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Innovation and Technology Policy and the Development of a High-Skilled Workforce: Lessons from Automation, Robotics and Digital Technologies in Advanced Manufacturing

Background

National Governments have identified "digital technologies" as being a societal and economy-wide phenomenon which impacts most occupations in some way[1]. Strategies and plans have been developed both to equip and raise awareness across the whole population and within key sectors seen as being most receptive (and vulnerable) to digitisation and related technologies[2]. At the same time, the convergence of technologies is also creating an opportunity to address long standing challenges of competitiveness, productivity[3], and the adverse demographic changes leading to a shortage of workers[4]. Recent attempts have been made to rate and rank individual countries based on their readiness to handle and benefit from automation and digital technologies with the top four being: Germany, Japan, Singapore and South Korea[5].

Due to the complexity, range and depth of the changes across businesses and occupations, Governments have tackled the challenge with a range of national, sector and local approaches[6]. The national level actions have focused on awareness raising[7], the development of joint agendas for action (for technology, for innovation, for workforce development)[8], and having a supportive infrastructure for occupational change and development i.e. active labour market policies[9]. While the sector and local approaches often overlap as institutes have been established to drive both the development and application of digital technologies alongside the delivery of workforce development plans[10].

What makes the so called, Industry 4.0 or the 4th industrial revolution, different from previous ones is the speed and widespread impact (changing operations, business models, and relationships across a whole supply chain), and while there are common directions of development, the actual details in practice can vary significantly by business (based on their legacy, their priorities, their networks and resources)[11]. This note looks at the application of automation and digital technologies within the advanced manufacturing sector and how workforce development is being tackled.

A Definition of Advanced Manufacturing and Digital Technologies

Advanced manufacturing is seen as being based on six key enabling technologies (KETs): advanced manufacturing technologies, industrial biotechnology, nanotechnology, advanced materials, micro/nanoelectronics, and photonics (see Table 1 below). It is on these six technologies that a range of KETs-based products are being further developed e.g. robotics, lightweight materials, batteries, etc.[12] While workforce development plans are focused on those competences needed to move a concept through to full development and demonstration and on into a competitive manufacturing operations[13]. It is these competencies which help bridge the progression and alignment along the technology and manufacturing readiness levels shown in Figure 1.

Figure 1: Technology Readiness Levels (TRL) and Manufacturing Readiness Levels (MRL)

TRL 1:	Basic principles observed and reported	**MRL 1:**	Manufacturing feasibility assessed
TRL 2:	Technology concept and/or application formulated	**MRL 2:**	Manufacturing concepts defined
TRL 3:	Analytical and experimental critical function and/or characteristic proof of concept	**MRL 3:**	Manufacturing concepts developed

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TRL 4:	Component and/or breadboard validation in a laboratory environment	**MRL 4:**	Capability to produce the technology in a laboratory environment
TRL 5:	Component or breadboard validation in a relevant environment	**MRL 5**	Capability to produce prototype components in a production relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment	**MRL 6:**	Capability to produce prototype system or subsystem in a production relevant environment
TRL 7:	System prototype demonstration in an operational environment	**MRL 7:**	Capability to produce systems, subsystems, or components in a production-relevant environment
TRL 8:	Actual system completed and qualified through test and demonstration	**MRL 8:**	Pilot line capability demonstrated; ready to begin low rate initial production
TRL 9:	Actual system proven through successful mission operations	**MRL 9:**	Low rate production demonstrated; capability in place to begin full rate production

Source: Executive Office of the President, National Science and Technology Council, Advanced Manufacturing National Program Office, *National Network for Manufacturing Innovation: A Preliminary Design*. Washington DC. January 2013. GAO-19-409

The workforce development focus is on those competences and people employed from TRL4/MRL 4 through to TRL9/MRL9. The learning factories, which are described later in this note, focus on TRL4/MRL4 through to TRL7/MRL7.

Employment and Workforce Predictions

Information and analysis of the future of work at the national and sector levels has provided clear guidance as to the potential shape and nature of occupations[14]. From these studies a few clear messages emerge:

- the rise in the prominence of a range of existing and new competences[15]
- the shape of occupations i.e. T-shaped meaning there needs to be breadth in understanding the context and fit alongside having depth in particular technologies and disciplines[16]
- the overall ability to work across disciplines and technologies[17].

At the corporate level, it has also been recognised that having a significant "skills buffer" (i.e. usually highly skilled and adaptable employees able to problem solve at speed) allows a business to absorb, modify, integrate and optimise automation and digital technologies[18]. Occupational and skills developments have been derived from using technology road mapping[19] and the use of tracking methods (often using digital technology)[20] and data collated by pan-national observatories and research bodies[21].

Table 1: Employment by Key Enabling Technologies, Europe 2015[22]

Key Enabling Technology	Employment
Advanced Manufacturing Technology	1,634,000
Micro- and Nanoelectronics	1,394,000
Advanced Materials	976,000
Photonics	760,000
Nanotechnology	258,000
Industrial Biotechnology	236,000
UK – Advanced Manufacturing Technology	1,300,000

Source: Key Enabling Technologies (KETs) Observatory Second Report. December 2015; UKCES (2015) LFS (2014)

Note: The absolute number of the single KET's shown cannot be added up as significant double counting would occur. This is due to the fact that some KETs-based products are linked to several KETs, due to their multi-KET dimension. It is estimated that the absolute employment enabled by all six KETs represents 3.3 million employees.

National Strategies and Plans

Most national strategies seek to combine support for innovation (commercialisation and application of a technology) with the development of workforce across a whole sector and its supply chain. To deliver this strategy, facilities and structures have been put in place to act as a bridge between the emergence of a technology and its application in industry[23]. Over the last 10 years we have witnessed most countries adopting aspects of the well-established and high functioning Fraunhofer Institute model[24]. To this has been added a clear ownership of the workforce development agenda (Table 2, to a much greater extent than in Germany) which is further developed across a community of employers, colleges, universities and coordinating bodies.

In the USA, for example, the 14 Manufacturing Institutes[25], which focus on technologies key to the future of manufacturing, have all developed workforce development plans[26]. These plans have been local in some cases and national in others[27]. They have sought to create key skills and occupation information applicable within a sector and across whole networks e.g. mapping of emerging skills needs with developing college and university courses (usually at the curriculum content level)[28]. There has also been a heavy emphasis on facilitating individual businesses to develop appropriate workforce development plans by the widespread sharing of case studies and the promotion of effective assessment and diagnostic tools[29]. Supporting these developments have been the development of certificated courses which carry micro-credentials, are employer-recognised (and valued) and stackable to allow entry into further education and training programmes[30]. The emphasis is on developing relatively discrete skill sets quickly and often using a mix of on-the-job experience (in an institute's/learning factories' own facilities), projects, and college and university programmes[31]. Significant investment has also been made in on-line certified programmes e.g. robotics[32].

Table 2: Relationship between Manufacturing USA Statutory Purposes, Program Goals and Objectives – Workforce Development

Program statutory purpose	Manufacturing USA program goal	Strategic plan objective
To accelerate development of an advanced manufacturing workforce To create and preserve jobs	Accelerate the development of an advanced manufacturing workforce	1: Nurture future workers for STEM related work 2: Support, expand, and communicate relevant secondary and post-secondary pathways, including credentialing and certifications 3: Support the coordination of state and local education and training curricula with advanced manufacturing skill-set requirements 4: Advanced-knowledge workers: researchers and engineers 5: Identify the competences needed by the next generation of workers

Source: Manufacturing USA Program 2018. US Government Accountability Office (May 2019) GAO-19-409. *Advanced Manufacturing Report* to the Congressional Committee. Extract from Table 3, page 35.

The learning factories are often part of a sector/technology cluster which brings with it a key role in workforce development as they bring together a wider range of businesses which supports a wider supply chain[33]. By combining and connecting the learning factories with their local neighbours adds a further momentum to their workforce development role. Evidence from several countries e.g. Denmark, USA, Korea, Japan, China, Sweden, Germany, Italy shows how clusters also bring together potential customers for the core cluster[34]. The robotics cluster in Boston, Massachusetts, for example, brings together suppliers, five related clusters, research bodies, institutions for

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collaborations, customers and downstream vendors. The whole value chain is present in the cluster sharing many common workforce development needs[35].

Due to the nature of the labour market in the USA and position of vocational education and training, there have been a few additional support developments. One has been a series of occupation (rather than corporate) competency models developed for automation and advanced manufacturing, and for specific sectors e.g. aerospace and automotive[36]. Another has been the role of international standards and certification bodies which have developed a range of new qualifications, and in some case, detailed, model curriculum e.g. for automation[37]. These two developments have informed local college initiatives working alongside the Manufacturing Institutes and the Advanced Manufacturing Partnerships present in every State[38].

Many of the above elements are to be found in similar programmes in Denmark, France, Italy, Japan, Korea, Singapore and the UK. There are a few notable differences though. One is the extent to which national, society-wide digital strategies are integrated with the one for advanced manufacturing. For example, in both Denmark and Korea there is a clear, consistent and mutually supportive digital strategy. These two countries also integrate it with their national STEM education and career programmes[39]. Another is the clarity of the ownership of the workforce development agenda. Clear and explicit ownership for workforce development is present in the USA (Table 2), Korea, Singapore (with 10% of the overall Research Innovation Enterprise 2020 Plan budget devoted to manpower development) and Japan but less so, say, in the UK and Germany. Funding levels and the extent (both number and range of technologies covered) of the core technology institutes vary with Japan having 180, Germany 74, Korea 17 and the UK 10.

What is less clear is how the national strategic positioning for leadership on some key elements of digital technology feeds through to specific workforce development plans. It is evident that Germany is seeking to lead, shape and influence the standardisation agenda; the USA on big data analytics; and, Japan on robotics. These national strategic targets are not owned by the various institutes but sit with specific government departments[40].

Certainly, in the case of the USA, where international migration plays an important developmental role and has been seen some technologies e.g. nanotechnology (a key enabling technology)[41]. Evidence from Asia shows migration is an important part of the technology transfer, and so might be an issue in the UK with its planned changes to immigration rules[42].

Universities, Research Centres Networks and Learning Factories

While the learning factories (sometimes also titled, teaching factories) have a critical role in developing and integrating technologies, providing facilities for experimentation and piloting developments, they also provide a central role in workforce development. Apart from the more general workforce development role i.e. collecting labour market information, identifying core occupations which are changing (more below), etc. they also provide a knowledge development and technology transfer service through company secondments, joint projects, etc. which involves a few key staff to develop and master a set of solutions to apply in their employers: a form of niche workforce development[43]. Learning factories usually work as a part of sector focus cluster of businesses covering the whole value chain, and central to the network of similar hubs focusing on related technologies. For example, the Fraunhofer Institutes in Germany also form groups around ICT (16 core members), a series of clusters of excellence, and a further series of alliances e.g. the Additive Manufacturing Alliance[44]. These networks allow expertise to be pooled and accessed across the country and to resolve specific mixed technology challenges[45].

Overall Workforce Development Process

While technology road mapping and general foresighting do form an important part of establishing likely direction and form future work activities, work processes and broader work organisation changes[46], there has been a preference to work from existing core roles and to map how they might change in the near future (Table 3)[47]. Additional data have been drawn from online postings and surveys, sourcing the work content of current vacancies, and some more novel methods have used e.g. patents, literature searches and CVs to identify emerging and future changes[48]. Most approaches have sought to develop initial profiles for changes to existing and new occupations and to widely share these within their manufacturing sector (supply chain) communities to receive feedback[49]. In some cases, detailed competency profiles have been established and then validated by company experts e.g. one covered automation maintenance roles in manufacturing in the USA[50], and one covered automation roles in mining in Australia[51].

Table 3: Numbers of New/Changed Occupations in Manufacturing due to Automation and Digital Technologies – Core Occupations for the Future

Source	Number of Core Occupations for the Future	Description
Automation and Digital		
MxD USA (Manufacturing x Digital)	165	20 core occupations focused on with Manpower; 7 domains which link to a digital evolution (career and development) pathway
Workforce Intelligence Network with Connected and Automated Vehicles (CAV), USA: Emerging Technology Skills Gap Analysis (2020)	76	7 major groupings: design and testing (12 in all); manufacturing (10); IT design (7); quality control (5); data management and cybersecurity (13); intelligent transportation systems (11); business, legal and marketing support (18)
REMADE (Reducing Embodied Energy and Decreasing Emissions), USA	59	17 Engineer occupations and 42 Technician ones
Instrumentation, Automation, Surveillance and Communication Sector Skills Council, India	171 (job roles)	Provides occupational maps, manpower plans, national occupational standards, qualifications, certification, accreditation for trainers and assessors
US Government Accountability Office (2019) Workforce Automation (GAO-19-257)	78	Used O*NET and identified 15 occupations in which workers monitor, install, develop and trouble shoot on robots; and 63 in which workers use robots as a tool or technology in their daily work activities
General Identification of Emerging, New and Changing Occupations		
O*NET (Occupational Information Network)	159	53% of occupations are data and digital centric – initial listing of new and emerging occupations for which data were collected
US Bureau of Labor Statistics (Pikulinski, J. No date BLS)	102	BLS annual occupational employment statistics (OES) survey review process identifying new and emerging occupations which did not fit with existing classifications and their definitions
Burning Glass for DCMS UK (2019)	246	Number of UK SOC occupations for which digital skills are an essential requirement

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In Europe there are the Key Enabling Technologies (KETs) skills observatories[52] which identify and supply data on skills developments across six technologies: micro and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies. These are complemented by a series of European Sector Skill Councils (now Alliances) which operate for 5 sectors after 14 feasibility studies[53]. The one for automotive studied five traditional roles and how they are changing, and five emerging occupations[54]. Similar approaches have also been adopted in the UK for advanced manufacturing occupations[55].

The initiating and lead body for the initial workforce development plan (the innovation hub/learning factory) has the role to define and set direction, access and direct funding to ensure actions are taken once new skills needs, emerging occupation are profiled and shared competences defined[56]. Discretion as to how occupations develop is apparent at this point as the information flows and communication patterns are being set[57]. After the 'workforce plan stage' a wide range of actors and projects are set-up with clear overall guidance still coming from the innovation hub/learning factory[58].

Within companies' tools such as Digital Thread (from GE[59]), Digital Compass (McKinsey[60]), Production Technology Radar (World Economic Forum[61]), Industry 4.0 Diagnostic (McKinsey[62]) and Industry 4.0 Maturity Index (Acatech[63]) are being used to establish direction and areas for attention. This is backed-up with best practice sharing and even a full workforce development playbook in Europe[64] and the USA[65].

Using the directional outputs from technology and occupation analysis has led to the development of occupational standards through further, more detailed analyses[66].

On the education and training delivery side, there are several key elements[67]:

- Short, quick cycle, modular curriculum for operational and maintenance roles
- Clear merging of teaching, learning and innovation
- Updating curricula with enough frequency to keep up with advances in science and technology and changing occupational requirements
- Focusing on experiential learning approaches that include work-based learning
- Use of employer recognised, college delivered and certified programmes which can be used to build a range of competences using online registries
- Entry and progression pathways are developed to allow existing occupation holders to adjust and ensure their role remains relevant
- Increasing the number of technically qualified teachers able to integrate technology into the classroom and engage with in the development of the curriculum
- Trainers and educators are treated as trainees just as like employees are within a virtual skills development system
- Overall labour market information to better assess and plan for changes driven by advanced technologies

Review and Evaluation

Review mechanisms vary and are mainly driven by annual and impact reports by institutes[68], and audits undertaken at the national level of whole policies and their key elements[69]. There are also several benchmarking groups for technology clusters and the overall rating a national competence to progress with automation and digital technologies across their economy[70]. At the company level, assessment and diagnostic tools exist to establish the progress and progression of individual businesses[71].

End Notes

[1] McKinsey and Co (2020) The Future of Work in Europe. Automation, workforce transitions, and the shifting geography of employment. 52 pages. At a more detailed level see: Muro, M. et al (2017) Digitisation and the American Workforce. Brookings Institution, Washington DC. Looks at the digital content of occupations between 2002 and 2016 and finds virtually all occupations have increased their digital score. Acemoglu, D. and Restrepo, P. (2019) "Automation and new tasks: how technology displaces and reinstates labor", Journal of Economic Perspectives, 33 (2), 3-30 extends this analysis further, while J.E. Bessen (2016) How computer automation affects occupations: technology, jobs and skills. Boston University School of Law, Law and Economics Research Paper, Number 15-4 found only one occupation has been totally automated since 1950: the elevator operator. Pratt, G.A. (2015) "Is a Cambrian Explosion Coming for Robotics?", Journal of Economic Perspectives, 29 (3) combines eight technical drivers for change with a series of 'big ideas' and their implications for the workforce.

[2] BRICS Skill Development Working Group (2019) Skill Development for Industry 4.0. See Figure 6: Ranking of key industries affected by Industry 4.0 which ranks 19 industries across 5 key indicators (virtualisation, level of value added and value-chain complexity, disruption technologies (game changer), resource efficiency of core processes, and foreseeing of new framework or regulation). Using this template, the top five industries were: machinery; print; electronics, optics and data processing; electrical engineering; and automotive. The position in Germany is captured by VDMA (2015) Industrie 4.0 – From Vision to Reality and quoted in E. O'Sullivan (2016) Global Trends in the Digitalisation of Manufacturing. Definitions, Priorities and Policies. Institute for Manufacturing, Briefing Day, University of Cambridge.

[3] McKinsey and Co (2015) Industry 4.0: How to navigate digitalisation of the manufacturing sector. This report identified major gains in productivity and improvements in overall competitiveness arising across eight value drivers: resources/process; assets utilisation; labour; inventories; quality; supply/demand match; time to market; and, service/aftersales. In Europe see: Industry 4.0 Digitalisation for productivity and growth (2015). European Parliamentary Research Service. PE 568.337 and for Germany see: Boston Consulting Group (2015) Industry 4.0 The Future of Productivity and Growth in Manufacturing Industries. 20 pages.

[4] Frey, C.B. and Osborne, M. (2018) The great escape: how workforce automation is the answer to Japan's secular stagnation. Oxford Martin School, University of Oxford.

[5] Economist Intelligence Unit (2018) The Automation Readiness Index. Who is ready for the coming wave of automation? Supported by ABB. 33 pages. The UK features in the top nine countries across the three main criteria: innovation 6th; skills and education 9th; and, labour market practices 6th. In a number of countries there are digital market barometers e.g. Wirtschaft DIGITAL (Germany), IoT International Competitiveness Index (Japan) – see Digital Economy Taskforce (2018) Toolkit for Measuring the Digital Economy. Prepared for the G20 meeting in Argentina.

[6] E.g. REMADE Institute (2019) Impact report 2019. Their process moved from Technology Roadmap (2018) and then into the Workforce Profile for Clean Energy, Innovation and Sustainability. Version 1 (2018/19)

[7] E.g. on the general information side of the changes occurring and forecast, see the CEDEFOP programme of work: CEDEFOP and The Future of Work addressing two questions: how technologies change demand for jobs and skills? And, how technologies change the way we work, collaborate, connect and learn? These are addressed through the CEDEFOP skills forecast, Skills Panorama, European skills and job survey, skills demand in online job vacancies, and the skills development and matching in online platform work. In Australia we have seen a raft of reports: Beyond the Boom: Australia's productivity imperative (2012), Compete to prosper: Improving Australia's global competitiveness (2014), and Australia's automation opportunity. Reigniting productivity and inclusive income growth (2019) – all by McKinsey and Co.

[8] Combines with [7] above and can take several focal points e.g. workforce development (Australia's Future Workforce (2015) followed-up by Automation Advantage (2017), Future Proof (2018) and Future Skills (2019) all of which seeking to create both a direction and clarity of actions around how best to handle at a national level. In the UK, the ECORYS report (Digital Skills for the UK Economy, 2016) identified 76 separate digital skills initiatives. In manufacturing, Reinventing the Manufacturing Workforce (2018) by the EEF pushes for a focused agenda. In the USA, M Foresight (Alliance for Manufacturing Foresight) (2017) America's Next Manufacturing Workforce: Promising Practices in Education and Skills Building identified five governing themes that define areas of need and innovation in workforce development programmes.

[9] OECD (2018) Public Expenditure and Participant Stocks on Labour Market Programmes. Only four countries spend 1% or more on active labour market policies and they are: Finland, France, Sweden and Denmark. Korea is 0.4%, UK is 0.25%; Germany 0.6% and the USA is 0.15%.

[10] See notes [24], [25] and [43] below

[11] Ezell, S. (2018) Why manufacturing digitalisation matters and how countries are supporting it. Information and Technology and Innovation Foundation. 66 pages.

[12] Ezell, S. (2018) op. cit. The development and application of the key technologies rests in large part upon the maturity of other ones: high-performance computing powered computer aided design and engineering software; cloud computing; the Internet of Things; advanced sensor technologies; 3D printing; industrial robots; data analytics; machine learning; and, wireless connectivity that better enables machine-to-machine communications. (page 2)

[13] Competences to manage both the progressive development of technological and manufacturing (and parallel development in product and service users) readiness and to bridge the gap between research and the full commercialisation of a product. This range of competences are by their very nature changing in their make-up and in the volume (numbers of people) required.

[14] National Skills Council/Expert Group on Future Skills Needs (2018) Digital Transformation: Assessing the impact of digitalisation on Ireland's workforce. Dublin, 101 pages.; most countries have some form of forecasting at the occupation level e.g. Working Futures in the UK, the US Department of Labor, Bureau of Labor Statistics produce employment projections 10 years into the future (see USDL 19-1571 – regularly updated). At the regional level you find studies like: Department of State Development, Queensland (2016) Advanced Manufacturing 10 Year Road Map and Action Plan – Powering the Queensland Economy leading to State of Queensland (2018) Advancing Manufacturing Skills. A skills, training and workforce development strategy for manufacturing industry in Queensland. The World Economic Forum using O*NET data derived a categorisation of skills into a set of skills families: 3 main categories and 9 sub-categories. Department for Business Innovation and Skills and Department for Culture Media and Sport (2016) Digital Skills for the UK Economy. Report by ECROYS UK for DBIS and DCMS. 130 pages. More recently for the UK see: DCMS (2019) No longer optional: Employer demands for digital skills. Report by Burning Glass. 108 pages.

[15] Burning Glass (2017) The Digital Edge: Middle-Skill Workers and Careers. Report for Capital One. This analysis indicates three types of digital skills (productivity software skills, advanced digital skills, occupationally specific digital skills and three digital skill pathways (door openers, career advances, specialised roles). The other side of this are the essential skills looked for by employers e.g. CEEMET (European Technology and Industry Employers) (2018) Digitalisation and the world of skills and education. See pages 9-10.

[16] PWC (2018) Skills for Smart Industrial Specialisation and Digital Transformation. Interim Report and Final Report (2019) Pages 342 and 522 pages respectively. See Table 20, pages 228-230 in the Interim Report which provides a structured overview of detailed competency areas per skills category and which builds on a series of corporate studies by ARM, IBM, Schneider, Amazon and SkillSET (in the USA). The T-skills in manufacturing are seen as the shape of the role to support innovation, integration and optimisation (Campbell, 2014, page 162).

[17] This is a trend which has been well established with the initial convergence of technologies (IT/computer control and units/systems of machines – the microelectronics revolution) in the 1970s and 1980s, and the trend has continued to this day with far greater convergence and integration of technologies.

[18] This is notably in a few areas e.g. with nanotechnology with the emergence of a series of engineer, technologist and technician roles (recognised at SOC level) and being filled by highly qualified (at least to master's level and often to PhD level). See: Rosenberg, N. (1972) "Factors affecting the diffusion of technology", Explorations in Economic History, 10, 3-33 and Wood, A.R. et al (1973) "Comparative managerial problems in early versus later adoption of innovative manufacturing technologies" RR-12, Technological Innovation Studies Program, Department of Industry, Trade and Commerce, Ottawa, Canada. We also see the growth of manufacturing companies providing extensive technical support for their technology users e.g. Rockwell Automation operates everyday of the year and employs 500+ engineers, 100+ consultants, 700+ field service professionals, and they run 100+ training courses.

[19] E.g. SPARC (The Partnership for Robotics in Europe) (2015) Robotics 2020 Multi-Annual Roadmap and the Roadmap for US Robotics. From Internet to Robotics – first developed in 2009 and updated in 2013 and 2016 with a new version due later in 2020 (available from Professor Henrik Christensen – hichristensen@ucsd.edu). This later example also gave rise to the US National Robotics Initiative. In some studies which have gone straight to occupations, they have by default done some technology road mapping but highly focused (see notes: [47], [53] and [55]).

[20] E.g. the European PES Vacancy Monitor; the Eurostat vacancy survey; the Monster Employment Index (started in 2004), the CEDEFOP on-line job vacancies and skills analysis (like the products and analytics produced by Burning Glass), and the BA-X labour market index of Germany published by the Federal Employment Agency (based on reported vacancies and not posted online vacancies).

[21] CEDEFOP (2009) PANORAMA skills for Europe's future: anticipating occupational skill needs. 191 pages.

[22] The UK figure comes from the LFS of September 2014 (see UKCES, 2015, op. cit.). The current total manufacturing employment in the UK is 2.7mn (HVM Catapult, Annual Report, 2018-19).

[23] Abele, E. et al (2017) "Learning factories for future oriented research and education in manufacturing", CIRP Annals – Manufacturing Technology, 66, 803-826. This piece build on Wagner, U. et al (2012) "The State-of-the-art and prospects of learning factories". 4th CIRP Conference on Manufacturing Systems. Procedia CIRP 3: 109-114. It is worth noting that in Germany the term "learnfabrik" was common in the 1980s and Penn State University established its own learning factory in 1994. Wiktorsson, M. et al (2018) "Smart factories: South Korean and Swedish examples on manufacturing settings", Procedia Manufacturing, 25, 471-478.

[24] There is clear pattern of cross-country learning with Australia's industry growth centres (six in all) being modelled on the fourteen USA Manufacturing Institutes which learnt from Germany's 72 Fraunhofer Institutes which also shaped the thinking in Korea (17 Creative Economy and Innovation Centres – these are regional and run by local government and large businesses). See: Ezell, S. (2018) op. cit. Parallel developments in China have marked a major shift away from innovation to the upgrade of manufacturing through a series of rolling technological advances working through the 40 Manufacturing Innovation Centres. Fraunhofer Institutes have been operating for over 70 years (set up in 1949) and now number 74 institutes employing 28,000 staff with a budget of 2.8bn Euros (2.3bn coming from contract research). Staffing is made-up of 18913 research and technical staff, 7225 students, and 510 trainees. Staff turnover is seen as positive with 1600 leaving in 2018 and 2548 joining the institutes. See: Annual Report 2018. This flow of staff between the Fraunhofer Institutes and manufacturing companies is seen by some as key to the development of the "hidden champions" as career progression is enhanced by developing new products and innovative solutions (Menkoff, T., 2016, "Lessons from Germany's 'Hidden Champions'", Singapore Management University website (4th Feb)

[25] There are 14 institutes across the Manufacturing USA programme: Advanced Functional Fabrics of America, American Institute for Manufacturing Integrated Photonics, America Makes, Advanced Robotics for Manufacturing, BioFab USA, Clean Energy Smart Manufacturing Innovation Institute, Institute for Advanced Composites Manufacturing Innovation, LIFT – Light Weight Metals, MxD (Manufacturing x Digital), Next Flex, National Institute for Innovation in Manufacturing Biopharma, Power America, Rapid Advancement in Process Intensification Deployment Institute, and Reduced Embodies Energy and Decreasing Emissions. They are sponsored by three difference US Government Departments and employ 1708 staff.

[26] Baratta, B.E. (2020) MxD Overview. Here are described three types of workforce development programmes: foundational, ongoing, and future ones. In terms of focus they cover developing a jobs taxonomy, MOOC programmes, a Mastering Manufacturing curriculum and pilot, a series of digital capabilities workshops (company focused); and an internship programme (includes the development of a nascent apprenticeship program). Also see: Stuck, L. (2019) MxD 2019 The Future of Work in the Manufacturing 4.0 Era. Describes the work of MxD with Manpower on their jobs taxonomy and domains: digital manufacturing (28% of jobs); digital thread (21%); digital enterprise (16%), digital product (8%); digital design (10%); supply network (11%); and Omni (6%).

[27] REMADE Institute (2019) Workforce Profile Report Version 1 covered the whole of the USA, while the Workforce Intelligence Network (2020) Connected and Automated Vehicles. Emerging Technology Skills Gap Analysis covered South East Michigan. The later report was used to drive local actions.

[28] USA Manufacturing has invested in a matching tool to link emerging skill requirements with current curriculum offers across the USA to help improve the quality of alignment and to build on existing programmes and use digital credentials. The SMART Manufacturing Workforce Development Model Programme run by the El Comino Community College which uses a tool to assess a businesses' readiness to adopt smart manufacturing and then links the analysis to the availability of corresponding education and training programmes. The initial focus in on aerospace across four occupations: operators, technicians, engineers, and managers. See Credly using the Acclaim Platform – https://info.credly.com/about-us - is also potentially useful to manage the development of a new accredited sets of competences and skills.

[29] See notes: [60] – [63]

[30] Advanced Manufacturing Partnership 2.0 (2014) in the USA agreed and developed a number of core pillars for workforce development: portable and stackable credentialing system, regional apprenticeships and internship models, bridging modules for career changers, project-based learning, develop more manufacturing-based courses and degrees at colleges and universities, leverage community colleges, and have public and private partnerships in all solutions. Much of this is detailed in their Workforce Development Overview which runs to 396 pages. See also: The International Software Testing Qualifications Board (ISTQB) e.g. certified tester, advanced level syllabus: test automation engineer. 84 pages

[31] See: Figure 5: Differences in skill requirements between various Key Enabling Technology Pillars in Boosting the potential of key enabling technologies. Addressing skills needs in Europe. (2016) Report prepared by PWC for the EU. For programme examples see: the 18 module programme for automation technicians at George Brown College in Toronto offered over 32 weeks part time (https://www.automationprogram.com) ABB have also supported modular automation and integration programmes. Campbell (2014) op. cit. describes the 23-skill block programme for mechatronics sponsored by the National Centre for Integrated Systems Technology and how this links to credits for later advancement into university. In Italy there is the accredited Industrial Automation and Robotics Training Course run in Milan and overseen by the Association of Engineers and run by two robot manufacturing companies. In the UK the Strategic Task Group led by Professor Tony Prescot, Skills and Education in Robotics and Autonomous Systems may provide some university level programmes.

[32] See Professor Harry Asada's programmes at MIT funded by Manufacturing USA – Teachbot which is a robotic apprenticeship education and training system.

[33] Consumer Goods Forum (2018) AI and Robotics Automation in Consumer-Driven Supply Chains. A rapidly evolving source of competitive advantage. Report by PA Consulting. 54 pages.

[34] E.g. the Federal Ministry for Economic Affairs and Energy (2019) Selected Cluster Successes. Results from the promotion of innovative services. 60 pages. Highlights 21 of the 90 clusters in Germany. There is a standard which a cluster must achieve before it can join the Go Cluster programme in Germany. See also: European Secretariat for Cluster Analysis (2020) Overview of Cluster Benchmarking Indicators. Two of the benchmarks cover human resource competence development. IRIS Group (2019) The Danish Robotics Cluster in a Global Perspective. Report for the Robotics Alliance. 41 pages. Looks at nine other robotics clusters in addition to the one in Odense, Denmark.

[35] Khamis, A.H. et al (2012) The Massachusetts Robotics Cluster. Harvard Business School. 33 pages. While the focus of this study is Boston, it also covers the ones in Pittsburgh and Silicon Valley for robotics. ABI Research (2016) The Massachusetts Robotics Cluster. Report for the Massachusetts Technology Collaborative. 123 pages. Makes the point that the foundational technologies apply across many industries and sectors and the skill sets can move across them as well.

[36] Competency Clearinghouse (2020) Advanced Manufacturing Competency Model which was developed from the Automation Competency Model (2014). The latest model has five tiers: personal effectiveness (7 competences); academic (7); workplace (9); industry-wide technical (6); and, industry-sector technical (6). Ones for aerospace (2018) and mechatronics (2017) which build on the core one for advanced manufacturing and is supported by the National Association of Manufacturers, the National Council for Advanced Manufacturing, and the Society of Manufacturing Engineers – all of the USA. We see also other competency models developed by individual Institutes of Manufacturing USA e.g. the LIFT foundation competency model for the "multi-skilled technician" and the MxD IGNITE Mastering Manufacturing (2018) and its Multiskilled Advanced Manufacturing Technician.

For Industry 4.0 skills portfolios have been developed too: Eherhard, B. et al (2017) "Smart work: the transformation of the labour market to the fourth industrial revolution", International Journal of Business and Economic Sciences Applied Research, 10 (3), 47-66.

Broader digital competence and literacy models are widely described e.g. Canada Centre for Digital and Media Literacy (2017) Digital Literacy Model: Media Smarts; European Digital Competence Framework for EU Citizens (2017) and its' Dig.Comp 2.1; UNESCO (2017) Working Group Education: Digital Skills for Life and Work. 128 pages.

There would appear to be very few corporate competency models, yet in the five-year corporate plans, corporate competences are a significant feature e.g. Kurumatani, N. (2019) The Toshiba Next Plan – Financial Years 2019-23 Business Plan. 69 pages.

[37] International Software Testing Qualifications Board (ISTQB) op. cit.

[38] E.g. Tennessee Department of Education, Program of Study Justifications for Advanced Manufacturing (2018) covering electromechanical technology, machining technology, mechatronics and welding. 43 pages.

[39] Larosse, J. (2017) Europe's Digital Progress Report: Country Profile Denmark. Analysis of National Initiatives on Digitising European Industry. Report for DG CNECT. 28 pages. See chart on page 6 which brings together all the national initiatives in support of Industry 4.0 and Digitalisation. Within the detail there are programmes on robotics, a network of technological institutes (8 in all, the GTS Network), a sector specialisation strategy etc. Sung, T.K. (2018) "Industry 4.0: A Korean Perspective", Technological Forecasting and Social Change, 132, 40-45 and Lee, Y-H. (2007) Workforce Development in the Republic of Korea. Policies and Practices. Asian Development Bank Institute. A brief overview of the position in the UK is described in AI and Automation in the UK, House of Commons Library, Briefing Paper No 8152. (2017)

[40] Ezell, S. (2018) op. cit. page 13 Germany is seeking to be the centre for standards and is exporting them to other countries via China.

[41] Walsh, J.P. (2015) "The impact of foreign-born scientists and engineers on American nanoscience", Science and Public Policy, 42 (1), 107-120.

[42] LinkedIn Talent Solutions (2018) The Digital Workforce of the Future: Acquire, Build and Grow Tech Talent. Looks at how best to close the skills gap based on taking a view as regards the nature of the skills gap: if skills needed are complementary to existing one and easy to scale; and, if niche, emerging, in-demand skills are required. In the latter case the proposed approach means acquiring the skills through becoming an attractive employer and building a pipeline of talent. Their analysis of tech talent in Asia shows a marked outward flow from Asia to the USA (21% difference: 43% from USA to Asia; 64% from Asia to the USA). For the UK, the outflow is 15% versus an inflow of 8%. Also see: Khatiwada, S. and Veloso, K.M. (2019) New Technology and Emerging Occupations: Evidence from Asia. Asian Development Bank. ADB Economics Working Paper Series No. 576. 67 pages

[43] In Japan, for example, the Public Industrial Technology Research Institutes (180 in all) train and develop company staff transferred to the Institute. The Institutes are part of a network of bodies and initiatives which include the Industrial Value Chains Initiative (leading to SMART Manufacturing Solutions which has four core themes ones of which is "new era of human-centric manufacturing powered by IoT"), the Strategic Innovation Promotion Programme (robots in the IoT era), the Robots Revolution Initiative and the IoT Acceleration Consortium. See: Ezell, S. (2018) op. cit.

[44] See: https://www.fraunhofer.de – provides access to the oversite portal and allows access to the 74 institutes and then into the alliances, groups, and centres of excellence, and their external networks.

[45] See [44] above

[46] Processit.EU (2018) ProcessIT.EU European Roadmap for Process Industrial Automation. 2nd Version. 32 pages. Builds on road maps from 7 other European initiatives. Robert Phaal (2011) Public-Domain Roadmaps identifies and provides an inventory for 2000+ roadmaps many of which are for manufacturing and technology. Centre for Technology Management, Institute for Manufacturing, University of Cambridge.

[47] Deloitte Insights (2019) The Future of Work in Manufacturing. What will jobs look like in the digital era? Deloitte, USA. 32 pages. Looks at six roles: digital twin engineer, predictive supply network analyst, robot teaming coordinator, digital offering manager, drone data coordinator, and smart factory manager. For each role the study looks at responsibilities, time spent on activities (2018 v 2025), experience of the job holder, their personal toolbox (for productivity, decision making, and learning), and what a working day looks and feels like. Innovation and Business Skills Australia (2018) Preparing for Industry 4.0 – Will digital skills be enough? IBSA, Melbourne, Australia. 31 pages. Identified three emerging sets of skills (digital analysis/diagnosis; 3D printing/ additive manufacturing skills; and, programming/coding) and mapped these across five types of occupations: operators; technician; engineers (domain specialist); engineers (IT); and, plant managers for a 5 year period. MxD of USA Manufacturing developed 20 profiles from the 165 roles they identified as being digital and core to manufacturing. The World Economic Forum (2018) Eight Futures of Work. Scenarios and their implications. 22 pages.

Equally useful is the project being run by MIT, Penn State and Arconic under the title, Factory 4.0 Educational Toolkit, which is creating a four-year electro-mechanical engineering technology programme. This is sponsored by CESMII (Clean Energy Smart Manufacturing Innovation Institute) – see: Harnessing the power of SMART Manufacturing (2020).

[48] Florea, A. (2019) "Digital design skills for factories of the future". Proceedings in Materials Science, Engineering and Chemistry. Uses the Scopus database to derive potential skill statements and clusters. Used articles over the period 2000-2019. Patents have been used in much the same way – see: Webb, M. (2020) The Impact of AI on the Labor Market. Stanford University. 61 pages. And there is also the Upwork Skills Index based on its freelancer's database which matches projects (and their sponsors) with capable self-employed individuals and those in-work double-jobbing.

[49] See note [47]

[50] Hsieh, T. (2016) "Skill sets needed for industrial automation careers". Paper presented to the American Society for Engineering Education. Focuses on the competences required for industrial automation technician role and these are rated as to their significance and importance to the role by role holders and their colleagues.

[51] Dudley, J. et al (2009) "Skills formation to support the future of automation in the resource industry", Australian Mining Technology Conference, October 27-28. Creates a series of task/skills inventories for automation and examines at three times frames: now, in 5 years, and in 15 years. The work with a "automation competency map". The output was then matched to the most similar and related vocational qualification as the start point for certified skills development.

[52] For extensive coverage of the work of the KETs Skills Observatories see: Skills for Key Enabling Technologies in Europe. Vision for the Development of Skills for Key Enabling Technologies (2016) report by PWC for the EU.

[53] Five European Sector Skill Councils were set-up for textiles; clothing and leather; commerce (retail and wholesale), automotive; audio-visual and live performance; and, marine technologies. The Council for Automotive produced European Skills Council Automotive Industry (2016) Automotive Industry Report focused on two sets of occupations: five traditional ones and how are changing (maintenance technician, CNC operator/tool and die maker, paint technician/motor vehicle painter, assembly line operator/assembler, and materials planner analyst; and, five emerging occupations: product engineer, R&D engineer/technician, process engineer, 3D printing technician, and product design and development technician. The move from Councils to Alliances has brought with it a greater focus on digital skills e.g. The Digital Skills and Jobs Coalition. One of the Alliances called Skillman (Sector Skills Alliance for Advanced Manufacturing in the Transport Sector) and seeks to offer a one-stop shop for competences across automotive, aerospace and train industries. Work by McKinsey (New Tech Talent you need to succeed in digital) identified six emerging roles: designer engineers, scrum master/agility coach, product owners, full stack architect, next generation machine learning engineers, and development-operations engineers.No one has brought together these studies to tried to match and align the various roles they have identified.

[54] See note [53] O*NET some additional insight into a number of roles also around robotics where two are recognised: Robotics Engineer (17-2199.08) and Robotics Technicians (17-3024.01) along with 13 other occupations with some robotics-focused tasks. Japan has also recognised a role in robotics, the Robot System Integrator for which there are various certificates (see: www.robotics.org – started in 1974 and offers 38 certificates in this area).

[55] UKCES (2015) Sector Insights: Skills and performance challenges in the advanced manufacturing sector. 82 pages. Examines in detail five roles: production managers and directors in manufacturing; biological scientists and biochemists; production and process engineers; metal working production and maintenance fitters; and, assemblers (electronics and electrical).

[56] See note [24] where in the Fraunhofer Institutes, 30% of the staff are either students or trainees in addition to the turnover of staff to join manufacturing companies.

[57] Fraunhofer IOSB-INA and VDMA (2017) Industrie 4.0 Communication Guidelines. Fraunhofer Application Centre for Industrial Automation. 32 pages. See the toolbox (Figure 7, page 12) and migration strategy (page 16); Combemale, C. et al (2018) Not all technological change is equal: disentangling labor demand effects of automation and parts consolidation. Carnegie Mellon University Working Paper.

[58] This is most notable in the USA with the 14 manufacturing institutes reviewing progress and evaluating the benefit and impact of their workforce projects.

[59] Ezell, S. (2018) op. cit. page 11

[60] Baur, C. and Wee, D. (2015) Manufacturing's next act. McKinsey and Co. The digital compass seeks to help companies find tools to match their needs relating a set of value drivers with Industry 4.0 levers. As a part of the Digital Entrepreneurship Monitor Project in Europe a similar tool was developed. See: Strategic Policy Forum on Digital Entrepreneurship (2016) A digital compass for decision makers: toolkit on disruptive technologies, impact and areas for action. DG Internal Market, Industry, Entrepreneurship and SMEs. 28 pages.

[61] World Economic Forum – see http://www3.weforum.org/docs/WEF_White_Paper_Technology_Innovation_Future_of_Production_2017.pdf Covers the interplay between mainstream, maturing and emerging technologies across seven areas: connectivity and computing, analytics and intelligence, digital physical transformation, production philosophies, advanced materials, advanced production processes, and human-machine interface.

[62] McKinsey and Co (2016) Industry 4.0 after the initial hype. Where manufacturers are finding value and how they can best capture it. 36 pages. See: Exhibit 5, page 16: McKinsey's Industry 4.0 Diagnostic Consists of 4 Steps: status quo assessment, improvement ideas, impact estimation, and road map; also see Warwick Manufacturing Group (2017) An Industry 4.0 Readiness Assessment Tool. Developed with Crimson and Co, and Pinsent Masons. WMG, University of Warwick. 20 pages

[63] Acatech (Academy of Science and Engineering, Germany) Industrie 4.0 Maturity Index. RWTH Aachen University. Six stage model: computerisation; connectivity; visibility (What is happening?); transparency (Why is it happening?); predictive capacity (What will happen?); adaptability (How can an autonomous response be achieved?) which charts the evolution of a firm's capabilities from simple digitalisation to full self-optimising factories. There are related tools to those listed in the above notes e.g. The Manufacturing Extension Partnership in the USA which uses its Digital Manufacturing and Design Assessment Tool to benchmark SME for their digitalisation journey. It covers five core areas: support operations, supply chain, design and engineering, factory floor, and cybersecurity (See: Ezell, S. (2019) The Future of Work in a Digital Environment. Presentation at the Purdue Spring 2019 Digital Enterprise Symposium.

[64] See note [16]

[65] Campbell, K.S. (2014) Manufacturing Workforce Development Playbook. Summit Media Group, Chicago. 218 pages.

[66] UKCES (2015) Skills and Performance Challenges in Advanced Manufacturing. This study identified that occupational and professional standards have a role to play in the advanced manufacturing sector.

[67] US Government Accountability Office (2019) Workforce Automation. Better data needed to assess and plan for effects of advanced technologies on jobs. Report to Congressional Requesters. GAO-19-257. 84 pages – the same was found by the Georgia Institute of Technology (2015) Emerging Robotics Region: Insights for Regional Economic Development in which they found both NAICS and SOC failed to capture robots in a helpful way; National Academies of Science (2017) Building America's Skilled Technical Workforce; and, Monitor Institute by Deloitte/Autodesk Foundation (2019) Supporting Worker Success in an Age of Automation.

[68] National Institute of Standards and Technology (US Department of Commerce) (2018) Manufacturing USA Annual Report.

[69] US Government Accountability Office (2019) Advanced Manufacturing. Report to Congressional Committee. GAO-19-409. 77 pages.

[70] See notes [60] to [63]

[71] See notes [60] to [63] Also see Tooling-U-SME's Competency Framework for Manufacturing Excellence which supports the assessment and building of knowledge, skills and abilities as well as creates career pathways for employees (page 5 in Building Talent to Accelerate a Digital Transformation, Smart Manufacturing Industry Report, Vol 1, Number 3).