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The impact of Industry 4.0 on supply chains and regions: innovation in the aerospace and automotive industries

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\textbf{ABSTRACT}

This paper explains the spread of Industry 4.0 technologies in two globalized, manufacturing industries. It then goes on to suggest ways in which the widespread adoption and integration of these technologies may impact upon their geographical distribution – not least engaging new regions and perhaps altering the significance of established ones.

\textbf{KEYWORDS}

Innovation; supply chains; regions; aerospace; automotive

\section*{Introduction}

Automotive and civil aerospace have much in common. Each has a complex and highly stratified, globalized supply chain. Significantly, both industries are already widely engaged in the adoption of Industry 4.0 technologies. The two industries are both globalized and regionalized – on specialized islands of innovation with long industrial histories, like Detroit in automotive and Toulouse in aerospace. These regional\textsuperscript{1} agglomerations, of automotive or aerospace businesses, also contain other sectorally-focused resources (e.g. universities, research institutes) and, most importantly, have a capacity to innovate (Hickie, Jones, and Schloderer 2019; Hilpert 2019). There are technological spillovers between the sectors, for example from automotive to aerospace in robotics and from aerospace to automotive in composite materials. The key structural distinction between the sectors is that civil aerospace is a Boeing-Airbus duopoly, whilst automotive Original Equipment Manufacturers (OEMs) are competing in an increasingly overcrowded marketplace. Industry 4.0 technologies are already bringing significant changes to the structure of supply chains and their global distribution in both sectors. The case made here is that the increasing adoption of digital technologies is likely to further enhance these tendencies in the coming decade.

\section*{The character and impact of Industry 4.0}

Whilst the term Industry 4.0 has been used in various contexts and its boundaries appear somewhat flexible (e.g. Brettel et al. 2014), it is clear that it is driven by the rapid growth in our ability to gather and process data, and then to transmit and store it. More
particularly, although Artificial Intelligence (AI) has been around for decades (Hickie 1991; Hilpert 1991), recent, rapid developments in AI have been driven by greatly enhanced computer power, big data and advances in machine learning (Rotman 2017) and by the falling costs of new technologies. Although the automotive and aerospace industries have been major users of computers since the creation of the silicon chip in 1973 (e.g. in robotics, Baldwin 2016), rapid advances in Industry 4.0 technologies offer major opportunities for rapid innovation.

Industry 4.0 technologies create opportunities for enhanced synergies and greater optimization of activities across the board, from R&D to customer relations. For example, Augmented Reality (AR) can allow access for manufacturing workers or consumers to expert advice, without an expert present. Virtualizing supply chains can enhance inter-company collaborations and the closer integration of companies’ core competences (Brettel et al. 2014). Telemigration can allow firms to draw on the expertise of part-time or contract workers to provide a cheaper, more flexible workforce, a prospect that will grow with improvements in machine translation and telepresence technologies (Baldwin 2019). Advances in the digital economy have driven a move from capital-based value creation to knowledge-based value creation and, in advanced economies, this has led to a shift in the balance of investments away from investment in capital goods and towards investments in intangibles (e.g. R&D, design, software, Haskell and Westlake 2017).

The advance of the digital economy is likely to have profound effects on employment. Beginning in the 1970s the ICT revolution saw the displacement of skilled and semi-skilled manual workers’ jobs by robots. However, whilst this was highly detrimental for certain types of worker, its effects on employment were not always detrimental. Many highly skilled, well paid service jobs were created for those who could write software, manage robots and so on. Industry 4.0 technologies are likely to have a similarly disruptive effect on labour markets. As a World Economic Forum (2016) report suggested, automation will displace many current jobs and even occupations. However, in this case, the jobs displaced are more likely to be service jobs, in particular those performed by less well-educated employees (Rotman 2017). Those who continue in employment are likely to find that they need to acquire new knowledge and skills to compete effectively in the labour market (Wright 2019). This is not to say that computers will perform better than humans at all tasks, or even be able to undertake all tasks. Currently, humans are better than machines at understanding language, although increased computer power and larger databases may reduce aspects of that advantage (McKinsey Global Institute 2017). However, humans have qualities which give them ‘unique advantages’ (Baldwin 2019, 236), like using judgement when faced with incomplete data, that are not replicable by machines. Similarly, humans can explain their decisions and take responsibility for them, both matters of great significance in automotive and aerospace.

The specific impacts of Industry 4.0 technologies on aerospace and automotive are too recent to be well represented in the academic literature. There are studies of digitalization which helpfully use these sectors as examples (e.g. Grendel et al. 2017) point out that digital technologies are more immediately useful in highly automated sectors (like automotive) rather than in sectors which involve significant levels of manual assembly to
create very large structures (like aerospace); see also Theorin et al. (2017)). Similarly, Ceruti et al. (2019) look at the potential uses of additive manufacturing and AR in aerospace MRO. Other writers report specific technology projects to support one sector or the other (e.g. Valachek et al. (2017) describe a project to construct digital twins to support the Slovak automotive industry). Beyond this there are non-academic reports: with a general digital technology focus (e.g. the World Economic Forum’s (2016) study of the potential impacts of digitalization on employment; or, PwC’s (2018) study of digital champions in the Asia-Pacific region); and, reports with a specifically sectoral focus (e.g. KPMG’s analysis of mobility in 2030 (2019b)). The business focused press (e.g. The Financial Times, The Economist) and the professional and sectoral press (e.g. The Engineer, Aerospace) also contain useful and up-to-date insights into both sectors. Finally, some major consultancies are producing advice about how these sectors might respond to the Covid crisis using digital technologies (e.g. PwC (2020a, 2020b); Times Tempus (2020)). Inevitably, given the rapid advances in digitalization, much of what is written for current consumption is inevitably speculative.

Some impacts of digitalization upon the geographical distribution of the aerospace and automotive industries can be discerned, but are presently still in their infancy. What is well established is that innovation in both industries is already highly regionalized in locations that have strong, specialized regional innovative ecosystems (Hickie 2006; Adner 2017) which support Research and Development (R&D) and new product and process developments, for example in universities and through networks of experienced specialist suppliers (Hickie, Jones, and Schloderer 2019). Furthermore, these specialized regions can be understood as islands of innovation (Hilpert 2019), not innovating in isolation, but collaborating with other geographically dispersed technologically advanced regions or islands (Hilpert 1991). A similar process of regional concentration can be found in digital technologies, most obviously in Silicon Valley. Clustering brings with it various benefits, which both keep established firms in a region and attract new firms to it, and such clustering tends to be more common for knowledge-based R&D activities than for production (Alcacer and Chung 2007; Siedsschlag et al. 2013).

The potential impacts and challenges of Industry 4.0 technologies

Technological innovation is critical to competitiveness in both industries. Significant advances have taken place, for example in the use of automation, composites, driver aids and fly-by-wire technologies. However, it is arguable that the technological trajectory of both sectors has been incremental since the advent of jet airliners sixty years ago. Industry 4.0 technologies have the potential to underpin more radical changes in both sectors, significantly increasing the pace of both product and process innovations. In both sectors Industry 4.0 technologies have the innovative potential to engage both mature, well established firms and new entrants with niche expertize, and to impact the regional distribution of their innovative activities.

Managers in both sectors see Industry 4.0 technologies creating a step change in product innovations (e.g. KPMG. 2019a). The most critical are in vehicle autonomy, shared passenger mobility, product deliveries and the enhancement of customer relationships. In automobiles, advances have already allowed vehicles to take over functions from drivers, and are leading towards either to semi- or wholly autonomous vehicles (http://
It is clear that global digital technology companies (e.g. Uber and Waymo – an Alphabet subsidiary) are undertaking ambitious research to develop fully autonomous vehicles. Autonomous vehicles create the possibility for new services with far reaching consequences (Economist 2018). Digitization and autonomous vehicles have the potential to reshape individual mobility, allowing on-demand consumer mobility and using autonomous vehicles which can radically cut consumer costs. Greater connectivity also allows for the development of Mobility as a Service integration, in which timetabling and payment for different forms of transport can be integrated. Over the next decade or so, these developments may reduce the need for individual and company car ownership (PwC 2019). In the automotive sector they may also radically change the relationship between manufacturers and customers, for example enabling manufacturers to establish individual relationships with customers bypassing dealerships (PwC 2020b). Immediate ambitions for large, autonomous airliners are less advanced, reflecting passengers’ and regulators’ wariness. However, both sectors are involved in developing new, faster, cheaper delivery ecosystems, radically transforming retailing. In aerospace there are drones and cargo planes with only a single pilot under development to speed up short- to medium-range deliveries. These can complement self-driving delivery platforms (e.g. the Toyota e-Palette), localized delivery robots and dynamic routing systems (e.g. the Via Van – a Via and Mercedes joint venture) (KPMG 2018).

Industry 4.0 technologies are key to speeding up design processes to bring new vehicles to market more quickly. For example, in automotive it is expected that the time between R&D and production will shrink from 3–5 years today to 2 years. (PwC 2019). The automotive industry has traditionally relied on physical prototyping (Pittman 2019). Now VR allows designers to visualize a whole vehicle without physical prototyping, or ‘see’ inside a new engine during its design. In manufacturing, Industry 4.0 technologies are having an impact from the level of the individual worker to the global supply chain (e.g. Airbus already uses cobots). More broadly, robots can raise quality, and automate material movements, repetitive tasks and predictive maintenance. Enhanced connectivity can greatly improve customer service. It is already critical in modern airliners (e.g. an A350 transmits 30 gigabytes of data daily). Aeroengine manufacturers are already delivering servitization to customers, monitoring every engine in flight in real time, detecting faults and predicting its maintenance requirements. It is projected that in aerospace advanced data management will allow the development of digital twins for every aircraft produced that trace every component of an aircraft from its manufacture to disposal and recycling (e.g. Economist 2019). Finally, although automobile customers and airlines already expect to receive vehicles built to their exact specifications, VR has the potential to enhance their experience further (e.g. enabling car buyers to ‘test drive’ the exact vehicle they intend to buy).

Of course, Industry 4.0 innovations create challenges as well as opportunities (Klaas 2019). They create competitive pressures, major technological uncertainties and pose an existential threat to firms that lag behind or make poor investment choices. Automotive and aerospace are engineering-based industries, which inevitably draw on many technologies. In a time of rapid technological change, there are leads and lags in technological development. One technology may apparently offer enormous immediate potential, but be hindered by the slow pace of other technologies upon which it is dependent (e.g. the time taken to develop additive manufacturing for composites). Technological
complexity makes for difficult decision making. Not only are the various Industry 4.0 technologies advancing very quickly, but both industries need to incorporate a range of other technologies into their products. For example, there are currently three major technological drivers in automotive – electric vehicles, connected and autonomous vehicles and on-demand mobility services (KPMG 2019b). The impacts of Industry 4.0 technologies are also dependent on people’s responses to them. Consumers may not accept some innovations based on Industry 4.0 technologies because they do not offer sufficient individual or societal benefits. Citizens may object to their broader social consequences. Reservations about an innovation may arise because it is seen as unsafe (e.g. consumers may be reluctant to trust autonomous cars, let alone driverless air taxis). Worse still, customers may be unwilling to use a product if it actually proves unsafe is use (e.g. the Boeing 737 MAX). Public attitudes towards these technologies are mediated through public policies that may help or hinder their development (e.g. with subsidies and preferential traffic regulations for electric cars). What may be technologically possible may not be socially and politically acceptable. Regulators are becoming more influential on automotive design (e.g. KPMG 2019a). Similarly, the 737 MAX disasters have led to a reassertion of regulatory authority by the FAA. Inevitably, such reactions are likely to have spatial impacts – particular products and services which are acceptable in some markets may be unacceptable, or be discouraged, in others (Financial Times Lex 2019). The complex relationships between these technological, managerial, social and political capabilities condition both the development and implementation of Industry 4.0 technologies in general and their spatial distribution. Hence regions have different technological and economic strengths and weaknesses regarding Industry 4.0 which are reflected: both in the diverse roles they play within the automotive and aerospace supply chains; and in enabling diversities of innovation as firms and research institutes collaborate across regional boundaries.

**The impacts of Industry 4.0 innovations on established manufacturers**

**The reinforcement of established regions**

Even when a technology is sufficiently developed, is economical, and consumers want it, for the individual firm there still remain critical decisions. The firm needs to consider – its own capabilities and resources, those within its supply chain and the impact of the technology on its competitive advantage. Many of the qualities that firms need to respond to the innovative demands of digitization are in common with the qualities they need to engage with other technologies. A firm will need not only technological knowledge and skills, but also a blend of managerial and commercial knowledge and skills to assess the potential competitive implications of the technology (e.g. Maisonneuve et al. 2013). Such decisions can be acute.

The issues facing a firm vary depending on whether it is an established player or a new entrant in the sector, and where it positions itself in the supply chain. In mature, high technology, engineering-based industries like these, established firms have enormous competitive advantages, in terms of their huge capital investments, their generations of R&D, their established supply chains, the experience and culture of their workforces, their brand recognition and so on. Established OEMs, and many of their Tier 1 suppliers,
are global businesses, but they are also firmly rooted in particular regions by their human, physical and financial capital investments and so are unlikely to relocate core activities (e.g. Hickie 2006). Regions like Stuttgart in automotive or Seattle in aerospace demonstrate the competitive advantages to be drawn from their immense regional legacies.

It is important to recognize that customer companies and a local supply chain are not in themselves sufficient to create the fully functioning regional innovative ecosystem (Adner 2017). To flourish innovative companies need to draw on the services of governmental and non-governmental agencies. Ubiquitous in both industries is the need for research, design and manufacturing skills. Until the Covid outbreak the aerospace industry was experiencing both regional and national skilled labour shortages for postgraduate and graduate engineers, technicians, supervisors and factory workers (Azouzi 2014; Walker 2014; Washington State 2015). The growth of Industry 4.0 technologies creates an imperative in both sectors to build a workforce capable of innovating and implementing them. Both have recruited staff with digital skills from other sectors with more advanced digital skills (Aerospace Technology Institute 2018), but competition for talent is increasingly tight (especially regionally). Of course, these shortages are not likely to be felt equally across all types of employment or all regions. PwC (2019) forecast a halving of assembly line workforces in automotive due to automation and new types of shared mobility vehicle, whereas the number of software engineers may increase by up to 90%. Hence, plants focused on manufacturing may lose process workers, but suffer shortages of digital skills.

To help train and rebalance their workforces, firms are often heavily dependent on their regional education and training infrastructures. Clearly, OEMs and Design and Build suppliers generally will require a greater supply and variety of specialist skills, but even simple Build-to-Print suppliers need their own engineers with highly developed digital skills, if they are to fit themselves into highly integrated supply chains and the Internet of Things. Hence firms are reliant on educational and training institutions (e.g. schools, technical colleges, universities) to ensure they are competitive in Industry 4.0 technologies. Furthermore, in these highly innovative regions automotive and aerospace firms combine with their non-commercial partners in regional cluster organizations (e.g. HEGAN for Basque aerospace and automotive-bw for the Stuttgart auto industry). These organizations often play a key role in both coordinating and providing education and training, and in developing the industrial culture. They can lobby and negotiate with local education and training providers and with national and regional governments to ensure that the education system is providing for the industry’s future demands for skilled labour (e.g. by ensuring school leavers have a good STEM education). In addition, cluster organizations play a role in marketing the industry in their region, both to help sell its products and to attract new OEMs and suppliers to set up in the region.

In essence, there is strong evidence that automotive and aerospace are still centred on long-established highly innovative regions with intense concentrations of innovative resources. Rather than moving, such businesses can choose to train and hire the talent and create the R&D facilities they need for the new technologies. They act as a magnet for startup companies that wish to supply Industry 4.0 products and services to their sector. Hence, there are regional agglomeration effects which both benefit established OEMs and their suppliers in a region, and attract new automotive or aerospace
companies (Hickie, Jones, and Schloderer 2019). Over the past several decades, some globally significant new centres have developed (e.g. in Mexico in both automotive and aerospace), often based on FDI from major industry players. These can form the basis for regional ecosystems with their own local supply chains. Such supply chains may be made up both of indigenous supplier companies and by branches of global suppliers. Some of these regions (e.g. Singapore in aeroengines and MRO) (de Meyer et al. 2014) are developing as islands of innovation with a significant capacity to innovate that impacts beyond their own region (Hilpert 2019; Adner 2017). In general, these new innovative regional centres have not yet fully equalled, let alone displaced, the long established global centres as innovation hubs (except, arguably, Sao Joao dos Santos in Brazil for regional airliners). However, it is a clear intention of Chinese industrial policy (Ministry of Industry and Information Technology 2015) that China develops its own innovative centres in aerospace and automotive.

**Drawing new regions into the supply chain**

The ‘gravitational’ pull of established OEMs in well-established regions does not mean, though that, even within these global businesses, the geography of innovation is unchanging. Where a technology has a high degree of novelty is progressing quickly, and is critical to competitiveness, even globally dominant OEMs may need to look beyond the regions where they are long established. These global players can choose to locate new R&D investments in particular new technologies at new locations, which are established or developing global centres for those technologies. In Industry 4.0 technologies this has most obviously occurred in and around Silicon Valley. Major automotive and aerospace companies have been attracted by the existing innovative ecosystem there and invested in it in three key ways. Firstly, they have used their immense financial and technological strength to buy up startup ventures with innovative potential (e.g. in 2016 GM took over Cruise, a San Francisco-based autonomous vehicle startup, which is developing an autonomous electric Chevy Bolt). Secondly, they can invest heavily in an existing technology company, as Honda also did in Cruise in 2018. Or, thirdly, they can set up their own, focused R&D facility in a region they identify as having the necessary innovative ecosystem to enable their activities (e.g. Ford, Nissan and Airbus all have research facilities in Silicon Valley). Hence, the geography of innovation in both sectors has grown to incorporate Silicon Valley, whilst further strengthening Silicon Valley’s regional competitiveness in Industry 4.0 technologies.

Simply being an established global player is no guarantee of technological success. Despite their accumulated knowledge and expertise, even well-established OEMs can lack sure footedness when introducing new products and technologies. Furthermore, being a legacy manufacturer can involve liabilities as well as strengths. Legacy status brings with it heavy past investment in existing technologies and the culture, values and careers built around them. Boeing’s unfortunate decision to introduce the MCAS anti-stall system on its 737 MAX can be interpreted as a consequence of attempting to adapt a 1960s airframe. Legacy in the automotive industry can most obviously be seen in chronic oversupply amongst its most established players (e.g. Ford's sale of 6 of its 24 European plants; the sale of GM Europe to PSA). Here, consolidation and mergers are directly related to the need to share the cost of developing new vehicle platforms.
and speed their time to market using digital technologies. Closing outdated, inefficient plants inevitably reduce a company’s footprint, both regionally and globally. Cultural legacies can lead to a certain conservatism and a reluctance to make the profound changes necessary to make full use of Industry 4.0 technologies. Such conservatism is a potential drag on established regions’ ability to adapt to Industry 4.0, and hence on their long-term competitiveness. Currently, there is some evidence of conservatism in aerospace companies. The evidence in automotive is more mixed. The new digital technology-based competitors in the automotive market have chosen to develop fully autonomous vehicles, regarding the more incremental R&D into semi-autonomous vehicles by some established automotive OEMs as legacy-based conservatism (Economist 2015). However, PwC has found that, globally, automotive was especially advanced providing 20% of the most digitally advanced manufacturers (digital champions) (PwC 2018).

Whilst legacy can be a source of strength for OEMs, global Tier 1 suppliers and technologically advanced suppliers, it is often a marked disadvantage for less advanced suppliers lower down the supply chain. Here, the adoption of digital technologies tends to be slower and less advanced. This can be a profound risk for smaller companies, which may lack the financial, technological and managerial resources to engage with radical technological developments (Hickie, Jones, and Schloderer 2019). Such firms often supply on a build-to-print basis (not owning critical IPR), are heavily invested in existing technologies, and may be manufacturing components which are highly commodified. Such firms can simply be unaware of the impending technological changes imminent in their supply chains. Their low margins mean they may lack the investment funds necessary to innovate, and cannot afford the specialist labour they would need. It was clear some years ago in aerospace that significant numbers of these established SME suppliers were ill-prepared and struggling to keep pace with the key new technologies. This applied even to SMEs in regions where the industries were well established (e.g. Maisonneuve et al. 2013). Both sectors have global supply chains with Tier 3 or 4 suppliers in lower wage economies whose competitive advantage lies significantly in lower labour costs rather than in their own, or their region’s, advanced technological skills (e.g. many suppliers of automotive parts in Eastern Europe). Industry 4.0 threatens to displace such suppliers with companies employing advanced technologies and potentially with even lower costs. The demise of these weaker suppliers could have a significant impact the geography of manufacturing, but would have much less of an impact on the geography of innovation, because the firms worst affected would not be strong innovators.

Industry 4.0 technologies and opportunities for new entrants and locations

New entrants

Despite the strengths of legacy OEMs and global suppliers there are, as suggested earlier, opportunities for new entrants in both sectors. More particularly, digitization offers opportunities for those developing whole vehicles incorporating digital technologies, and those developing as specialist suppliers of digital products and services. There are new OEMs designing and manufacturing complete new vehicles, which attempt a step change beyond what is currently being manufactured, perhaps even planned, by
established OEMs. These firms, often startups, should not be seen simply as digitization specialists. In order to take on established players and produce highly innovative vehicles they will draw widely on the range of technological advances being employed in their chosen sector. Furthermore, these new OEMs are not necessarily attracted to set up in regions because of their previous expertise in automotive or aerospace. Tesla is a particularly interesting example. Although its competitive advantage currently rests primarily in the qualities of its electric engines and its marketing, it has chosen to locate in Silicon Valley and is developing its own vehicle connectivity to contribute to developing automated cars (Economist 2015). Its decision to locate there appears to have been driven by its proximity to digital expertise, which was reinforced by its purchase of the former NUMMI plant in Fremont. Similarly, the new Chinese electric car makers Byton and Nio are both using advanced digital technologies to enhance the appeal of their vehicles (advanced touch screen technology on the M-Byte and AI-enabled functions on the Nio). Yet the tasks facing new OEMs, whether Tesla or its Chinese competitors, are considerable. Tesla has only recently posted its first full year of profit, has ongoing problems with manufacturing quality, and has some way to go in developing its autonomous vehicle technology. Chinese car manufacturers, perhaps, have a more competitive opportunity, relying not only on new technologies, but also on long-term domestic market growth (28 million vehicles in 2018) and significant industrial policy support (not least in robotics) (McGee 2019). However, Chinese auto manufacturing startups still face a daunting prospect if they are to become globally competitive. For example, Nio recently undertook a new round of funding because of poor sales and cash flow issues.

In aerospace, producing large airliners is potentially technologically, financially and industrially even more taxing for new entrants. There have been two significant OEMs designing wholly original airliners to challenge Airbus and Boeing, COMAC in China and Bombardier in Canada. Both had to use composite materials and digital technologies to have even a chance of competing in global markets. In addition, both have relied heavily upon key suppliers and regions in the established aerospace supply chain. For example, while the COMAC C919 airframe is designed and built in China, many of its key systems are foreign designed. Although these systems may be assembled in China, and so help provide a knowledge base for future Chinese aerospace development, currently they embody innovations developed elsewhere. For example, its engines are from the Franco-US partnership CFM, while its flight controls are from the leading US supplier Honeywell. Despite being able to call on world leading suppliers, both COMAC and Bombardier have found the development of airliners ab initio very challenging. Both aircraft have experienced very lengthy delays in development, which in Bombardier’s case led to the takeover of its airliner activities by Airbus as the project bled cash. Currently, the market leading capability to design large airliners remains with Boeing, Airbus and their supply chains.

A more promising market for new aerospace OEMs has been the cheaper and relatively simpler task of designing, and sometimes building, small aircraft relying heavily on digital technologies. These new aircraft are not intended directly to take on Boeing or Airbus in their key markets, but are regional executive jets (e.g. the Israeli Eviation Alice, Zunum Aero in Seattle), (Economist 2019), and air taxis – with or without pilots (e.g. e-Hang in China, Volocopter in Germany and Wisk in the US). Such
companies are often supported by financial investments from established aerospace companies and/or digital entrepreneurs (e.g. Wisk has funding from both Boeing and Larry Page). In addition, major, digitally strong, delivery companies like Alibaba, Alphabet and Amazon are investing heavily in the development of pilotless delivery drones (e.g. Alibaba for remoter parts of China). What these developments have in common is that they rely heavily on digital technologies to allow autonomous or single pilot operation, as well as drawing on advances in composite materials and electric engines.

**The locational choices of new entrants**

New OEMs entering the automotive and aerospace industries, whose competitiveness rests on their Industry 4.0 technologies, have locational decisions to make about their manufacturing, design and R&D activities. Manufacturing decisions are influenced by a range of quite disparate factors, such as the supply of skilled industrial workers (especially those with sectoral experience), the proximity of suppliers, public policy and an element of serendipity (e.g. Tesla’s decision to manufacture in Fremont). However, it is clear that when new automotive companies decide where to locate innovative R&D and design activities they are frequently attracted to well established regions, where there are well established innovatory ecosystems, networks and technologically skilled labour. So, for example, Nio’s HQ is in Shanghai but it chose to set up: its design centre in Stuttgart; its software development centre in San Jose, California; and its motor racing centre in London. Similarly, Byton has design, engineering and software centres in Munich and Santa Clara, California – despite planning to manufacture in Nanjing. Similarly, Tesla’s Fremont facility is close to Palo Alto, which can attract a ready supply of experienced and highly skilled software engineers more easily than in Detroit, even if at significantly higher wages. Tesla plans to build its European HQ in Brandenburg, close to Berlin, which again offers a ready supply of software engineers but, critically, has ready access to the Berlin’s market potential for shared transportation. In aerospace the closest parallel is with OEMs designing small electric aircraft, often autonomous, for use in urban areas. Such companies are drawn to set up close to established R&D centres, to highly skilled engineering labour and often to major investors. For example, Volocopter is based at Bruchsal in Baden Wurtemburg, where it is close to Daimler-Benz, a major investor and a major research centre of the DLR (the German Government aerospace research body), as well as to a large pool of skilled labour from which it has drawn (e.g. its Chief Technical Officer came from Safran, a Tier1 aerospace supplier with a local base). Similarly, the Opener Blackfly electrical VTOL aircraft and the Kitty Hawk Cora flying car are both based in Silicon Valley, where their lead investor is based and expertise is abundant (Economist 2019).

Similarly, the introduction of new digital suppliers is adding a significant geographical diversification to innovation in both sectors. Industry 4.0 has its own established innovative geography, most obviously in Silicon Valley. Here established digital companies and new startups are developing innovative products that they can supply to both industries. For these new, innovative suppliers the most influential attractants, when choosing to locate their activities, are highly skilled labour, networks of suppliers, potential investors and potential customers. On the supply side, for example, Silicon Valley is an obvious location for highly specialist digital companies which want to supply AI-based
driving platforms (e.g. Nauto and Plus.ai). AI-trained software engineers are essential to their competitiveness. However, some of the most highly specialized digital suppliers prioritize proximity to customers -OEMs and their established suppliers, – who provide a ready market for sector-specific Industry 4.0 innovations. For example, in Toulouse ID-Product, a robotics and automation specialist in cabin interiors, has identified a niche acting as a ‘go-between’ linking highly specialist SMEs lower down its supply chain and top tier manufacturers. It identifies SMEs capable of meeting very precise customer needs and, if necessary, assembling components from several suppliers for delivery to the OEM. Similarly, nearby Vodea supplies multimedia visualization of products for aircraft (e.g. for cockpits, for taxiing) employing AR, metadata management and machine learning. Stuttgart has a similar variety of new SMEs using Industry 4.0 technologies mainly to fill automotive market niches. For example, CVEP, created in 2016, provide electrical control systems with intelligent controls for vehicle electrics and electronics, whilst Drag&bot provides programming software for manufacturing robots. Around Detroit, Clinc is developing voice interface software for the automotive industry, and Advanced Collective Vehicle Solutions is developing communications technologies for vehicle entertainment, fleet tracking and security. Serendipity can also influence new firms’ locational decisions (e.g. Detroit Flying Cars’ founder has lived and worked in the region for decades).

The entry of new OEMs and digital suppliers into the automotive and aerospace sectors has the potential to make radical changes to the geography of manufacturing (e.g. the potential for major new automotive factories in China producing AI equipped electric vehicles). However, their impact on the geography of innovation is presently less marked. Even major new OEMs like COMAC, Byton and Nio in China are heavily reliant upon innovations developed in well-established innovative regions. Amongst new small OEMs and digital suppliers the concentration of innovative activity is, if anything, even more concentrated in established innovative regions – whether based on proximity to other digital businesses or to customers. Even where a new company appears to deviate from these tendencies, its departure can be less complete than it seems. For example, the Israeli aerospace OEM Eviation may appear to be a very long way from global aerospace innovation centres, but it has the support of a highly innovative indigenous digital sector. Furthermore, although its designs are Israeli, it test flies its aircraft in Washington State.

**Potential changes in the geography of innovation in supply chains**

Industry 4.0 technologies offer a range of opportunities for further offshoring in both sectors. For example, the exchange of vast amounts of production data has the potential to allow manufacturers to coordinate production processes in distant locations even more closely than before, and to avoid mismatches both in timing and in product specifications. This would allow experienced manufacturers to continue to export their manufacturing knowledge to lower wage economies. For example, if fully realized, the Internet of Things would allow robots at European or US car plants to communicate directly with robots at a supplier’s plants in Mexico or Indonesia to coordinate production directly without human intervention. Indeed, automotive managers expect Europe’s share of automotive manufacturing to continue to shrink further (KPMG...
2019a). Similarly, an aerospace MRO facility in Dubai or Singapore could use 3D printed components using data transmitted direct from a manufacturer in North America to repair an aircraft. The Internet of Things could allow suppliers at distant locations to make process innovations and still ensure close coordination with their customers. However, it seems likely that the impact of these changes would be primarily on the geography of manufacturing. The locus of innovation would probably remain with OEMs and established Tier 1 suppliers, so the spatial impact of these developments would be primarily on manufacturing and routine services. Telemigration offers the possibility of offshoring technology-based services to low wage economies using instantaneous translation, enhanced connectivity, Big Data, AR and VR.

On closer inspection, however, even this seems an incomplete analysis. Advances in robotics require less of the semi- and low-skilled labour which gave developing economies much of their competitive advantage. This has the potential power to alter the economics of the supply chain. If labour costs become relatively less significant, in principle then, reshoring to newly automated plants in Japan, Western Europe or North America becomes a more attractive proposition, especially when they are located in regions with a strong transport and data transfer infrastructure. If components can be manufactured nearby by robots, and requiring only a small element of very highly skilled labour, it may make little sense to manufacture them thousands of miles away using the same or similar robots, especially as the Covid crisis has demonstrated the vulnerabilities of long supply chains. PwC has recommended that ‘Manufacturers should be reviewing their supply chains and looking at where they can exert greater control, what they can bring closer to home and what technologies, such as 3D printing, can be used more to create greater agility in the supply chain’ (PwC 2020b, 10; see also PwC 2020a). This will also enhance the industries’ existing trend to operating with fewer suppliers. Furthermore, in a knowledge-based economy, competitive advantage lies primarily in people’s heads, in teams and in organizations. In general, these are more likely to be found in well-established industrial regions with sophisticated innovative ecosystems. The nature of these innovations suggests that regions whose competitive advantage lies primarily in a ready supply of cheap unskilled, semi-skilled and technician labour may be more vulnerable to advances in digitalization. Hence, these innovations could benefit those well-established automotive and aerospace regions, with strong innovatory ecosystems in Europe, Japan or North America, provided that they are not overburdened with legacy investments and cultures.

Conclusions and discussion

It is clear that Industry 4.0 technologies are having quite profound effects upon product and process developments in both automotive and aerospace. For example, the switch away from direct sales to servitization in the aeroengine market is currently having profound adverse effect on Rolls Royce because so many airliners are not flying due to the Covid crisis. It is also clear that academics, industry observers and industry insiders fully expect that Industry 4.0 technologies will have even more profound effects on both sectors in the 2020s and 2030s (e.g. the introduction of semi-autonomous and autonomous vehicles, the introduction of MaaS in major conurbations). But it is also clear that we are currently still only in the foothills of such developments, still unable to
forecast precisely the directions that innovation will take, nor to estimate with precision the technological or economic success, or otherwise, of particular innovations (e.g. autonomous cars or air taxis). This position is not unusual at this stage in the development of new technologies (e.g. it has parallels with the development of biotechnology in, say, 1990).

Furthermore, these new technologies are not simply sources of boundless innovative opportunity for firms. They also bring with them challenges and uncertainties. Advances in Industry 4.0 technologies are both potentially disruptive and expensive. Furthermore, they are not a single technology, but multiple related technologies, often developing rapidly. Hence, they involve risks, even existential risks, for firms. Levels of risk are enhanced because innovation in automotive and aerospace also involves other technologies. For example, both see innovations in engine technology as critical to their future development, as well as developments in vehicle autonomy. Finally, the economic success or failure of these innovations is not simply a technological or supply side matter. It is dependent on the societal response to them by consumers and regulators.

Despite these technological, economic and societal uncertainties, some of the ways in which Industry 4.0 is impacting on the geography of both sectors are becoming clear. In regions that are already technologically advanced firms are reinforcing their competitiveness as OEMs and leading suppliers by investing in digital technologies. In addition, these companies and their regional ecosystems act as powerful attractants to new, innovatory OEMs and to specialist digital suppliers. However, even among established players there is also an expansion of their innovatory footprint to encompass new regions which are already leaders in digital technologies (most clearly Silicon Valley), both by drawing world leading digital companies into their supply chains, and by establishing their own specialist digital research facilities in those regions. This new collaboration is complementary and enhances the competitiveness of the regions involved. The other key point of geographical diversification by established players in their desire to develop and test products that need early consumer and regulatory acceptance in major potential markets (e.g. autonomous vehicles in Berlin or Shanghai).

Digitally focused new entrants, whether OEMs or suppliers, usually choose between setting up in the strong existing aerospace and automotive regions, or locating in regions which are primarily strong in digital technologies, and so benefit from the strong local innovative ecosystem, local potential investors and a supply of highly skilled labour. There are, however, exceptions, most obviously in China, where national industrial policy and the prospect of a large home market require new entrants to set up domestically. Here, though, there is a difference between aerospace and automotive. Chinese aerospace companies design and build aircraft domestically, though they draw heavily and critically on overseas suppliers. Chinese automotive companies manufacture at home, but often conduct R&D and design in innovative regions abroad. However, both Chinese automotive and Chinese aerospace illustrate a key finding of this study. Currently, whilst manufacturing may be globally dispersed, leading edge R&D and design tends to be more focused on established regions with strong innovative ecosystems, whether based on aerospace, automotive or digital technologies. The future geography of manufacturing is potentially more uncertain. Whether supply chains continue to be located offshore, or are subject to reshoring, depends upon the continued progress of digital technologies (notably to support the Internet of Things), the digital and
managerial capabilities of firms in dispersed supply chains, and OEMs’ appetite for supply chain risk.

These findings are not only relevant to these two industries. They raise issues relevant to the analysis of the technological, economic and spatial impacts of Industry 4.0 technologies on other sectors especially, but not only, in manufacturing. In particular, they demonstrate: the need to understand Industry 4.0 technologies within the context of the other sector-based technologies with which they are applied; the impact of sectoral histories and company legacies upon their capacity to use Industry 4.0 technologies; the continuing prominence of well-established knowledge-based, regional ecosystems and their capacity to co-opt new technologies, whether locally or from elsewhere; the capacity for new centres of regional excellence to develop based on digital technologies; and that Industry 4.0 technologies are still at quite an early stage in their development so that much about them remains uncertain.

Notes
1. Predicting the collective future impact of a wide variety of interconnected technologies like Industry 4.0 is intrinsically uncertain. Whilst very broad directions of travel for both sectors are relatively clear, it is also evident at the time of writing (December, 2020), that the economic consequences of the Covid 19 virus pandemic have added further layers of uncertainty – most obviously for aerospace given the projected 3–5 year dip in passenger numbers.
2. For example, General Electric uses 3D printing to make weight saving shapes (e.g. voids) that are difficult to make using conventional manufacturing.
3. For example, in 2017 most UK aerospace companies were introducing digital technologies incrementally, rather than as a basis to transform their businesses, Aerospace Technology Institute 2018. See also Maisonneuve et al. 2013.
4. For example, a third of European automotive sector companies lack confidence in their ability to the necessary recruit talent (KPMG 2019a).

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