areas: skills and training; research; and business growth.

The faculty is now in its sixth year and has about 130 undergraduates, 20 masters, and 30 PhD students. The delivery of the curriculum for the undergraduate degree course, which is set by an industry advisory board, is designed to bring together academic learning with activity-based learning that is integrated into operations. Each semester the students spend half their time on theory, a quarter of their time on the AME simulated shop floor and a quarter of their time in a real factory, undertaking a problem-solving project supervised by an industrial tutor.

Key research and innovation themes have been identified from analysis of industrial challenges and enabling technologies, and these contribute to teaching, research and business growth targets. Individual research projects are run with Unipart and other industrial partners using the AME facilities with some of these securing funding from bodies like Innovate UK, EPSRC and Advanced Propulsion Centre.

An example that draws on a range of AME capabilities, and illustrates the role a learning factory facility can play in linking together a new skills value chain, is the H1PERBAT project which was established to build a high-performance, low-volume, flexible battery capability in the UK. This started as a consortium of organisations including Unipart, Coventry University and Aston Martin, led by

Williams Advanced Engineering with funding from the Advanced Propulsion Centre. In 2018 it progressed to the formation of a joint venture company (Hyperbat) between Williams and Unipart, with a new factory being built on the Coventry site close to the AME. The AME's role going forward will be to develop the skills and capabilities required for the future, both for Hyperbat and for the broader electric vehicle supply chain.

A specific research and innovation theme is 'People-Centred Productivity' which focuses on taking a multi-disciplinary perspective to address challenges faced by manufacturing and engineering businesses (including digital, technical and soft skills, behavioural and trust factors, innovation and implementation of new technology in the working environment, and businesses models). The AME utilises its existing industrial relationships and the learning emanating from industrial projects undertaken at its factory facilities to identify skills gaps in hidden areas that would not be obvious from the initial presentation of an operational manufacturing issue. As an example of this approach contributing to the foresighting stage of a skills value chain, manufacturing digital systems, manufacturing cyber-security, business management and intellectual property management skills were identified as being lacking across AME partners. These areas have since been built into the engineering curriculum, CPD courses and the research roadmap.

A significant expansion of the AME is now underway with financial support from the local LEP in order to engage and support the wider UK Manufacturing Value Chain. This involves creating a digital manufacturing demonstrator which will consist of a series of physical stations with fully configured digital systems to represent real, individual manufacturing businesses of varying complexity at each point in the value chain – end customer, original equipment manufacturer (OEM), tier 1, tier 2. This will enable Industry 4.0 principles to be demonstrated in terms of vertical integration, horizontal integration and end-to-end engineering. The OEM cell is being kitted out with Festo Didactic learning factory equipment using Siemens systems, and content from the Siemens Connected Curriculum (see page 7) will be drawn on and reconfigured into customised learning modules. These developments, which will double the size of the AME, will enable it to open up to a wider range of companies throughout the supply chain, offer training at all levels, and host visits and demonstrations for the public.

Key learning points:

- Authentic manufacturing environment. The focus throughout has been on creating a live engineering and manufacturing environment where research and learning can be integrated into operations, enabling theory and practice to be brought together.
- Industry/Academic partnership. The AME's development has been underpinned by the core partnership between the Unipart Manufacturing Group and Coventry University.
- Skills value chain. The Hyperbat project and People Centred Productivity theme both illustrate how a learning factory that addresses skills and innovation alongside each other can support a skills value chain approach.
- Supply chain integration. Extension to all steps in the high-value manufacturing chain enables the end-to-end integration principles of Industry 4.0 to be demonstrated as well as opening up the facility to a wider range of potential users.

- Shared learning resources. Customising learning resources from the Connected Curriculum for the new digital manufacturing demonstrator shows how new facilities do not need to create all their own new content.

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CASE STUDY 5: NATIONAL CENTRE FOR FOOD MANUFACTURING

The National Centre for Food Manufacturing (NCFM) at the University of Lincoln is an interesting example of a purpose-built, learning factory type facility that has evolved over a period of some 15 years in response to serving the needs of the food industry. It now forms part of the Lincolnshire Institute of Technology (IoT).

The Centre is a satellite campus of the University, situated at Holbeach in South Lincolnshire. The surrounding area is the UK's biggest food industry cluster, accounting for 42% of local employment compared with 4% nationally. The NCFM serves this local cluster as well as now being a national centre for skills development and applied research for the whole UK industry.

The origins of the Holbeach facility were as a day release centre for apprentices. In the 1990s it was mothballed for a decade on account of there being a hiatus in education and training for the industry and institutional change. In 2002 the centre was passed to the newly opened University of Lincoln, a civic university created by local investment to unlock the economic potential of the county. It was then recognised that there was a huge gap in meeting industry need. Investment by the University and regional partners in 2004 provided specialist labs and a small-scale food processing facility for teaching. These could be considered an early prototype of a learning factory.

The initial focus was on delivering good quality, relatively low-level FE provision to meet the immediate needs of employers. Over time there was a shift to addressing emerging higher-level skills needs. This was made possible by the University developing a programme of 'train-the-trainer' courses which became the standard accepted by local businesses for competence in work-based training, enabling hundreds of work-based trainers to effectively deliver the routine training that their businesses required. This in turn allowed the University and employers to step up support for higher-level technical courses in food science, technology and manufacturing practice.

The 2004 prototype learning factory development whilst small in scale was equipped in partnership with employers and highlighted the potential for the facility to act as catalyst for employer engagement. The first large-scale learning factory development came in 2008, initiated by a group of employers who had seen the purpose-built Nissan automotive training factory in the North East. The University secured EU funding for the building whilst the employers helped design the purpose-built food factory and invested in equipment using their network of some 20 different technology and equipment suppliers to ensure that the building was equipped with state of art technologies and full-scale plant and equipment. Although primarily developed as a skills training centre, the increasing academic and research expertise of the University enabled its growing usage for research and innovation purposes with the partnerships with technology suppliers and employers evolving to support both skills development and innovation in parallel.

The NCFM has subsequently continued to evolve and grow, with its research partnerships driving continued investment in the latest full-scale manufacturing equipment which is also used for teaching. It is now recognised as a national centre of expertise for the food industry, employing more than 50 staff, with income split roughly evenly between skills and innovation sources.

The skills provision ranges between levels 2 and 7, with most at levels 3 to 5 and all of it is part-time. The majority is made up of levy-funded apprenticeships, including higher and degree level apprenticeships, with the balance made up of shorter courses funded directly by employers. Larger companies like Bakkavor act as anchor employers, providing the scale and continuity needed for a sustainable business model, while smaller companies can also benefit from the facilities. As a national provider of apprenticeships, the NCFM uses a blended model. This combines distance learning for the trainees, wherever they may be located, with 2 to 3 weeks attendance each year at the Centre where they get to experience the advanced technology at its food factory and laboratory facilities.

As part of the University of Lincoln, the NCFM has been able to develop into a research centre and attract innovation funding from UK and European sources such as Innovate UK and Horizon 2020. This means that all teaching staff are engaged in innovation projects with industry and have the opportunity to work alongside researchers with deep academic knowledge.

The NCFM is now one of the key hubs within the newly formed Lincolnshire IoT which extends across the whole county and specialises in agri-tech and food manufacturing, energy and engineering, with a unifying digital theme. It is envisaged that the learning factory type approach pioneered at NCFM will be applied more extensively across what is a widely distributed geographical network of centres, enabling each major town to have its own centre of expertise, while being able to share resources for remote learning digitally.

Key learning points:

- Industry culture and partnerships. The bedrock of how the NCFM has been able to develop and sustain its learning factory facilities has been its culture and responsiveness to industry and the long-standing relationships this has enabled it to build with larger companies that are its anchor partners.
- University clout. The University's scale and expertise has been the other key ingredient for the evolution from a relatively low-level local FE provider to a national industry centre combining research and innovation with progression to higher-level technical skills.
- Multiple funding streams. The industry/university partnership has made it possible to access and combine multiple funding streams for skills and innovation.
- Hybrid teaching staff. All teaching staff are expected to have relevant industry experience and to be engaged in innovation projects. They could be considered 'tri professionals' – teaching, industry, innovation. This ensures the expertise is there to make good use of the learning factory facilities. Being able to attract the relevant expertise and ensure this flexibility is made possible by multiple funding streams.

- Apprentices as innovation ambassadors. Bringing in apprentices to experience working with the latest equipment and technologies means that when they go back to their companies they can act as innovation ambassadors. This can be particularly important for knowledge transfer to smaller companies.
- Hub and spoke blended delivery model. Although embedded in a local industry cluster, the NCFM gets best value from its specialist learning factory facility by making it accessible to apprentices from across the country as part of a blended delivery model.

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