Department for
Business, Energy
& Industrial Strategy

THE ECONOMIC IMPACT OF ROBOTICS & AUTONOMOUS SYSTEMS ACROSS UK SECTORS

Final Report

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The views expressed in this report are those of the authors, not necessarily those of the BEIS, nor do they reflect Government policy.

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Glossary

Artificial Intelligence: The term artificial intelligence (AI) is used to describe machines or computers that can learn and adapt from experience and mimic cognitive functions (Russell & Norvig, 2009).

Automated Guided Vehicles (AGVs): An automated guided vehicle (AGV) is a wheel-based robot that uses carts, pallets or trays to move goods. AGVs are programmed to move between different locations without a driver. They are most often used in industrial applications to transport heavy materials (Knell, 2019).

Automated Storage and Retrieval System (ASRS): Automated storage and retrieval system (ASRS) refers to a variety of computer-controlled systems for automatically placing and retrieving loads from defined storage locations. They are most commonly used in manufacturing and distribution facilities (MHI, 2020).

Autonomous Vehicles (AVs): An autonomous vehicle (AV), or a driverless vehicle, is one that is able to operate itself and perform necessary functions without any human intervention, through ability to sense its surroundings (TWI, 2020). Semi-autonomous vehicles incorporate some autonomous features such as autonomous steering, acceleration or stopping, but continue to require a human driver.

Collaborative Robot (Co-Bot): “Collaborative robots are articulated robots specially designed to interact with human workers in a shared workplace” (ABI Research, 2020b).

Eight Great Technologies: In autumn 2012 the Chancellor highlighted ‘eight great technologies’ which will propel the UK to future growth and where the UK can lead the world, announcing an additional £600 million investment to support their development. The eight technologies are big data, satellites and commercial applications of space, robotics and autonomous systems, synthetic biology, regenerative medicine, agri-science, advanced materials and nanotechnology and energy and its storage (Department for Business, Innovation & Skills , 2013).

Exoskeletons: A (powered) exoskeleton is a wearable mechanical device that work in tandem with the user, allowing for limb movement with increased strength and endurance (Exoskeleton Report, n.d.).

Industry 4.0: Industry 4.0 refers to fourth industrial revolution which can be described as the advent of cyber-physical systems involving entirely new capabilities for people and machines (Davis, 2016). The focus of Industry 4.0 is automation, machine learning, big data and the interconnectivity of people and robotics (Epicor, 2020).

Mobile Robot: A mobile robot can locomote within an environment or terrain (Encyclopedia.com, 2020). According to ABI Research (2020b), “[t]he most important distinction between mobile robots is between automated guided vehicles (AGVs) which require external infrastructure to move, and autonomous mobile robots (AMRs) that can navigate an environment without the need for external infrastructure. Many robots are remotely-operated, but have a high degree of autonomy and operate at least partially without the need for fiducial markers or magnetic tape and are, therefore, classed as AMRs”.

Remotely operated vehicles (ROVs): A remotely operated vehicle (ROV) is an underwater vehicle which is usually tethered. ROVs are unoccupied, usually highly maneuverable and fitted with sensors, lights and sampling tools. They are typically operated by a crew either on proximate land or a vessel (Dasgupta, 2019).

Robot shipments: Robot shipments refer to units sold.

Robotic Process Automation (RPA): Robotic Process Automation (RPA) uses software to capture and interpret existing IT applications to enable transaction processing, data manipulation and communication across multiple IT systems (Deloitte , 2020).

Rover: A rover (usually used in the context of space exploration) is a vehicle for driving over rough terrain, which can be partly or fully autonomous and may be driven by remote control (Lexico, 2020a)

Soft robotics: Soft robotics is the specific subfield of robotics dealing with constructing robots from highly compliant materials, similar to those found in living organisms (Trivedi et al. 2008). Soft robotics are often used for manipulating and grasping fragile objects like crops and other food products (Srivastava, 2020).

Swarm robotics: Swarm robotics is the use of large numbers of relatively simple robots to collectively solve problems. The behaviours of these robots are usually coordinated in a decentralised manner and their structures sometimes mimic those observed in natural systems, such as swarms of bees, birds, or fish (Schranz, Umlauft, Sende, & Elmenreich, 2020).

The Internet of Things: The Internet of things (IoT) describes the interconnection via the internet of computing devices embedded in everyday objects, enabling them to send and receive data without requiring human-to-computer interaction (Lexico, 2020b).

Executive summary

In May 2020, BEIS commissioned London Economics (LE) to undertake an assessment of the economic opportunities of robotics and autonomous systems (RAS) across UK sectors. This study will enable BEIS to understand where the key future economic opportunities lie for RAS uptake across the wider economy.

What is RAS?

There is no single agreed definition for RAS, with definitions continuing to evolve as the technology develops over time. However, for the purpose of this study a useful description of RAS is provided by BEIS:

> Definition: Robotics and Autonomous Systems (RAS)
>
> Robotics and autonomous systems (RAS) include machinery and physical systems that can act independently of human control, by sensing, reasoning and adapting to a given situation or environment. In contrast to more traditional machines that have a single, pre-determined purpose, RAS applications are able to understand what is happening in their sphere of operation and tailor their behaviour to particular circumstances with varying degrees of decision-making autonomy.

Source: BEIS

The scope of this research covers RAS applications with a physical dimension in a commercial setting, excluding robotic process automation and other digital-only solutions, as well as smart home devices.

Background

RAS has the potential to bring about significant economic impacts: the annual global economic impact of advanced robotics is estimated to lie between $1.7 to $4.5 trillion per annum by 2025 (McKinsey, 2013). According to more recent estimates, boosting robot installations 30% above the baseline could add an extra $4.9 trillion per year to the global economy by 2030 (Oxford Economics, 2019). While estimates of future impacts are naturally surrounded by significant uncertainty, these figures highlight the magnitude of the potential RAS opportunity.

In contrast to previous waves of robotics, which were mostly focused on industrial applications, RAS has the potential to impact a much wider range of sectors, with use-cases and opportunities emerging across the economy. These include, for instance, automated guided vehicles, mobile retail robots, and humanoid customer service robots.

RAS also offers a potential solution to key challenges to the UK's continued economic growth:

- In the UK, productivity is lower than in many peer economies such as the United States, France and Germany (King, 2019 based on OECD statistics). Moreover, productivity growth in the UK has been sluggish since the 2008/09 recession (ONS, 2015; see also ONS, 2020a).

- In addition, growth in labour productivity will be needed if growth in living standards is to be sustained, given that the UK has an ageing population and a low birth rate (see e.g. Government Office for Science, 2016).

Productivity increases from RAS can help mitigate these challenges by reducing the number of human work hours needed to produce a given output, as well as by freeing up workers for higher value tasks.

However, unlocking the potential economic benefits of RAS is not straightforward. The UK failed to capitalise on the opportunities presented by the previous wave of industrial robotics, with the use of industrial robots in the UK lagging behind other nations.[1] Moreover, recent research by Boston Consulting Group (BCG) (2019) suggests that there is a significant gap between companies' ambitions to implement advanced robots and actual implementation. More than 90% of the companies surveyed by BCG reported that at least one of three key enablers – including a complete vision of their future operations, sufficient knowledge of and training with RAS and related issues, and the development of a system architecture to support future operations – was not fully present in their company (ibid.).

It is therefore encouraging that RAS has, over the last decade, increasingly been recognised as a priority area by government. For instance, in 2013 RAS was identified as one of the "Eight Great Technologies" where the UK could have a leading global position. In the Government's 2017 Industrial Strategy (UK Government, 2017a), the opportunities presented by robotics, in conjunction with other digital technologies such as artificial intelligence and data analytics, were again acknowledged.

However, in order to inform potential policy interventions to stimulate RAS adoption within particular sectors, it is important to understand where the key future economic opportunities exist for RAS uptake across the wider economy. Moreover, RAS also has the potential to support other government priorities, including Net Zero, and provide wider benefits such as an increase in safety for workers, and to replace mundane, repetitive tasks. Understanding these wider impacts is also key to making informed policy choices.

Study objective and sectors considered

Given this background, this study sought to provide a robust evidence base to answer the following overarching research question:

What is the potential future economic opportunity of RAS adoption across UK sectors?

Desk-based research was conducted to determine an initial longlist of 14 sectors to be included in the study. A range of criteria were then applied to identify a final shortlist of seven sectors, including the size and growth of the industry, the maturity of RAS applications, and evidence of potential future uptake of the technology. The sectors selected were:

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[1] Data from the International Federation of Robotics shows that industrial robot installations in the UK are relatively low when compared to the likes of Germany, the US, or China: Around 2,500 industrial robots are estimated to be installed in the UK in 2020 (0.5% of an estimated world total of 520,900). This compares to estimates of around 6,000 (1.2% of world total) in France, 8,500 (1.6%) in Italy, 25,000 (4.8%) in Germany, and 55,000 (10.6%) in the US, and 210,000 (40.3%) in China.

- Agriculture
- Construction
- Energy
- Food & drink
- Health & social care
- Infrastructure
- Logistics

Having selected these sectors, a quantitative analysis of the future economic opportunity of RAS deployment across each industry was undertaken. This quantitative analysis began by estimating RAS adoption levels across the economy and in each of the selected sectors, based on forecasts of robot shipments by ABI Research. It then estimated the economic opportunities from RAS in each selected sector given current adoption trends, in terms of productivity improvements, reductions in employment needs and impacts on GVA. It also assesses the size of the “automation gap” – the gap between estimated future adoption and automation potential – in the selected sectors, and considers to what extent the barriers to RAS adoption in each sector can be addressed through policy.

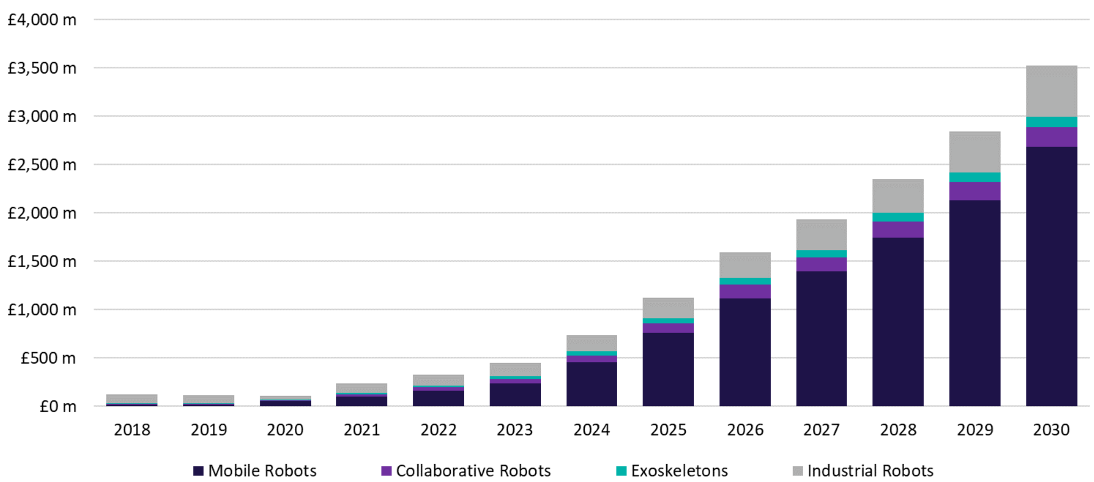
The remainder of the executive summary summarises the key findings of this study.

Trends of RAS uptake

Analysis undertaken for this study estimates, based on ABI Research (2020a) robot shipments (units sold) forecasts, that the total UK RAS market will grow at a compound annual growth rate of more than 40% per annum between 2020 and 2030, reaching an estimated market size of almost £3.5 billion by 2030.

A significant proportion of this growth is expected to be driven by the rise in mobile robots (defined as robots that can navigate an environment without the need for external infrastructure). Data for mobile robot shipments was not directly available from ABI Research. However, if UK shipments follow a similar trend to the European market as a whole, the mobile robot segment is poised to experience the most significant growth; from an estimated level of around 1,500 shipments per annum in 2020 to over 90,000 annual shipments by 2030.

Estimated total UK robot market, by 2030, size based on current trends



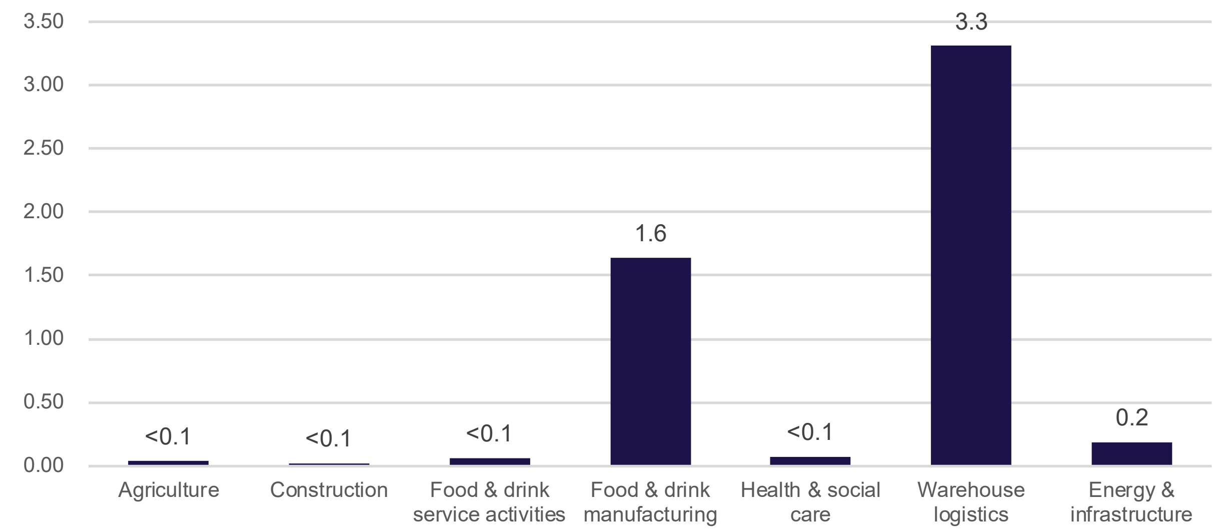
Note: Converted to Sterling using the 2018 Bank of England exchange rate. Data for mobile robots estimated, by London Economics, from estimated shipments of mobile robots and global unit revenue. **Source: London Economics’ analysis of ABI Research (2020a)**

Sectoral trends of RAS uptake

While the estimated growth in future robot shipments (see previous Figure) is significant, this growth should be seen in light of a relatively low base, with robots in UK industry historically lagging behind other nations (see e.g. International Federation of Robotics, 2018). Moreover, estimates of the economy-wide uptake mask significant variation across UK sectors.

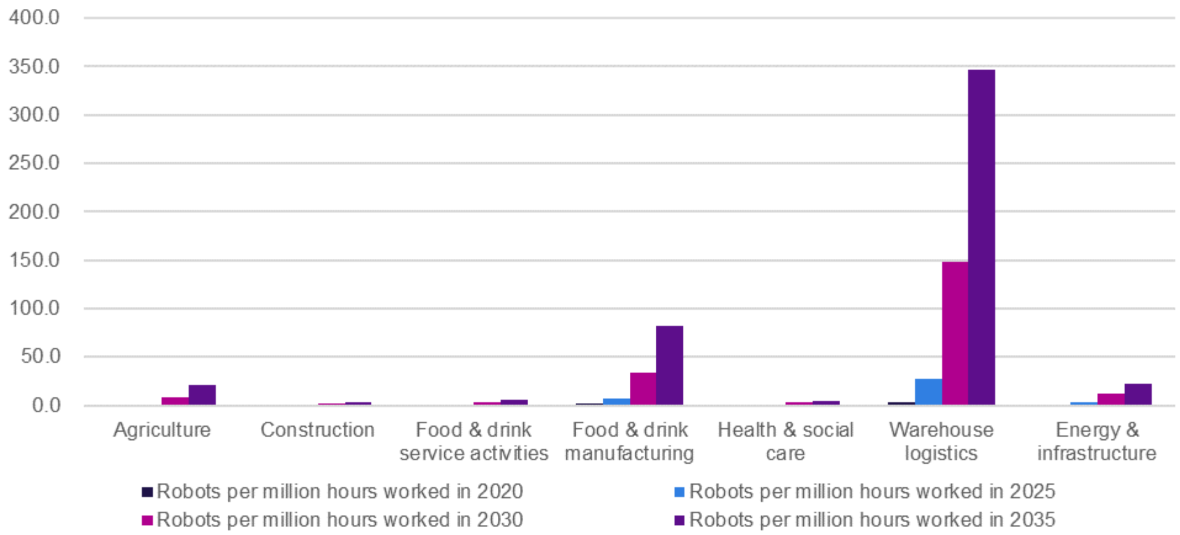
The analysis undertaken for this study suggests that uptake may be concentrated in some industries. Estimates of current robot density (robots per million hours worked) for the sectors selected highlight significantly stronger uptake in the warehouse logistics and food & drink manufacturing sector compared to other industries. Estimates of future uptake also suggest that this concentration is expected to continue over the period being assessed.

Estimated current robot density (robots per million hours worked)



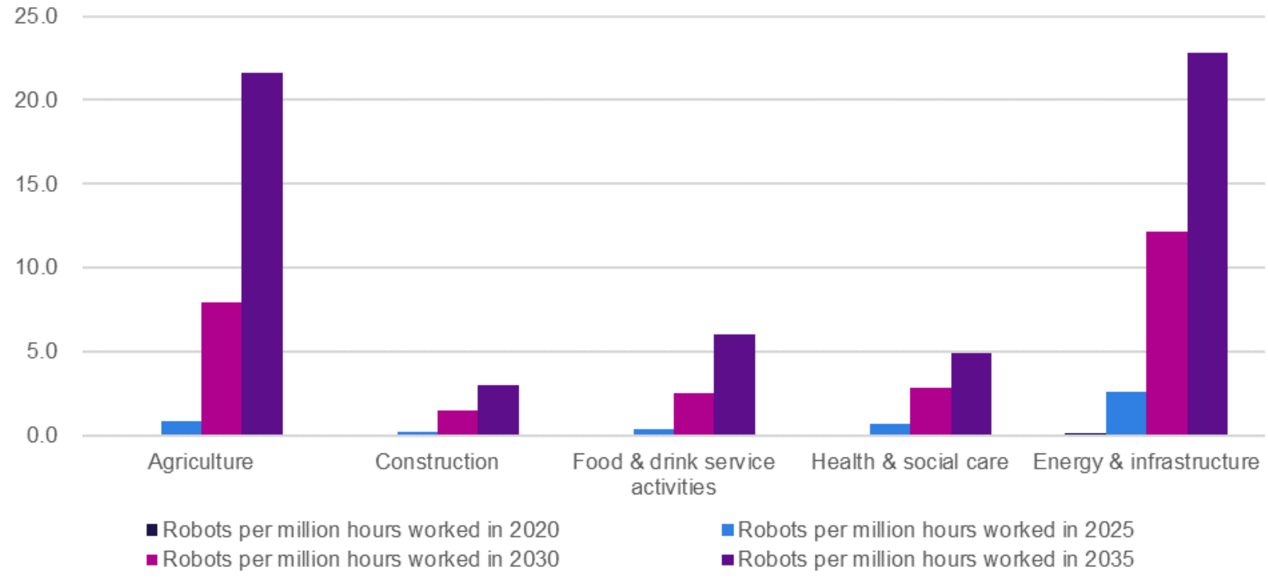
Note: The figure shows estimated number of robots per million hours worked, given estimates of current adoption of RAS across UK sectors. **Source: London Economics' analysis**

Estimated future robot density on current trends



Note: The figure shows estimated number of robots per million hours worked under baseline, given estimates of future adoption trends. **Source: London Economics' analysis**

Estimated future robot density on current trends (excl. warehouse logistics and food & drink manufacturing)



Note: The figure shows estimated number of robots per million hours worked under baseline, given estimates of future adoption trends. **Source: London Economics' analysis**

Economic impact of RAS uptake across sectors

In order to translate estimates of future RAS uptake into economic benefits, the analysis combined RAS uptake estimates with economic baseline scenarios for each sector, and with assumptions of the potential productivity benefits and level of displacement that RAS may generate. A brief overview of the methodology used, and assumptions made, can be found in the methodological annex at the end of this report. A separate methodological note accompanying this report provides further details.

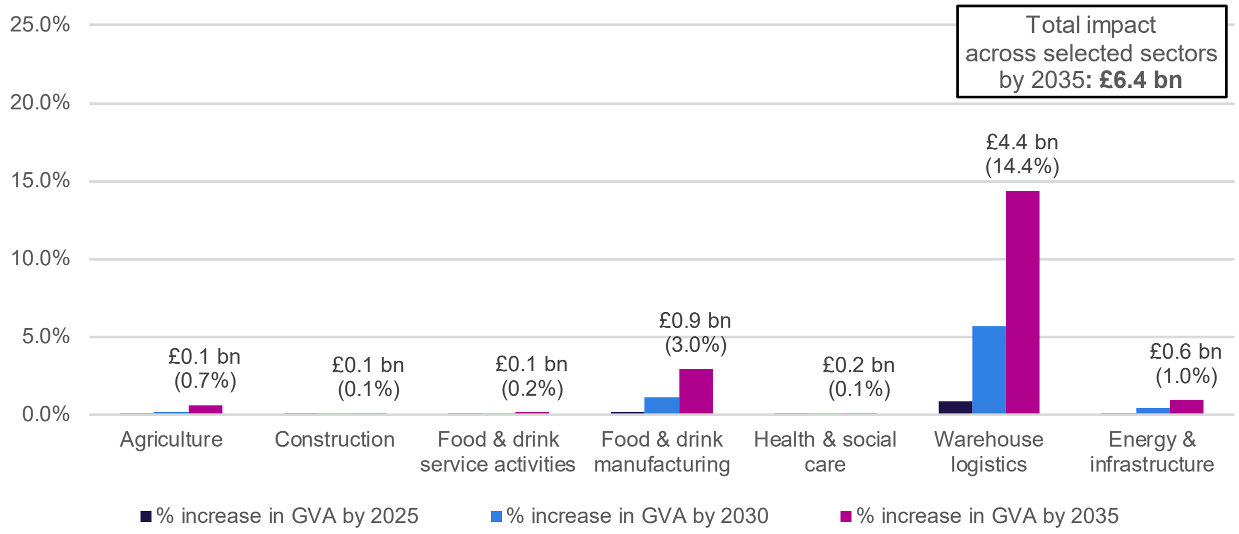
Based on this analysis, the **total economic impact of RAS uptake across all selected sectors** is estimated to be in the region of **£6.4 billion** by 2035 (based on current adoption trends). The figures overleaf show how this impact is distributed across selected sectors, as well as how the impact is expected to evolve over time.

Given the significantly higher estimated adoption of RAS in **warehouse logistics**, this sector is expected to see the most sizeable increase in value-added of approximately **14% (£4.4 billion)** of baseline value-added by 2035. Similarly, the impact of RAS in **food & drink manufacturing** is estimated to reach around **3% (£0.9 billion)** of baseline value-added by 2035.[2]

Given the relatively low levels of estimated future RAS uptake, impacts in other selected sectors are estimated to be more modest when compared to warehouse logistics and food & drink manufacturing (under current adoption trends). The productivity increases associated with these trends are also estimated to be relatively modest for most sectors.

[2] Note due to their continued importance in this segment, industrial robots were included in the estimation of robot density, and therefore impact, in the food & drink manufacturing sector. The expected comparatively larger role of industrial robots should therefore be kept in mind when interpreting the results.

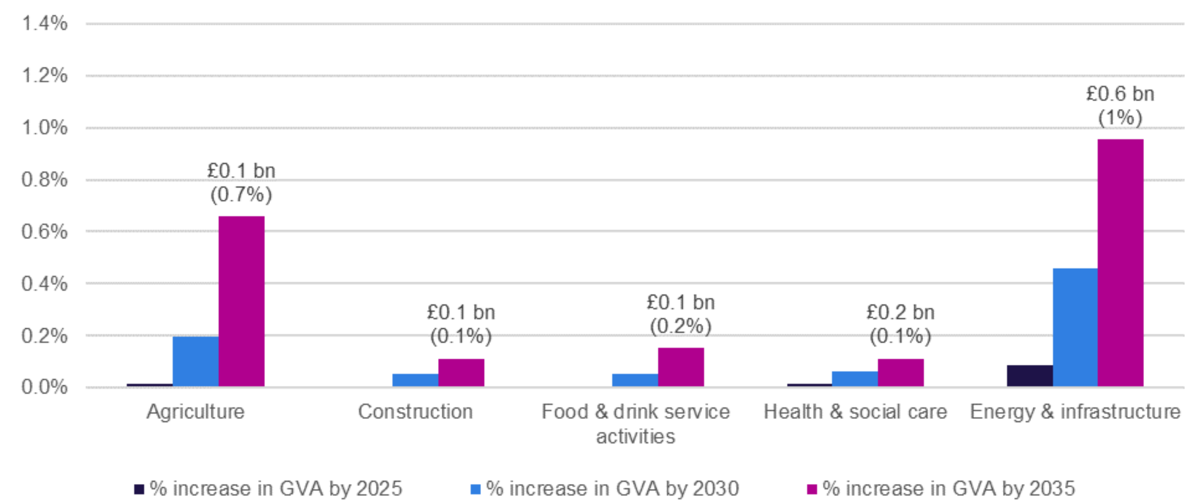
Estimated increase in value added



Note: The figure shows the % increase in gross value added relative to baseline, given estimates of future adoption trends and displacement assumptions made.

Source: London Economics' analysis

Estimated increase in value added (excl. warehouse logistics and food & drink manufacturing)



Note: The figure shows the % increase in gross value added relative to baseline, given estimates of future adoption trends and displacement assumptions made.

Source: London Economics' analysis

A more detailed summary for each selected sector, focusing on the expected uptake and associated economic impacts, as well as select use cases highlighting where key opportunities lie, is provided overleaf:

Warehouse logistics	**Uptake and impact:** Warehouse logistics is expected to experience the strongest uptake of RAS on current trends. Robot density in the warehouse logistics sector is estimated to grow from 3.3 robots per million hours worked in 2020 to 27.2 robots over the next five years, to 147.8 robots over the next decade, reaching 346.7 by 2035. Results of the quantitative analysis undertaken for this study suggest that uptake of this magnitude could translate to labour productivity increases of around 23.3% relative to the baseline (see methodological annex below) with the potential to add around 14.4% to GVA relative to baseline by 2035. **Opportunities:** Examples of RAS in the logistics sectors include lifting, picking, and sorting stored items. In RAS-equipped warehouses, robots controlled by a central computer can automate large parts of warehouses, greatly increasing warehouse efficiency and productivity. RAS can also be used in the logistics supply chain to automate the packaging process, as well as in the wider logistics sector, for example, via autonomous vehicles or last-mile delivery via drones (though challenges such as regulations on airspace, package weights, and the low margins in the industry remain).
Food & drink manufacturing	**Uptake and impact:** Food & drink manufacturing may also see significant benefits from increased RAS uptake. While the sector already sees higher levels of automation than other selected sectors (with the exception of warehouse logistics), the variability of food items has caused difficulties for RAS to grip and handle them, meaning that automation levels remain lower than in other manufacturing sectors such as automotive. Developments in soft robotics are changing this, and adoption of RAS is increasing within food & drink manufacturing. Robot density in the food & drink manufacturing sector is estimated to increase from 1.6 robots per million hours worked in 2020, to 6.9 in 2025, and to 34.1 by 2030, and is estimated to rise further to 82.3 by 2035. Associated economic impacts are estimated to be more modest compared to the warehouse logistics segment, with productivity estimated to increase by around 4.6% relative to the baseline by 2035, raising GVA by an estimated 3.0% relative to the baseline.[3] **Opportunities:** RAS in food & drink manufacturing can be adopted in the form of food packaging and manufacturing robots, which can automate picking, packaging, and preparation of food products. RAS applications also include advanced grippers enabling quick but gentle handling of fragile food products, such as soft fruit and vegetables. The sector also overlaps with food and drink services, as well as agriculture. Despite increasing RAS use-cases, 'traditional' industrial robots are expected to continue to remain important in the manufacturing sector. Industrial robots are estimated to account for approximately one-third of annual robot shipments to UK food & drink manufacturing in 2030.

[3] Note due to their continued importance in this segment, industrial robots were included in the estimation of robot density, and therefore impact, in the food & drink manufacturing sector.

Energy & infrastructure	**Uptake and impact:** The energy & infrastructure sectors are estimated to experience later uptake of RAS, with robot density estimated to remain below 3 robots per million hours worked by 2025. However, this is estimated to rise to 12.2 by 2030 and to 22.9 by 2035. As a result, associated productivity impacts are estimated to be relatively modest, reaching approximately 1.3% relative to baseline by 2035. This is estimated to translate to GVA impacts of 1%, relative to baseline, by 2035. **Opportunities:** Use cases in the energy & infrastructure sectors include repair and maintenance of infrastructure assets such as pipes, cables and roads, as well as in difficult or dangerous locations. These include inspection at height (e.g. of bridges or towers), or maintenance works in extreme environments (including off-shore oil rigs, off-shore wind farms, and deep-sea oil pipelines, as well as applications in nuclear decommissioning), thus improving worker safety.
Agriculture	**Uptake and impact:** Agriculture is also estimated to see a later increase in robot density, with robot density remaining below 1.0 robot per million hours worked by 2025, increasing to around 8.0 robots per million hours worked by 2030 and further to 21.6 robots per million hours worked by 2035. Associated productivity increases are estimated to be in the region of 0.9% relative to baseline by 2035, adding an estimated 0.7% to GVA relative to baseline. **Opportunities:** RAS use cases in the agricultural sector include crop harvesting and fruit picking robots, weeding and phenotyping, precision agriculture, as well as use cases in wider livestock management, in addition to dairy farming which is already highly automated. Adopting RAS in agriculture can reduce the use of pesticides, herbicides and fertilizers, which have well-documented negative impacts on ecosystems and biodiversity, as well as reduce greenhouse gas emissions. Use cases in the sector also benefit from synergies with advances in other technologies. For example, the combined benefits of electrification (e.g. replacing large diesel tractors with electric motors), artificial intelligence, satellite tracking for earth observation and the deployment of autonomous robots. As mentioned above, the agricultural sector also overlaps, and has synergies, with the wider food and drink sector.
Construction, food & drink services, and health & social care	**Uptake and impact:** Impacts on the construction, food & drink services, and health & social care sectors are estimated to remain relatively modest under current adoption trends. Robot density is estimated to reach, by 2035, only 3.0 robots per million hours worked in the construction sector, 6.0 in the food & drink services sector, and 4.9 in the health & social care sector. Associated labour productivity increases and GVA impacts for these sectors are estimated to reach between only 0.1% and 0.2% relative to baseline by 2035. This suggests that roles involving complex tasks or operating environments, with lots of human contact, will largely be undertaken by people. RAS in these environments may be more limited to specific, niche roles that augment the work of humans.

Opportunities: Nevertheless, important use cases for RAS in these sectors exist; including:

- In health & social care, use cases include robot-assisted surgery, robotic nursing and disinfectant robots. Critically, while economic impacts in healthcare may be more modest, the application of RAS could lead to vast improvements in patient outcomes such as improved accuracy of diagnosis, improved precision in surgical interventions, and the reduction of negative outcomes for patients. Nepogodiev et. al. (2019) estimate that at least 4.2 million people worldwide die within 30 days of surgery each year, more than from all causes related to HIV, malaria, and tuberculosis combined (2.97 million deaths). Similarly, in social care and nursing multiple use cases exist where RAS can improve patient experiences. For example, RAS can reduce the strain on caregivers and nurses by helping to lift patients, schedule appointments, monitor patient vitals, and provide new forms of patient care.

- In construction, robots could be used for off-site prefabrication of components or indeed entire structures, for the demolition of buildings, in site surveying and mapping, as well as supporting workers lifting heavy items by utilising powered exoskeletons – bringing potential accuracy, efficiency and safety benefits.

- RAS applications in food & drink services may be less obvious, but interesting use cases include food & drink preparation robots and robot waiting staff. RAS applications in services could bring particular benefits in the automation of repetitive tasks (such as baking, sandwich making, etc.) as well as in reducing the need for humans to work within close proximity (e.g. kitchens and canteens) – an area that is perhaps particularly pertinent given the ongoing challenges resulting from COVID-19 and the associated social distancing restrictions. The sector also overlaps with, and has synergies with, the wider food and drink sector and the agricultural sector.

Wider impacts

In addition to the economic impacts described above, RAS also has the potential to bring about significant wider socio-economic impacts. These wider impacts include:

Creation of jobs along the supply chain:

- In addition to the direct creation of jobs, increased RAS activity can lead to the creation of new roles along the supply chain (e.g. in the design, manufacturing, maintenance and integration of these systems).

Wider economic impacts:

- RAS also leads to economic impacts in other sectors and across the economy. For example, by enabling a given stock of goods or services to be produced more efficiently, it means that economic resources are freed up to deliver other goods and services.

R&D and scientific research:

- R&D in RAS leads to new innovations, increases knowledge, fosters the UK's leadership role and international recognition, and leads to economic spillover impacts.

International competitiveness and standing of UK:

- International recognition of the UK as a leading RAS nation leads to a number of benefits, such as FDI and the attraction of companies and talent.

Development of adjacent technologies:

- RAS is complementary to, and interconnected with, other key technologies such as artificial intelligence, sensor technology and the 'internet of things', as well as batteries and materials. Advances in RAS are thus also likely to lead to further development of these connected enabling technologies, and vice versa.

Skills development and training:

- The development and deployment of RAS requires highly skilled workers, such as engineers. This leads to the need to train new workers and upskill the existing workforce, and associated benefits such as higher wages, improved job security and satisfaction, and ultimately a more productive workforce, as well as safer, more attractive jobs in industries that have struggled to attract workers.

Better consumer experience and increased welfare:

- RAS enables a better consumer experience and increased welfare from new, improved, or cheaper products and more personalized and/or flexible services. RAS also brings safety benefits, particularly in hazardous environments.

Improvements in resilience:

- RAS may also bring about significant improvements in resilience across UK sectors, making businesses more able to withstand and recover from exogenous shocks such as the recent COVID-19 pandemic and associated lockdown measures. RAS can enable resilience to climate change and extreme weather; resilience to labour shortages; as well as higher operational flexibility and resiliency to fluctuations in demand.

The adoption of RAS will also have distributional impacts. Those who primarily perform tasks that are complemented by RAS, and who work in a job for which labour supply is inelastic with respect to wages and the demand for outputs is elastic with respect to income, are likely to see a greater benefit than those for whom the opposite is true (Autor, 2015). A detailed assessment of the distributional implications of RAS is beyond the scope of this study.

The size of the automation gap

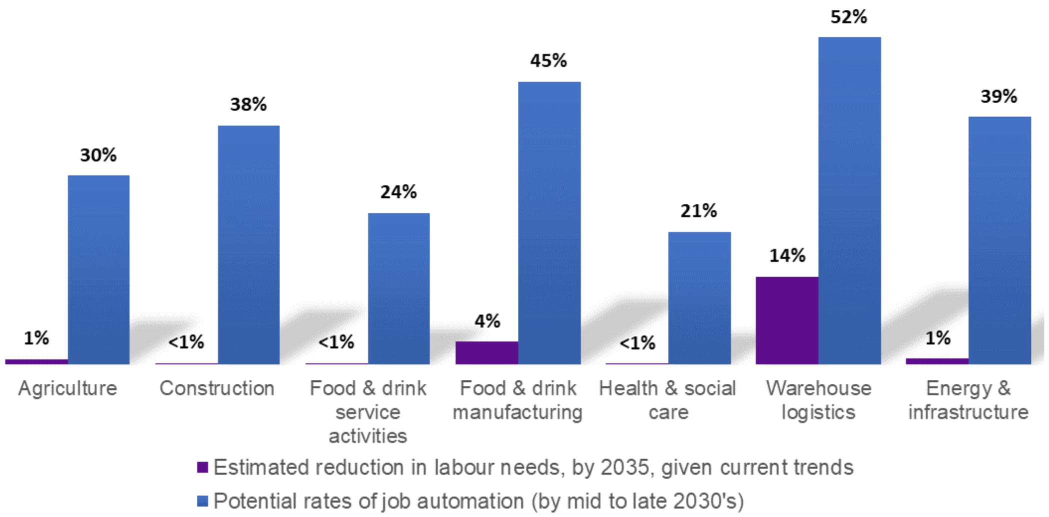
As the quantitative analysis makes clear, most of the sectors selected for this study are unlikely to see significant levels of RAS adoption if current trends continue. At the same time, the qualitative analysis has shown that significant potential for RAS uptake exists across all selected sectors. This section therefore seeks to understand the size of the gap between both the estimated and potential rates of future RAS adoption in each sector.

The first figure below compares the estimated and potential rates of automation across individual sectors. It compares the proportion of jobs that are expected to be automated given current trends, with the proportion of jobs that could technically be automated (see box below for further details on this comparison).

Based on these estimates, the second figure compares the estimated gross value added (GVA) contribution that could be achieved by 2035, given current adoption trends (using the results of the analysis undertaken for this study), with the potential GVA contribution that could be achieved if the full automation potential was to be reached.

The figure again highlights the sizeable gap between estimated impacts under current adoption trends (i.e. what could be achieved if adoption follows current trends) and the potential impacts that could be achieved based on the technical feasibility of automation alone (i.e. what could be achieved under full automation).

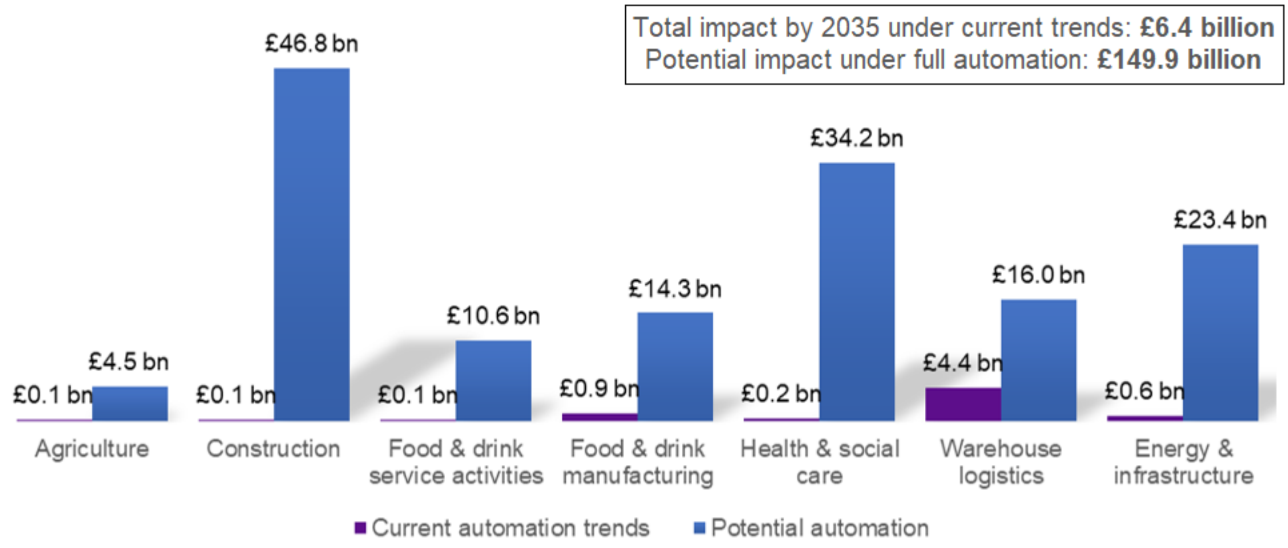
Estimated vs. potential rates of automation across sectors



Note: The figure compares the estimated reduction in labour needs by 2035, given current estimates of future RAS adoption, and the potential rates of job automation in each selected sector. The potential rates of job automation across sectors is based on PwC (2018b).

Source: London Economics' analysis.

The size of the prize: Potential value of GVA that could be attributable to RAS, by 2035, if potential rates of automation were achieved



Note: The figure provides, for each selected sector, an approximation of the potential GVA attributable to automation, by 2035, if potential rates of automation were achieved. These approximations are the result of a simple calculation multiplying 2035 baseline GVA by the potential rate of automation from PwC (2018b).

Source: London Economics' analysis

The following points are worth highlighting in particular:

- The comparison suggests that up to 38% of tasks in the **construction** sector could be automated, equivalent to an estimated £45 billion of 2035 construction sector GVA. As discussed previously, opportunities in the construction sector range from off-site prefabrication of components and entire structures, to the demolition of buildings, in site surveying and mapping, as well as supporting workers lifting heavy items by utilising powered exoskeletons. However, current trends suggest that RAS adoption in the construction sector will remain low, with less than 1% of tasks estimated to be automated by 2035, equivalent to only around £0.1 billion of construction GVA.

- Similarly, significant opportunities for RAS adoption exist in the **health & social care** sector. While only around 21% of tasks in the industry could feasibly be automated by 2035, the size of the sector means that automation on this scale could translate to nearly £35 billion of GVA. However, under current trends RAS adoption is expected to result in automation of less than 1% of health & social care tasks, equivalent to around £0.2 billion of GVA. While economic impacts in the sector may remain small, RAS adoption can also generate human impacts – for example, surgical robots improving the accuracy of diagnosis and reducing negative outcomes for patients.

- The comparison suggests that up to 52% of tasks in the **warehouse logistics** sector could technically be automated by 2035, equivalent to an estimated £16 billion of GVA. Under current trends, however, RAS adoption is expected to result in the automation of 14% of tasks in the sector by 2035 (less than a third of the potential fraction), equivalent to an estimated £4.4 billion of GVA. Therefore, while the economic impact of RAS in this sector is expected to be significant, it is less than one third of the impact that could be achieved if its automation potential was reached.

- The comparison suggests that up to 39% of tasks in the **energy & infrastructure** sector could technically be automated by 2035, equivalent to an estimated £23 billion of GVA. Under current trends, however, RAS adoption is expected to result in the automation of just 1% of tasks in this sector, equivalent to an estimated £0.6 billion of GVA. This indicates a significantly lower economic impact of RAS than could be achieved if its automation potential was reached. It is worth noting that no official definition of the energy & infrastructure sectors exists, meaning impacts will vary depending on the definition used[4]. The sector also has overlaps and synergies with the construction sector – meaning that some impacts counted as part of the construction sector could also be classified as infrastructure impacts.

- In the **agriculture** sector up to 30% of tasks could technically be automated by 2035, equivalent to an estimated £4.5 billion of GVA. Under current trends, however, RAS adoption is expected to result in just 1% of tasks in this sector being automated, equivalent to an estimated £0.1 billion of GVA. This also indicates a significantly lower economic impact of RAS than could be achieved if its automation potential was reached. However, as with health & social care, the agriculture sector – and the food & drinks sector – is of significant wider importance to the UK.

- In the **food & drink manufacturing** sector up to 45% of tasks could technically be automated by 2035, equivalent to an estimated £14.3 billion of GVA. Under current trends, RAS adoption is expected to result in the automation of 4% of tasks in this sector, equivalent to an estimated £0.9 billion of GVA. Therefore, while the economic impact of RAS in this sector is expected to be significant relative to other sectors, it is a small fraction of the impact that could be achieved if its automation potential was reached. Combining the potential impact across the agriculture, food & drink services, and food & drink manufacturing sectors, suggests that the total impact of automation in **food & drink** could be up to nearly £30 billion if its automation potential were to be reached by 2035.

Barriers to adoption: The feasibility of policy interventions for addressing the automation gap

Whether, and to what extent, policy interventions may be fruitful in raising the level of adoption in a sector depends, at least to some extent, on the nature of the barriers (though it should be noted that these do not mechanically drive the estimated impacts). Barriers to RAS adoption take a number of forms, including – but not limited to – regulatory, financial, and skills-related barriers. The form of barriers and their extent will vary between sectors. Sectors where barriers are mostly related to issues that are more readily addressable by policy, such as regulation, are more likely to benefit from policy interventions than sectors with significant structural barriers.

A detailed analysis of challenges and barriers faced by selected sectors was not part of the study scope. The Made Smarter Review, an independent report for BEIS published in 2017, contains a more detailed discussion of barriers to the adoption of industrial digital technology in UK manufacturing industries. However, the importance of the nature of barriers for RAS uptake means that this report would not be complete without at least some discussion on the barriers faced in selected sectors. Therefore, we provide here a brief analysis of the extent to which

[4] Note the sector was assumed to be equivalent to the electricity, gas, steam (D) and water supply, sewerage and waste management (E) sectors – see methodological annex.

identified barriers in selected sectors (as discussed in the qualitative chapter of each sector) may be addressable through policy interventions:

- **Agriculture:** Identified barriers in the agricultural sector include drone regulation; digital skills shortages; and problems with research and testing. These barriers include both barriers that are readily policy-addressable and barriers that are less so. Policy can quite readily address the identified barriers relating to farmers' inability to make use of RAS technology. Specifically, policy interventions improving rural broadband and 4G and 5G access, as well as digital skills, could be put in place. While low margins faced by many UK farms are difficult to address with policy, a potential policy solution to this barrier could be the provision of loans on favourable terms to farms seeking to purchase or rent RAS. Policy could also be used to address the lack of coordination of RAS research in agriculture. However, policy cannot feasibly address the small size of UK farms and the unpredictability of UK weather, which hamper the achievement of economies of scale and generate technical challenges for RAS (see the qualitative assessment of the economic opportunities from RAS in agriculture below for more detail).
- **Construction:** Barriers in the construction sector were identified to be less readily addressable by policy. They include: a fragmented industry with low margins; technical barriers associated with working in complex environments on complex tasks; barriers related to human-robot interaction; as well as cultural barriers. Digital skills shortages are also affecting the sector. It is harder for policy to change the fact that there are technical challenges associated with the nature of the construction industry. However, policy makers could help address this barrier by funding R&D in RAS in construction. Policy interventions could also be used to address the skills gap and demographic barriers in the construction sector (e.g. by facilitating digital skills training). However, addressing structural characteristics of the sector will be difficult to achieve via policy interventions.
- **Energy and infrastructure**: The energy and infrastructure sectors encompass a wide array of different segments (such as offshore wind, oil & gas, nuclear, etc.), each facing their own distinct challenges. Nevertheless, major challenges include risk aversion in the sector and high standards for validation, driven by the critical nature of tasks and resulting high stakes of failure across many segments, as well as technical challenges presented by the complexity of energy and infrastructure projects. Policy cannot remove these barriers immediately, but it can support the proper networks and funding of research and development aimed at solving these challenges. Moreover, policy can also help by addressing the need for safety validation and the establishment of the right legal frameworks.
- **Food & drink**: Barriers to RAS adoption in food & drink manufacturing include the need for soft robotic technology capable of handling fragile packaging, and the need for robots that can withstand sanitisation procedures. Policy measures that can address this are likely to be limited to those supporting testing and research into solutions to the relevant problems. There are also barriers relating to the supply of labour: the incentive to adopt RAS is tempered by the ready availability of labour, and the adoption of RAS brings with it additional skill requirements. In the hospitality side of the food & drink sector, barriers include a need for RAS to be able to interact with humans and to be flexible in accommodating dietary requirements, etc. These are largely technical challenges, to which the feasible policy response is likely to be funding R&D and supporting other research and testing.

- **Health & social care**: Barriers in the health & social care sector are diverse. They include the continued high cost of RAS; restrictive patents; and difficulties with interoperability with existing NHS systems. Other barriers include negative views of RAS from professionals and patients, including a lack of trust; and ethical and legal challenges, including a lack of clear, established liability rules. Many of these barriers are difficult to address with policy. For instance, the ethical concerns around the use of RAS cannot readily be removed by policy, though information campaigns might be used to assuage ethical concerns that are based on misconceptions about RAS. The cost of RAS is also difficult to address by policy beyond providing support for the development of cheaper RAS solutions. However, technical and digital skills barriers can be mitigated by facilitating training.
- **Logistics**: In logistics, barriers include the increased demand for higher flexibility of packaging and the number of stock keeping units needed; additional workforce skills requirements; regulatory barriers; as well as low profit margins. A number of the barriers to adoption can be readily addressed by policy. Drone regulations can be liberalised to keep pace with developments in drone technology. The skill requirements and need for staff engagement and “buy-in” could plausibly be addressed by information campaigns and increased funding for education and training. The technical challenges around interoperability and the need for greater flexibility should lessen as technology advances; plausible policy interventions to address this are limited to supporting research into and development of new RAS technologies.

Concluding remarks

This study identifies economic opportunities from RAS across a diverse group of UK sectors. Use-cases for RAS range from crop harvesting to surgery to nuclear decommissioning, among many others. The adoption of RAS offers the potential for significant economic benefits, providing opportunities to raise efficiency, free up labour for higher-value tasks, and help drive the UK’s economic growth. In addition to these economic impacts, RAS offers a number of potential wider benefits. These include the development of adjacent technologies, increased consumer welfare from new, improved, cheaper or more personalised products, and increased resilience to exogenous shocks such as pandemics and extreme weather events.

However, current adoption trends across UK sectors are generally not high enough to realise significant economic benefits. In most sectors, there exists a large gap – the “automation gap” – between current trends of adoption and the potential rate of automation that could be achieved. This means that the potential benefits of RAS, including but not limited to GVA improvements and reductions in labour needs, are unlikely to be realised fully in these sectors. Current forecasts of adoption suggest that only the warehouse logistics sector and, to a lesser extent, the food & drink manufacturing sector are likely to see sizeable benefits from RAS over the next ten to fifteen years if current trends continue. However, a gap between current trends and potential levels of automation still exists in these sectors.

There is, therefore, room for policy to mitigate barriers to adoption in these sectors and thereby support RAS uptake. However, whether, and to what extent, policy interventions are successful in raising the level of adoption in a sector depends on a range of factors, including the nature of the existing barriers. While the study did consider the feasibility of policy interventions based on the nature of barriers in different sectors, a detailed assessment of the impact of different policy interventions on RAS adoption was beyond the scope of this work. Further research in this area would be both interesting and worthwhile.

Introduction

In May 2020, the Department for Business, Energy & Industrial Strategy (BEIS) commissioned London Economics (LE) to undertake an assessment of the economic opportunities of Robotics and Autonomous Systems (RAS) across UK sectors. This study will enable BEIS to understand where the key future economic opportunities lie for RAS uptake across the wider economy. This introduction provides an overview of what is meant by RAS, the relevant policy background, the objectives of this study, the sectors covered, and the structure of the remainder of the report.

What is RAS?

There is no single agreed definition for robotics and autonomous systems (RAS), with definitions continuing to evolve as the technology develops over time. However, for the purpose of this study a useful description of RAS is provided by BEIS:

> Definition: Robotics and Autonomous Systems (RAS)
>
> Robotics and autonomous systems (RAS) include machinery and physical systems that can act independently of human control, by sensing, reasoning and adapting to a given situation or environment. In contrast to more traditional machines that have a single, pre-determined purpose, RAS applications are able to understand what is happening in their sphere of operation and tailor their behaviour to particular circumstances with varying degrees of decision-making autonomy.

Source: BEIS

The scope of this research covers RAS applications with a physical dimension in a commercial setting, excluding robotic process automation and other digital-only solutions, as well as smart home devices.

While the focus of this study was not on ‘standard’ industrial robots, data and definitional limitations meant that industrial robots were included in the estimation of quantitative impacts for the food & drink manufacturing sector, as well as to establish the current stock of robots in each sector. Their role in other selected sectors is expected to be limited.

The importance of RAS

Robotics and Autonomous Systems (RAS) are becoming increasingly important for the UK economy and are a key technological driver of Industry 4.0 – the fourth industrial revolution. RAS technologies have far-reaching economic effects, with the potential of bringing significant opportunities for companies looking to reduce costs or improve efficiency.

The size of this opportunity is significant with the annual global economic impact of advanced robotics estimated to lie between $1.7 to $4.5 trillion per annum by 2025 (McKinsey, 2013), and an estimated market for non-military Robotics and Autonomous Systems products and technologies of £70 billion by 2020-2025 (cited by Special Interest Group Robotics and

Autonomous Systems, 2014). A more recent study estimated that boosting robot installations to 30% above the baseline forecast by 2030 could lead to a 5.3% boost in global GDP that year, equating to adding an extra $4.9 trillion per year to the global economy by 2030 (Oxford Economics, 2019).

Estimates of the impact of RAS on the UK economy suggest an impact of 15% of GVA (more than £200 billion), and a potential to raise manufacturing sector productivity by up to 22%, generating a long-term employment increase of up to 7% (cited by Special Interest Group Robotics and Autonomous Systems, 2014).

New forms of RAS, combining advances in robotics technologies with Artificial Intelligence as well as sensor technologies utilising the Internet of Things, are increasingly emerging. Examples include ‘smart mobile robots’ such as autonomous forklifts and tote conveyors to heavy-lift platforms enabling users to work with existing, non-standardised facilities and helping avoid the costs of bolted-down infrastructure such as stationary conveyors, multi-layer racks, and positioning systems (see Collaborative Robotics, 2019); as well as the increasing variety of Collaborative Robots focusing on human-machine interaction with robots assisting humans in undertaking certain tasks more easily or efficiently.

In contrast to previous waves of robotics, which were mostly focused on industrial applications, the current range of RAS technologies have the potential to impact a wide range of sectors, with increasing use-cases and opportunities arising across the economy. These include, among others, logistics applications such as automated guided vehicles, mobile retail robots, and humanoid customer service robots.

Unlocking the potential of RAS: the UK’s position

The UK failed to capitalise on the opportunities presented by the previous wave of industrial robotics, with use of industrial robots in industry in the UK lagging behind other nations.[5] However, RAS has increasingly seen as a priority area by government in the last decade. For instance, in 2013 RAS was identified as one of the “Eight Great Technologies” where the UK could have a leading global position. In the Government’s 2017 Industrial Strategy (UK Government, 2017a), the opportunities presented by robotics, in conjunction with other digital technologies such as artificial intelligence and data analytics, were again acknowledged.

Although it has seen comparatively low levels of uptake of industrial robots, the UK is in a strong position to take advantage of these new forms of RAS. The UK has world-leading robotics research, as well as highly innovative robotics companies (Made Smarter Review). This includes a number of collaborative research centres and institutes such as the Bristol Robotics Laboratory, Dyson Robotics Lab, RACE, the Hamlyn Centre at Imperial College, the Edinburgh Centre for Robotics, EPSRC Centres for Innovative Manufacturing, and Sheffield Robotics; as well as thriving RAS groups at research institutions (e.g. Heriot-Watt University, Imperial College London, University College London, University of Bristol, etc.), and from industry (e.g. BAE Systems, Rolls-Royce, OC Robotics, Tharsus, etc.).[6]

[5] Data from the International Federation of Robotics shows that industrial robot installations in the UK are relatively low when compared to the likes of Germany, the US, or China: Around 2,500 industrial robots are estimated to be installed in the UK in 2020 (0.5% of an estimated world total of 520,900). This compares to estimates of around 6,000 (1.2% of world total) in France, 8,500 (1.6%) in Italy, 25,000 (4.8%) in Germany, and 55,000 (10.6%) in the US, and 210,000 (40.3%) in China.

[6] A fuller analysis of the UK RAS landscape is provided in Council for Science and Technology (2015).

The UK also has a strong Artificial Intelligence (AI) ecosystem. The UK ranked second in McKinsey's AI Readiness Index behind the United States (McKinsey Global Institute, 2019). The UK's AI research base is excellent; the UK ranked fourth in terms of the number of AI publications between 2015 and 2018, behind China, the United States and India, and third in terms of number of citations (Perrault et. al., 2019). Moreover, the UK is home to many companies developing and using AI, some of which are seen among the world's most innovative. This includes subsidiaries of major players such as IBM and Microsoft as well as a thriving landscape of start-ups and SMEs (Hall, W., & Pesenti, J., 2017). With 758 companies, London has an AI supplier base double the size of those in Paris and Berlin combined (The Law Society, 2019). The UK also has a comparatively strong funding environment; in 2019, the UK was third in the world – and first in Europe – for venture capital investment into AI and deeptech companies (Tech Nation, 2020), behind the United States and China.[7]

However, unlocking the potential of RAS is not straightforward. A recent study by Boston Consulting Group (2019) found that while companies have high ambitions for deploying advanced robots, there is a significant gap between ambition and actual implementation. While 86% of companies surveyed planned to deploy advanced robots in their operations within the next three to five years, only 20% had created a holistic vision of their future operations and a comprehensive implementation roadmap. Moreover, 92% thought that one or more of the key enablers – including a holistic vision of their future operations, sufficient knowledge of RAS and related issues, and the development of a system architecture that will support the future operations – were not fully achieved in their companies.

The study further suggests that, while European and Asian companies currently lead in implementing advanced robotics, UK companies' ambition is lagging behind their European neighbours. In response to the Boston Consulting Group survey, 75% of UK respondents said their company is planning to implement advanced robotics within the next three years; compared to 89% in Italy, 89% in Austria, 92% in France, 92% in Germany and 96% in Poland. This finding highlights that, despite the UK's strengths in advanced robotics research and AI, the UK needs to ensure that it is not left behind other nations when it comes to implementation.

Study objectives

Given this background, it is important to understand where the key future economic opportunities for RAS uptake exist across the wider economy. This will help to inform choices around the case for policy interventions to stimulate RAS adoption within particular sectors, and to identify near-term and long-term sectoral opportunities for UK uptake. This study therefore sought to provide a robust evidence base to answer the following overarching research question:

> What is the potential future economic opportunity of RAS adoption across UK sectors?

Considering this overarching objective, this study sought to identify:

- how the use of RAS technology can affect business productivity, output, and resilience, and the different channels through which this can occur;

[7] However, Israel is catching up, and the Tech Nation Report 2020 calls for continued government support to ensure that Israel does not overtake the UK in this measure.

- how RAS technology can be applied in different sectors of the economy, and in which sectors the potential opportunity could be largest in future;
- which RAS applications are creating a value proposition in each sector, and what the underlying drivers are enabling these use cases; and,
- the current level of RAS adoption across UK sectors, as well as the level of likely and possible deployment forecast in future.

Based on this evidence, a quantitative analysis providing estimates of the future economic opportunity of RAS deployment across a number of selected sectors was undertaken. This quantitative analysis begins by estimating RAS adoption across the economy and in each of the selected sectors, based on forecasts of robot shipments by ABI Research. It then estimates the economic opportunities from RAS in each selected sector given current adoption trends, in terms of productivity improvements, reductions in employment needs and impacts on GVA. It also presents the size of the "automation gap" – the gap between estimated future adoption and automation potential – in the selected sectors and considers to what extent the barriers to RAS adoption in each sector can be addressed through policy.

Sector selection

Desk-based research was conducted to determine an initial long-list of sectors to be included in this study. A long-list of 14 sectors, covering the breadth of the UK economy, was identified. These were:

- Agriculture
- Construction
- Defence and military
- Energy
- Food & drink
- Health & social care
- Hospitality
- Industry and manufacturing
- Infrastructure
- Life sciences
- Logistics and transport
- Professional services and finance
- Retail
- Space

These were assessed using the following criteria in order to reach a final shortlist:

- the sector's size, both in terms of output and employment,
- the growth rate of the sector,
- the maturity of RAS applications, and
- the potential for future uptake of RAS.

A RAG (red-amber-green) rating was developed for each of these characteristics. In addition to the characteristics themselves, the rating also took the quality and quantity of available evidence into account. An overall RAG rating, for each sector, was made based on the ratings of each of the characteristics of that sector.

These ratings were used in conjunction with sector specific policy considerations to select the final list of sectors used in this study. These were:

- Agriculture
- Construction
- Energy
- Food & drink
- Health & social care
- Infrastructure
- Logistics

Note that there is some overlap between the agricultural and the food & drink sectors. Analysis of the opportunities of RAS in the food & drink sector focused on non-agricultural use cases.

Sectoral definitions for quantitative analysis:

Definitional and data availability issues meant that modelling the energy and infrastructure sectors separately was not possible. Therefore, these sectors are treated as one in the quantitative analysis.

Due to similar issues, the manufacturing and hospitality aspect of the food & drink sector were also modelled separately. Moreover, the food & drink sector also overlaps with the agricultural sector. Modelling agriculture, food & drink services, and food & drink manufacturing separately also avoids issues of overlapping sector boundaries for the food & drink sector.

For the logistics sector, only the warehouse logistics could be modelled quantitatively. Transport logistics was also excluded from the qualitative analysis. Further details on the coverage of each sector can be found in the methodological note accompanying this study, for the quantitative analysis, and the respective qualitative chapters.

The SIC sectors used for the analysis are provided overleaf.

Further details can be found in the methodological note accompanying this study.

Scope and use cases included

The qualitative analysis of selected sectors did not adopt specific definitions for each selected sector. Rather, the analysis considered sectors in a broad sense, highlighting use cases, trends and opportunities where these where relevant to the sector more widely.

For the quantitative analysis, data on robotics uptake is limited. The quantitative analysis therefore had to be more narrow in scope. To our knowledge data is only available from the Institute of International Federation of Robotics (for industrial and service robots) and ABI Research.

The analysis used data from *ABI Research (2020a)* as the focus of the study was on non-industrial robots where ABI Research provided more detailed breakdowns. Robot categories included in the quantitative estimates are:

- **Collaborative robots:** robots specially designed to interact with human workers in a shared workplace);

- **Mobile robots**: robots that can navigate an environment without the need for external infrastructure); and,
- **Exoskeletons**: a wearable mechanical device that works in tandem with the user.

While the focus of this study was not on ‘standard’ industrial robots, data and definitional limitations meant that industrial robots were included in the estimation of the overall robotics market value, to establish the current stock of robots in each sector, as well as in the quantitative impacts for the food & drink manufacturing sector (due to their importance in this sector). Their role in other selected sectors is expected to be limited.

Sector	SIC sector	ABI Research data coverage
Agriculture	A: Agriculture, forestry and fishing	Robots deployed by farmers to perform specific tasks in farms, plantations and fields, such as weeding, fertilizing, watering, data collection, and fruit picking.
Construction	F: Construction	Mobile systems for material handling, data collection, and task-based use cases for construction.
Energy & infrastructure	D+E: Electricity, gas, steam + Water supply, sewerage and waste management	Robots to improve inspection, as will bridges, sewage systems, airports, and ports for non-oil and gas utilities, like nuclear and renewable energy; and, robots for industrial inspection, monitoring, and other use cases in fossil fuel-related facilities.
Food & drink service activities	56: Food and beverage service activities	Robots deployed by food and beverage operators either to serve dining guests or to prepare dishes.
Food & drink manufacturing	CA: Manufacture of food, beverages and tobacco	Robots deployed in factories and plants for example to transport goods between production cells or lines. Includes industrial robots, mobile robots, collaborative robots, and exoskeletons.
Health & social care	86+87: Human health + residential care	Includes robots deployed by healthcare institutions to transport goods within the healthcare facilities as well as exoskeletons. NB: This does not cover surgical robots which are unlikely to yield direct economic impacts, though they will yield significant human benefits (as discussed in the sectoral impacts section).
Warehouse logistics	52: Warehousing and transport support activities	Robots deployed in warehouses for goods transfer, picking, sorting, and palletization.

Stakeholder consultations

To support this study, we conducted six interviews with important stakeholders in the selected sectors as well as cross-sector experts in RAS.

The interviews explored subjects including the potential of RAS across different sectors, current use and drivers, short- and long-term future uptake, the benefits of RAS, and cross-country comparisons.

The findings from these were used to inform the qualitative discussion and to validate and refine the findings of the literature review.

Structure of the report

The remainder of this report follows a modular approach focused on three distinct sections. Each section may be read on its own or in conjunction with the other sections:

- The first section is a more theoretical discussion of RAS. This section begins by discussing the economy-wide impacts of RAS as well as the drivers and channels behind these impacts at a theoretical level. This section also highlights some of the economy wide challenges RAS can help mitigate, and literature evidence on the potential employment effects of RAS.
- The second section then examines the qualitative evidence of RAS across selected sectors. Each sector has its own sub-section discussing the current RAS landscape in the sector, including qualitative evidence of adoption and maturity of RAS, as well as select use cases; the drivers and barriers influencing RAS uptake in the sector; and, the potential impacts of RAS, including qualitative evidence on the environmental and social as well as and business resilience impacts.
- The third section presents the results of the quantitative analysis undertaken for this study. The section begins by examining the economy-wide trends of RAS adoption, given current forecasts, and then presents estimates of the potential impacts of current adoption trends across selected sectors. Finally, the section discusses the gap between current adoption and potential automation as well as the feasibility of policy interventions for addressing this gap.

The executive summary provides a more concise overview of findings across all sections.

A methodological annex provides a brief overview of the approach used to derive quantitative estimates; an extensive methodological discussion is provided in a separate methodological note accompanying this report.

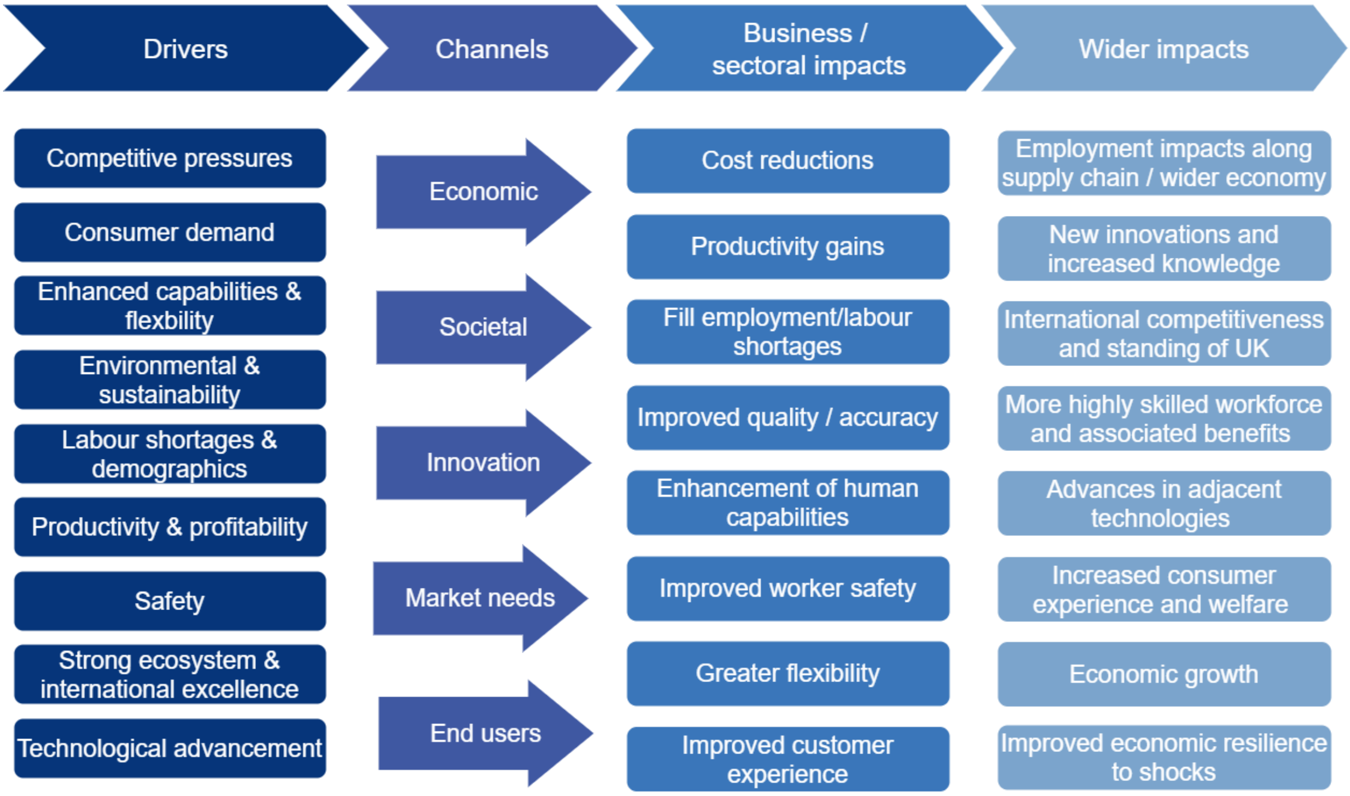
The case for RAS: Theoretical assessment

This section discusses the theory of how RAS will impact the UK economy and its sectors. First, it describes the drivers, channels and impacts of RAS adoption at the economy-wide level. Next, it describes the impacts of RAS adoption on business resilience. It then presents the economic case for RAS, describing the benefits RAS can bring to the UK economy and the problems it offers a potential solution to. Finally, it presents key findings from the literature on how the adoption of RAS affects employment.

Drivers, channels and impacts of RAS

As discussed in the introduction of this study, RAS has the potential to bring about significant economic opportunities across UK sectors. The logic model below highlights, at an economy-wide level, the drivers of RAS adoption, the channels those drivers fall into, and the business, sectoral and wider impacts of RAS impacts. Individual sector sections provide further detail on drivers and impacts for selected sectors of the economy.

Logic map for the economy-wide impacts of RAS



Source: London Economics

Impacts of RAS can arise in a multitude of ways. At the firm level, RAS can bring about significant cost reductions, and drive improvements in productivity, fill labour shortage and deliver quality improvements. Following Muro et al. (2019), (direct) impacts arising from advanced automation can broadly be classified into three categories[8]:

Robots complementing human activity	Impacts arising from robots complementing human activity, where robots (particularly Co-Bots) enhance human capabilities leading to higher productivity. For example, Co-Bots and exoskeletons allowing humans to lift much heavier weights, or surgery robots supporting surgeons when performing difficult or critical operations. The automation of menial tasks and workflows can allow workers to instead focus their skills on elements which cannot be replaced by robots.
Substitution of work from humans to robotics technology	Impacts arising from substitution of work from humans to robotics technology, thereby reducing costs and potentially improving efficiency and/or accuracy. For example, cutting robots can perform cuts much faster and with higher accuracy than humans and do not tire. While automation through substitution may lead to a reduction in jobs of workers, the increase in speed, volume and accuracy gained from this substitution may in turn lead to an expansion of the industry, therefore offsetting this reduction.
Creation of new work	Adoption of robotic technologies creates new tasks and roles. For instance, workers will be required to operate drones as they are used, and engineers will be needed to maintain and service the robots.

In addition, RAS technologies can also help improve worker safety and deliver impacts through facilitating greater flexibility. This could allow firms to respond to changing customer demands more quickly or to offer more personalised products or services, with significant end-user benefits.

Looking beyond the firm level, RAS has the potential to deliver significant wider impacts, including:

- **Creation of jobs along the supply chain:** In addition to direct creation of jobs, increased RAS activity leads to the creation of new roles along the supply chain (e.g. in the design, manufacturing, maintenance and integration of these systems).
- **Wider economic impacts:** RAS also leads to economic impacts in other sectors and across the economy, for example, by reducing prices of goods and services leading to increased demands elsewhere.
- **R&D and scientific research:** R&D in RAS leads to new innovations, increases knowledge, fosters the UK's leadership role and international recognition and leads to economic spillover impacts.
- **International competitiveness and standing of UK:** International recognition of the UK as a leading RAS nation leads to a number of benefits such as FDI and the attraction of companies and talent.

[8] While Muro et. al. focus their argument on impacts arising from AI, it seems reasonable to adopt a similar classification for impacts arising from advanced robotics technologies.

- **Development of adjacent technologies**: RAS is complementary and interconnected with other key technologies such as Artificial Intelligence, sensor technology and the Internet of Things, as well as batteries and materials. Advances in RAS and improved activity are thus also likely to lead to further development of enabling technologies.
- **Skills development and training:** Advanced robotics requires highly skilled workers such as engineers, leading to a need to train new workers and upskill the existing workforce, and associated benefits such as higher wages, improved job security and satisfaction, and ultimately a more productive workforce, as well as safer, more attractive jobs in industries that have struggled to attract workers.
- **Better consumer experience and increased welfare:** Better consumer experience and increased welfare from new, improved, or cheaper products and services and more personalized, and/or flexible experience. RAS also brings safety benefits, particularly in hazardous environments.
- **Improvements in resilience:** RAS may also bring about significant improvements in resilience across UK sectors, making businesses more able to withstand and recover from exogenous shocks such as the recent COVID-19 pandemic and subsequent lockdown measures. RAS can improve business resilience across sectors by facilitating resilience to climate change and extreme weather; resilience to labour shortages; as well as by enabling higher operational flexibility and resiliency to fluctuations in demand.

As highlighted in the logic model, the strong growth in the robotics market is driven by a number of socio-economic factors. These can broadly be summarised into five key channels:

Economic: RAS provide a significant opportunity for businesses to reduce costs and drive improvements in productivity. On the one hand, RAS can be more cost-efficient than manual labour because RAS can operate for longer than human labour without rest, and is able to execute tasks often much quicker and to a higher accuracy to manual labour. The economic argument for RAS is particularly strong in the face of rising labour costs, increasingly low margins as well as competitive pressures in some industries, combined with the decreasing cost of robotics seen in recent years. On the other hand, RAS can free up personnel for other, higher value, tasks, thus increasing overall productivity.

Societal: Societal factors such as the aging demographics in the UK (and globally) and environmental and sustainability concerns create additional factors increasingly driving uptake of RAS. While around 19% of the UK population were above pension age in 2016, this is estimated to rise to 23.1% by 2066 (Ramanauskas, 2019). For example, in the healthcare sector, an ageing population is putting strain on health and long-term care and has already resulted in robotic innovation to help relieve this burden. Changing demographics are also likely to exuberate labour shortages over the long term. Similarly, the drive towards a greener economy is creating increasing environmental and natural-resource-management pressures. RAS can help alleviate these pressures. For example, in agriculture, which is responsible for around 10% of greenhouse gas emissions in the UK (WIRED, 2018), RAS can help reduce emissions by replacing large diesel tractors with guided systems with electric motors (Duckett et al. 2018).

Innovation: Continued innovation in robotics, AI, sensor, battery and other key enabling technologies mean RAS can be utilised for more and more tasks, which robots previously would not have been able to undertake. At the same time, technological advancements have also meant the cost of robotics has come down significantly in recent years. Together, these factors mean that RAS is becoming an ever more interesting attractive and feasible business proposition for businesses across all sectors of the economy. Innovation is underpinned by a strong UK research ecosystem in robotics and AI, including excellent UK institutes & research facilities such as EPSRC Centres for Innovative Manufacturing, High Value Manufacturing Catapult, the Alan Turing Institute, and many more.

Market needs: In addition to economic and external factors, internal market needs are another key channel facilitating uptake of RAS. For example, use of RAS can facilitate more pre-emptive and less disruptive maintenance and repair. Indeed, in some sectors such as nuclear decommissioning or space, the hazardous environment means that some tasks pose significant hazardous to humans. Human workers who operate in hazardous environments are often paid a premium in order to accept the attendant risks; using RAS in these environments can therefore achieve cost savings, significantly reduce the risk to workers, or indeed make tasks that are impossible for humans to undertake feasible. Increased safety of RAS is not restricted to hazardous environments but can reduce work-related injuries and fatalities across many sectors. The need for increased flexibility in order to meet increasing consumer demand and expectations, for example through adaptive manufacturing or the desire for ever faster delivery in the logistics sector, is another example where RAS can help meet market needs.

End users: Rising customer expectations and end-user requirements further strengthen the case for increased RAS uptake. Consumers, including retail and corporate customers, now demand higher quality products and better customer service. Changing customer expectations are also driven by the emergence of a new generation of customers that have grown up with technology. This new type of customer, the 'Millennial', demands higher quality products and customer service, but is also fluid in, for example, their needs, willing to shop around and wants to be recognised as having their own unique needs (PricewaterhouseCoopers (PwC), 2019). RAS can help firms to meet these rising customer demands, by providing businesses increased flexibility and adaptability.

The impact of RAS on business resilience

RAS also have the potential to bring about significant improvements in resilience across UK sectors, making businesses more able to withstand and recover from exogenous shocks. RAS can improve business resilience across sectors by facilitating:

- **Resilience to climate change and extreme weather:** The World Economic Forum has ranked climate change as the biggest global risk in 2020 (Edmund, 2020). Adopting RAS can help UK businesses build resilience to extreme weather and other climate related shocks. For example, adopting RAS in agriculture could help build resilience to the growing threat of climate change by allowing farmers to increase crop diversification and by bringing down the cost of indoor 'vertical farming' practices (see p.41). In infrastructure, RAS can quickly repair damages and restore operation with minimal disruptions. Better maintained infrastructure will offer greater resilience to extreme weather events caused by climate change (see p.63).

- **Resilience to labour shortages:** Brexit and COVID-19 have caused significant uncertainty in the labour market within many UK sectors. Transport, logistics, healthcare and farming are all at risk of facing significant labour shortages. RAS can help mitigate the risks arising from labour shortages. For example, autonomous vehicles (AVs) can help the UK transport sector tackle the shortage of HGV (heavy good vehicle) drivers which has climbed to 59,000 in the UK (Logistics UK, 2019)
- **Greater flexibility:** Higher levels of automation could bring about more operational flexibility and resilience to fluctuations in demand across the economy. Unlike a traditional workforce, RAS can work around the clock when demand is high and be left idle when it is low.

Economic and social life in the UK has been severely disrupted by the COVID-19 pandemic. RAS has helped to contain the spread of COVID-19 and can provide innovative solutions to the problems posed by the pandemic (Zeng et al., 2020). These are some of the main ways RAS can help the UK face the challenges presented by COVID-19 crisis across sectors:

- RAS **reduce the need for human contact** and hence lower the risk of virus transmission. Robotics are already being used in hospitals to help healthcare professionals treat patients from a safe distance (DiMaio et al., 2020). In airports, robots are being used to measure body temperature so that airport staff and potentially infected travellers do not come into contact (Zeng et al., 2020). In the transportation and logistics sectors, drones can deliver daily necessities to households without human contact (Ho and Lee, 2019). Cart-like robots have been used in China to bring food to people in quarantine (Murphy et al. 2020).
- RAS can help British businesses **deal with the shortages of workers** due to COVID-19 related travel restrictions and illness. For example, the coronavirus pandemic could lead to a shortage of 80,000 workers in farming due to travel restrictions and illness (CLA, 2020). Adopting RAS in agriculture could help farmers overcome these shortages.
- RAS can help to safely **sterilize and decontaminate** hospitals, airports, restaurants, offices, warehouses and other public spaces. For example, UVD robots has created robots which disinfect patient rooms and operating theatres in hospitals using ultraviolet light (Murphy et al., 2020). Outside of hospitals, public safety departments are using robots to spray disinfectant throughout public spaces.

The impact of RAS on business resilience is discussed more thoroughly in each sector chapter.

The economic case for RAS

As highlighted in the introduction to this study, RAS has the potential to bring about sizeable economic impacts. The size of this opportunity is significant with the annual economic impact of advanced robotics estimated to lie between $1.7 to $4.5 trillion per annum by 2025 (McKinsey, 2013), and a 30% boost of robot installations above the baseline by 2030 estimated to add an extra $4.9 trillion per year to the global economy by 2030 (Oxford Economics, 2019).

RAS offer a potential solution to a number of key challenges to the UK's continued economic growth:

- In the UK, productivity – output per worker[9] – is lower than in many peer economies such as the United States, France and Germany (King, 2019 based on OECD statistics). Moreover, productivity growth in the UK has been sluggish since the Great Recession of 2008/09 (ONS, 2015; see also ONS, 2020a). The OECD describes growth in productivity as “an essential driver of changes in living standards” (OECD, 2020). RAS has the potential to allow for continued improvements in living standards by increasing the rate of labour productivity growth.
- In addition, if labour productivity remains stagnant, GVA will grow commensurately with increases in employment. Meanwhile, the UK has an ageing population and a low birth rate (see e.g. Government Office for Science, 2016). This means that the working age population is unlikely to grow by enough to sustain trend rates of GVA growth in the absence of productivity gains. The link between these demographic changes and robot adoption has been empirically established. Acemoglu and Restrepo (2019a) find that countries experiencing a greater degree of demographic ageing have higher levels of robotics adoption. They also find that industries that are more exposed to the problem of demographic ageing (because middle-aged workers are presently a more important part of their workforces) have higher levels of adoption of RAS (ibid.). In an earlier paper, Acemoglu and Restrepo had suggested that higher adoption of RAS in countries with higher rates of demographic ageing explained the fact that demographic ageing is not negatively correlated with GDP growth in an observable way (Acemoglu and Restrepo 2017).

Productivity increases from RAS can help alleviate these challenges by reducing the number of human hours worked needed to produce a given output as well as by freeing up workers for higher value-add tasks.

Oxford Economics estimate that a 1% increase in the stock of robots is associated with a 0.1% increase in GVA per worker in the short term and a 0.3% increase in GVA per worker in the long term (Oxford Economics, 2019). The Centre for Economics and Business Research (CEBR), meanwhile, look at industrial robots and estimate (CEBR, 2017) that (labour) productivity rises by 0.04% with a one-unit increase in robot density (robots per million hours worked). An improvement in productivity reduces the amount of labour needed to produce a certain quantity of goods and services, allowing for more growth in value added for a given amount of growth in the labour supply.

Evidence on the employment effects of RAS

The labour market impacts of RAS depend on a wide range of factors. However, theoretically, the impact of RAS on employment can be summed up in through two competing effects. The first is the displacement effect, whereby RAS is used to complete tasks for which labour is currently employed (Acemoglu and Restrepo 2019b). This effect tends to reduce the labour share in a sector. The second is the reinstatement effect (ibid.), whereby RAS “reinstates” labour by increasing its productivity and creating new tasks to which labour is better suited than capital. This effect tends to increase the labour share in a sector. The overall impact of RAS adoption on sector labour share and labour demand depends which of these two effects dominates. Acemoglu and Restrepo (ibid.) suggest that the displacement effect of automation “may have come to” dominate its reinstatement effect in recent years.

[9] Strictly speaking, this is labour productivity. Labour productivity can alternatively be defined as output per hour worked.

Using firm-level data on French manufacturing firms, Acemoglu, Lelarge and Restrepo (2020) find that a 20 percentage point increase in industrial robot adoption is associated with a 3.2% reduction in employment across the industry. They find that firms that adopted industrial robots reduced their labour share (ibid.). However, adopting firms increase employment in absolute terms as the cost savings from RAS allow them to expand[10] (ibid.).[11] This increase in employment by adopting firms is, though, outweighed by a reduction in employment by non-adopting firms, who shrink because adopting firms have a cost advantage (ibid.).

Autor (2015) suggests that workers who perform work where automation is a complement to their labour are more likely to benefit from automation in terms of higher wages, whereas those for whom automation substitutes their labour are more likely to see reduced wages or a reduction in employment. If the supply of labour that performs the tasks that are complementary to automation is elastic with respect to wages, though, this can dampen the wage increases from automation (ibid.). In addition, workers are less likely to benefit from automation when the products in their sector have relatively income-inelastic demand (i.e. where demand for their sector’s goods and services is relatively unaffected by changes in real income). To illustrate this point, consider that demand for the products of agriculture is relatively income inelastic. As automation has progressed in the agricultural sector and yielded massive productivity improvements, the share of labour employed in the agricultural sector has fallen (ibid.).

With respect to labour being re-deployed in response to the adoption of RAS, it is important to note that this re-deployment may be primarily between different tasks within occupations, rather than between occupations. Freeman et al. (2020) find that between 2005 and 2015, which the authors present as pre- and post- the introduction of AI, changes in aggregate job characteristics are predominantly because of within-occupation changes in task composition rather than changes between occupations.

[10] That is, the increase in output outweighs the reduction in labour share in terms of their effects on employment amongst adopting firms.
[11] Koch et al. (2019) reach the same finding on the direction of the change in adopter-firm employment in a panel dataset of Spanish firms.

Qualitative assessment of economic opportunities across sectors

This part of the report presents qualitative evidence on the economic opportunities from RAS across the selected sectors in the UK. Evidence for each selected sector is presented in its own sub-section. These sub-sections begin by presenting qualitative evidence on the current RAS landscape in the sector, including current levels of adoption and maturity of RAS as well as selected use cases in the sector. They then explain the drivers and barriers influencing RAS adoption in the sector. Finally, they consider the wider impacts of RAS adoption in the sector – on society, the environment and business resilience.

Economic opportunities from RAS in agriculture

The agriculture sector accounted for just over 0.5% of the UK's GDP in 2019 (Department for Environment, Food and Rural Affairs, 2020). Notwithstanding its comparatively small size, the agriculture sector is of great wider significance. Food and food security are vital for the functioning of a society. The United Nations (UN) Food and Agriculture Organisation (FAO) projects that food production will have to rise by 70% by 2050 relative to 2005/07 if the world's population grows to 9.1 billion (UN FAO, 2009); this increase in production would have to occur while considering natural resource constraints. Moreover, agriculture forms part of the wider agri-food value chain, which is worth over £100 billion per year to the UK economy and employs nearly four million people (Duckett et al. 2018).

For the purpose of this study, the agriculture sector comprises the economic activities of arable farming, breeding and raising livestock, and soil cultivation. The qualitative food & drink sector section deals with the economic opportunities from RAS in the food & drink sector, which captures economic activity associated with its' manufacturing, packaging, and preparation.

Current RAS landscape

Current adoption and maturity of RAS

RAS has begun to penetrate the agriculture sector, but current levels of adoption and the maturity of the technology differ across different agricultural applications of RAS.

In dairy farming, RAS applications are well-established and increasingly prevalent. In the UK, robotic systems for milking became commercially available in 1994 (Heyden, 2015); such systems became available in 1992 in continental Europe and 2000 in the US (Sandey et al. 2017). In 2015, milking robots accounted for 30% of new milking systems purchased by UK farmers (Heyden, 2015). By that time, robotic milkers had been adopted by 5% of UK farms (ibid.). In some European countries, adoption is higher: in the Netherlands, for instance, most new milking systems purchased by farmers are robotic (University of Hull, 2012).

Drones have begun to deploy in but are not yet a mature technology in the agriculture sector. At present, drone use in agriculture is concentrated in analysis applications (European Commission, 2018). The uptake of drones on UK farms has been less than in the US and South America, where farms are typically much larger (Harvey, 2014).

Unmanned vegetable and fruit harvesting robots are largely at the prototype stage. There are differing views on how long it will be until such robots are commercially available and viable. The then-President of the National Farmers' Union, Peter Kendall, said in 2014 that "[t]he use of unmanned robots is rather more futuristic [than existing applications in dairy farming and data gathering] but people are working on it…[a]s well as field operations, there is potential in fruit harvesting and even livestock management" (ibid.). By contrast, Emma Hockridge, then Head of Policy at the Soil Association, argued that "[t]he potential use of robots on farms has been discussed for years, but we haven't yet seen anything practical close to reaching the market" (ibid.). In late 2018, Small Robot Company's customisable "farmbots" were said to be on course to be commercially available in 2021 (Varghese, 2018). Automation of the harvesting of non-delicate crops like grains is more advanced than for delicate crops; some commercially available combine harvesters have a number of automated assistance processes[12], while in 2017, a field of barley was harvested by an autonomous combine harvester in Harper Adams University's 'Hands Free Hectare' (Harper Adams University, 2017). However, RAS is likely to have more potential in higher-value fresh produce crops, like strawberries, than in lower value contexts where margins are lower.

Ultimately, RAS in agriculture is likely to exist within an integrated system encompassing multiple advanced technologies. The South West Dairy Development Centre (SWDCC) in Somerset offers a vision of this. It is owned by Agri-EPI Centre, one of four Agri-Tech Centres of Agricultural Innovation that received £90m of funding from Innovate UK (Agri-EPI Centre, 2020a). The SWDCC makes use of automated milking and feed systems and has trialled a 3D imaging system aimed at monitoring cow health, farm security systems making use of 5G, drones used to monitor grazing patterns, and other technologies (Agri-EPI Centre, 2020b).

Selected RAS use cases

- **Crop harvesting and fruit picking:** RAS, sometimes in fleets or swarms, can be used to harvest crops and pick fruit (Daniels, 2018), which can be labour-intensive tasks. Such robots use sensors to scan plants and are equipped with software that can determine whether the plant is ready for harvesting (ibid.). Foods for which there are examples of prototype harvesting robots include lettuce, strawberries and tomatoes (ibid.).
- **Crop monitoring:** Drones can be used for crop monitoring and assessing the health of crops (European Commission, 2018), performing these tasks quickly and frequently. Drones are also cheaper and more reliable for crop monitoring than satellite imagery (ibid.). SenseFly, a drone manufacturer that specialises in agricultural drones, reports that crop yields increased by an average of 10% when it began to use drones for crop monitoring (ibid.). Goldman Sachs estimate that the total addressable market for drones in the agriculture sector is just over $5.9 billion (Goldman Sachs, 2016).
- **Precision agriculture:** Robots – including drones – can be used to generate detailed data to facilitate 'precision agriculture', also known as 'smart farming' (Duckett et al. 2018). RAS can collect data on rainfall, soil moisture, soil composition, and other variables at a more detailed level than field level. This allows farmers to make more targeted interventions. For instance, it allows variable rate irrigation, where farmers use differing amounts of irrigation across a field.
- **Weeding:** RAS can also be used for weeding without the use of chemical pesticides. The Small Robot Company's customisable Jack robot has a boom that makes it a weeding

[12] See, for instance, https://www.claas.co.uk/products/combines/lexion-8900-7400?subject=CUK_en_UK.

robot called Dick (Varghese, 2018). Given the environmental impacts of pesticides (discussed further below), reducing their use is desirable.

- **Phenotyping:** Another important application of RAS in agriculture is the automation of phenotyping. Phenotyping (in the context of agriculture) involves collecting information on plants' characteristics such as height and leaf size. This informs the process of plant breeding, whereby plant breeders use techniques like selective breeding and genetic modification to improve crop yields, disease resistance and nutritional profiles. Using robots allows plant breeding to be more predictive (ibid.); Mike Gore of Cornell University says that "[u]sing phenotyping robots, we can identify the best-yielding plants before they even shed pollen", and that the use of robots can halve the amount of time taken to breed a new variety of plant (ibid.). A team at the University of Illinois have developed a robot called TerraSentia that automates phenotyping (Sheikh, 2020). TerraSentia is small, can travel amongst crops and is equipped with a camera to measure plants' height and leaf area (ibid.). At present, it moves at only one mile per hour to allow the camera to gather enough information, but it is hoped that it will eventually move quicker (ibid.). It is fully autonomous, but at present it sometimes requires user help when faced with obstacles (ibid.).
- **Robotic milking:** Another use case of RAS in agriculture are robotic milking systems. Such systems have sensors designed to detect where they should clamp onto a cow's udders, and use tags to identify cows and 'ration' milking (so that an individual cow is not milked too often) (Heyden, 2015). However, this is an older technology, as discussed above.

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

A key driver of RAS adoption in the agriculture sector is growing labour shortages and an ageing workforce. The average age of a farmer in the UK is 59 (Henriques, 2019). Between 2010 and 2018, the number of farmers in the UK aged over 65 rose by 70% and the number of UK farmers aged under 25 fell by just under two-thirds (Barclays, 2018). This is especially concerning given the physical demands of agricultural labour. In 2016, 75,000 seasonal workers from outside the UK were required by the horticulture sector (ONS, 2018a); as many as 90% of them may be from EU Member States (House of Commons, 2017). Brexit and other political changes may make access to this seasonal labour more difficult. The use of RAS can help to alleviate these pressures on the labour market.

Another important driver of RAS adoption in the agriculture sector are pressures on natural resources and the environment. Agriculture makes intensive use of natural resources and has significant environmental impacts. RAS can facilitate 'precision agriculture' that allows resources, such as water, to be used in a targeted way and therefore reduce the impact of agriculture on the environment and stocks of scarce natural resources. See p.40 below for a detailed discussion of agriculture's environmental impacts and how RAS can mitigate them.

Finally, the use of RAS in the agriculture sector can reduce the number of work-related injuries and fatalities associated with agricultural work. Agricultural work often involves physically demanding tasks and the use of dangerous heavy machinery. Agriculture, forestry and fishing was the UK industry group with the highest annual average rate of fatal injuries per 100,000 workers between 2014/15 and 2018/19 (HSE, 2019).

Barriers to RAS adoption

In addition to the factors set out above driving RAS adoption in the agriculture sector, there are a number of factors that discourage and inhibit the adoption of RAS in agriculture. This section concerns those factors.

Farmers' ability to make use of RAS technology is an important barrier to RAS adoption in this sector. This barrier takes two forms. The first is that a considerable portion of farmers do not have access to technologies that are needed to make (most) use of RAS. A 2019 survey of UK farmers by the National Farmers' Union (NFU)[13] found that more than a quarter of respondents said that poor broadband or slow broadband speeds were a barrier to their further use of digital technology; less than half of respondents believed that the mobile signal they received on their farm was sufficient for the needs of their business (NFU, 2020). It will be important for RAS adoption in the that farmers and rural areas are included in the rollout of 5G. It should be noted that there are a number of UK government policies aimed at improving rural access to broadband[14] and access to the internet for farmers has improved since 2015, when the NFU began surveying farmers on their access to mobile internet and broadband (NFU, 2020).

The second form of this barrier is a digital skills shortage amongst those working in the agriculture sector. If workers lack digital skills, they may be less keen and/or able to make use of RAS. This digital skills shortage exists partly because the agriculture sector workforce is ageing; around 40% of holders and 35% of managers of UK farms are over 65 (Department for Environment, Food & Rural Affairs, 2016). Another cause is that the agriculture workforce generally lives in rural areas where there is less access to the internet and other technologies.

Another barrier to the adoption of RAS in agriculture is the cost of RAS. The agriculture sector is largely characterised by low margins (European Commission, 2018). In the year ending February 2019, the average net business income of English farms was £36,300 (Farm Business Survey, 2019). Meanwhile, implementing RAS solutions in agriculture businesses involves significant up-front costs. The Lely Astronaut, a robotic milking system, costs between $150,000 and $200,000 (Reed, 2018); Bluegrass, a drone designed to allow farmers monitor and assess the health of crops, costs €5,000 per unit (European Commission, 2018). Therefore, even if a RAS solution's additional revenues or cost savings exceeds its cost, the upfront investment may mean that farmers are unable to afford that RAS solution.[15]

The UK's relatively small farms and unpredictable weather are another barrier to RAS adoption in the UK agriculture sector. The UK's small farms mean that economies of scale from the use of RAS are hard to achieve. Unpredictable weather creates technical challenges, as it means RAS deployed on UK farms will have to be able to navigate more diverse environments than if the UK's weather were more stable.

There are also cultural and attitudinal barriers to RAS adoption in the agriculture sector. An important barrier to investment in the sector is a lack of confidence in the technologies based on a view that they are unproven. This suggests a need for demonstration examples of RAS technologies in an agricultural setting.

RAS adoption in the agriculture sector may be inhibited by problems with the research and testing of RAS applications in the sector. In the UK, the community of those interested in RAS in agriculture (and in agri-food more widely) is small and fragmented (Duckett et al. 2018), and

[13] The survey covered 817 UK farmers and was conducted in September 2019 (FarmingUK, 2020).
[14] See https://www.gov.uk/guidance/building-digital-uk.
[15] In addition, the existence of present bias means that farmers may place greater weight on an upfront cost now than larger cost savings and revenue increases in the future.

there is a need for greater collaboration with the agriculture sector itself and with academic researchers (ibid.). It had previously been argued that the supply to this community of people with relevant education and training may be inhibited by the lack of specific training paths or Centres for Doctoral Training (CDT) (ibid.), but a Centre for Doctoral Training in Agri-Robotics was awarded in 2019 (Agri FoRwArdS, n.d.[16]). While there is significant research being conducted in relation to agricultural RAS in the UK, there is a risk that there is not enough of this research is basic research (Duckett et al. 2018) – this problem may be assuaged with the creation of this CDT. Finally, the commercial testing of RAS in agriculture requires both a greater number and size of projects than is currently the case (ibid.); larger projects are important to understand how different technologies interact on the farm (ibid.).

Finally, the uptake of drones in agriculture – and for commercial use more generally – is likely to be slowed and perhaps limited by regulations on drone use. Drones weighing more than 20kg are subject to UK aviation regulations in their entirety (though the Civil Aviation Authority (CAA) may provide exemptions from some requirements) (CAA, 2020a). Small drones – those weighing less than 20kg – are subject to a different regulatory regime. In order to use a small drone for commercial purposes in the UK, one must register with the CAA and pass a theory test (CAA, 2020b). In addition, beyond-line-of-sight use of drones is prohibited (CAA, 2020c). One is not allowed to fly a small drone at a height greater than 400 feet without permission from the CAA (ibid.). This constrains the amount of farmland a drone can cover in a given period of time; Goldman Sachs estimate that relaxing the maximum flight height restriction[17] by 40% would allow the drone to cover twice the amount of farmland (Goldman Sachs, 2016). There are further restrictions on the commercial use of drones.[18]

Wider impacts

Environmental and social impacts

Employing RAS in agriculture can help the UK achieve the twin ambitions of ensuring food security for a growing population while reducing the environmental impact of farming and preserving natural resources for future generations.

Adopting RAS in agriculture can reduce the use of pesticides, herbicides and fertilizers which have well-documented negative impacts on ecosystems and biodiversity (McLaughlin and Mineau, 1995). The use of RAS can enable precision agriculture, including the targeted application of fertilizers and pesticides. This can dramatically reduce the quantity of harmful chemicals used in farming. Balafoutis et al. (2017) report that across several studies, it was shown herbicide and pesticide use could be reduced between 11% and 90% by precision application in arable crops. Furthermore, the development of robotic crop-weeding technologies may eliminate the need for herbicides. One key environmental benefit of decreased pesticide, herbicide and fertilizer use is the reduction in harmful effluents from farms to water bodies (Balafoutis et al. 2017).

Another environmental benefit of using RAS in agriculture is the reduction in soil compaction. Much of the land in the UK has a relatively shallow fertile topsoil and is therefore susceptible to damage from compaction and erosion. Whilst traditional heavy tractors, which can weigh up to 31 tonnes, damage the topsoil by compressing it, lighter robots are less likely to cause soil compaction. Reduced compaction improves crop yield, reduces the need for fertilisers,

[16] Agri FoRwArdS (n.d.). EPSRC Centre of Doctoral Training in Agri-Food Robotics: AgriFoRwArdS. Available at: https://agriforwards-cdt.blogs.lincoln.ac.uk/

[17] The 400 feet flight height limit also applies in the US.

[18] See https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Small-drones/Regulations-relating-to-the-commercial-use-of-small-drones/.

reduces waterlogging, surface run-off and improves the habitat for soil fauna (Duckett et al. 2018).

The transition from large diesel tractors to RAS with electric motors would also cause a reduction in greenhouse gas emissions from agriculture, which currently constitute 10% of all greenhouse gas emissions in the UK (BEIS, 2018). The Small Robot Company (an agri-tech focused RAS producer) estimates that their robots could reduce emissions and chemical use by 95% (Varghese, 2018).

Agriculture uses 70% of global fresh water supplies (Duckett et al. 2018). RAS can make farm irrigation systems more efficient as field robots help farmers measure, map and optimise water use (Duckett et al. 2018). Evans et al. (2013) found variable rate irrigation to potentially imply water savings of up to 20–25%.

RAS could almost eliminate the competitive advantage of large rectangular fields in commodity agriculture. Large open fields are more susceptible to soil erosion and are hostile to wildlife (Finger et al. 2019). With robots, small, irregularly shaped fields in areas with good soils, reliable rainfall and market access may be more competitive. Hence, robotics might offer a way to increase farm productivity whilst keeping a wildlife friendly, small-field landscape.

The widespread introduction of RAS in the agriculture sector has profound effects on the labour market in the sector. The agriculture sector faces significant labour shortages that may be exacerbated by Brexit (Booth and Adam, 2018), with farms reliant on seasonal migrant workers to harvest crops and pick fruit. Very little harvesting work in the UK is performed by domestic workers, and this is often attributed (see e.g. Booth and Adam, 2018) to it involving long hours, unfavourable pay and conditions, and repetitive work. RAS adoption could help to ease the shortage of labour and shift the agriculture sector’s demand for labour away from dangerous, physically demanding jobs involving a lot of routine tasks to more skilled ones (Duckett et al. 2018).

The distributional effects of RAS in agriculture should be observed and analysed carefully. If they are prohibitively expensive for small farms but not for larger farms or groups of farms, RAS technologies may lead to further concentrations in the agri-food sector (Finger et al., 2019). This could mean that benefits of RAS are unequally distributed (ibid.). Finger et al. (ibid.) suggest that this issue could be mitigated by cooperation and technology-sharing between farms and the availability of technology appropriate for a wide range of farms.

Impacts on business resilience

RAS can help farmers increase resilience to greater climate variability, price fluctuations and shortages of workers.

Crop diversification can improve resilience in agriculture in a variety of ways. Diversified farms have a greater ability to survive pest outbreaks and buffer production from the effects of climate variability and extreme events (Lin, 2011). Furthermore, less dependence on a single agricultural commodity makes farmers more resilient to fluctuations in crop prices. RAS allows farmers to adjust their within-field management to account for different crops being planted in the same field, allowing them to cheaply increase crop diversification and hence resilience (Lin, 2011). The use of RAS to increase diversity within farm systems is essential to helping farmers adapt to climate change.

RAS is also used in “vertical farming” systems which utilise indoor farming techniques where all environmental factors can be controlled. The use of robotics enables these systems to move from niche low-volume markets to mainstream reliable delivery of volume produce

(Duckett et al., 2018). Vertical farming is less susceptible to exogenous shocks such as bad weather, crop diseases and climate change, making it a more resilient form of agriculture (Duckett at al., 2018).

Finally, using RAS makes farmers less susceptible to labour shortages, which are of special concern in agriculture where many labourers are seasonal/migrant workers. Government and industry figures show that over 60,000 seasonal labourers come to the UK each year, including many from the European Union, to help complete annual harvests (Lindsay, 2020). COVID-19 restrictions and any migration implications of Brexit mean labour supply in farming could be cut by up to 75% (Lindsay, 2020).

Economic opportunities from RAS in construction

The construction sector accounts for around 6% of the UK's economic output (Rhodes, 2019).[19] It has been a rapidly-growing sector in recent years; between 2012 and 2019, GVA in the UK construction sector grew by over 30% in real terms (ONS, 2020b).

The construction industry serves both commercial and residential markets. The BBC Housing Briefing estimates that in the UK there is a housing gap – the difference between the stock of homes and the required number for everyone to have a decent and affordable home – of 1.2 million homes, based on an average of the estimates of three recent studies on the subject (BBC, 2020). Meanwhile, last year the UK missed the Government target to build 300,000 new homes each year (Parsley, 2020). Just over half the target number of homes was built, despite more homes being built in 2019 than in any other year since 2007 (ibid.).

Current RAS landscape

Current adoption and maturity of RAS

A number of the technologies underlying the use cases of RAS in construction are well-established in other contexts. Drones use is well-established in infrastructure and energy inspection and monitoring, and drones have begun to be used commercially in agriculture. Exoskeletons, similarly, have been used for military and medical purposes for some years (Thilmany, 2019). However, RAS is not yet well-established in the construction sector. According to *Construction Manager Magazine* in 2019, "[m]ost robots are prototypes with technological shortcoming and do not comply with current Building Regulations or health and safety requirements" (Cousins, 2019).

Selected RAS use cases

- **Off-site prefabrication:** Prefabrication off the construction site by RAS is a key use case in the construction sector. RAS can be used to build entire structures or just components or parts of structures offsite (de Laubier et al. 2019). Advantages include cost savings of up to 10% (ibid.) from improved productivity and economies of scale, improved quality from quality checks, standardisation and a more controlled construction environment, shorter project times and lower legal, financial and weather risks (ibid.).

[19] Where economic output is measured by GVA.

- **Assembling and demolishing buildings and structures on site:** Robots can also be used for the assembly and demolition of buildings and structures on the construction site.

  The use of robots for on-site assembly can complement the use of 3D printing, with robots printing prefabs and components on site and then assembling them (ibid.). 3D printing on site can increase flexibility (by making it easier to replace a component or prefab with a new one made on site) and reduce transport costs and building times (ibid.).

  The use of robotics can improve accuracy and efficiency in the performance of repeated tasks, like brick-laying (Matthews, 2019). Construction Robotics have produced a commercially available robot, the SAM100, which is capable of laying bricks at a rate of 350 per hour, which is faster than most human bricklayers (ibid.). Improvements in the ability of robots to work together and with human workers – with the rise of collaborative robots or 'cobots' – facilitate this application of RAS in construction (ibid.).

  Teams of robots are at present slower but safer and cheaper for the demolition of concrete and structural elements than conventional methods (Robotics Industry Association, 2018).

  The integration of RAS with digital systems such as computer-aided design (CAD) systems and, relatedly, the automation of whole processes presents especially large opportunities.

- **Site surveying and mapping:** Drones can be used for surveying and mapping in the construction industry. PwC estimate that performing site surveys and mapping with drones can reduce costs by 40% and be 400 times faster (PwC, 2018a). Goldman Sachs estimate that the total addressable market for drones in the construction sector is worth $11.2 billion (Goldman Sachs, 2016).

- **Powered exoskeletons:** Powered exoskeletons can be used to support construction workers performing a range of tasks. Exoskeletons are devices that are worn by the user (Delgado et al. 2019) that use sensors to detect the user's movements and moves to support that movement. In the context of construction, exoskeletons can be used to ease the physical demands of lifting heavy objects and performing repetitive tasks for a prolonged period of time (ibid.).

- **Rovers:** Rovers have a number of uses in the construction sector. One use is carrying tools, equipment and materials around building sites, using cameras to detect and avoid obstacles (Cortese, 2018). Another use is in monitoring progress by using cameras and LIDAR (LIght Detection And Ranging) to gather visual information about a site and comparing the results to design models and plans (ibid.). Here RAS can be integrated with building information modelling (BIM), which uses 3D models for building project and management (Autodesk, 2020). As of 2019, at least three international construction firms had trialled a site monitoring robot developed by Scaled Robotics (Cousins, 2019).

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

RAS can be used to automate the large number of repetitive, dangerous and physically demanding tasks that exist in the construction sector. Construction work often involves working at height, carrying heavy loads or using potentially dangerous machinery. Use of RAS can reduce injuries to workers associated with these dangerous tasks (Delgado et al. 2019). Construction was the UK sector with the highest number of fatal workplace injuries and the one of the highest annual average rates of fatal workplace injury per 100,000 workers between 2014/15 and 2018/19 (HSE, 2019). RAS can also be used to automate boring, menial tasks.

Another important driver of RAS adoption in the UK construction industry is its ageing workforce. The number of construction workers in the UK aged 45 or over rose by 13% between 1991 and 2011 (Gerrard, 2018). In 2011, an estimated one-fifth of UK construction workers born in the UK were aged over 55 (ibid.). In a survey conducted by L&Q, just 9% of the 16- to 18-year-olds surveyed said they would consider a career in housebuilding (L&Q, 2019). The ageing of the construction workforce is especially significant given the dangerous, manual nature of much of the work in this sector (described above).

Finally, construction is a labour-intensive industry in which productivity has been stagnant or declining over the last five decades (Delgado et al. 2019). In this context, adoption of RAS can be used to improve labour productivity and save on labour costs (ibid.).

Barriers to RAS adoption

Despite the prevalence of simple, repetitive and manual tasks in the construction sector, adoption of RAS has so far been slow. This is because there are several barriers to the adoption of RAS in the construction sector.

One is the structure of the construction sector. Many firms are small and have small budgets for new technologies (Delgado et al. 2019). This makes the high up-front costs of adopting RAS prohibitive for much of the industry. Even amongst the 100 top construction companies in the UK, the average profit margin in 2017 was 1.5%. In this context, firms are likely to tend to avoid large investments in an immature technology whose benefits are uncertain in size (ibid.).

There are also technical barriers to the adoption of RAS in the construction sector. Many construction tasks are complex, and construction sites are typically not simple environments. This makes applying RAS to problems in construction more difficult (Delgado et al. 2019). “Task complexity” was the most commonly reported barrier to making use of RAS in construction in the Manufacturing Technology Centre’s (MTC) Infrastructure Industry Innovation Platform (i3P) survey (MTC, 2017). Construction is also a high-risk context: any errors by robots on construction sites could have significant consequences (Delgado et al. 2019).

Finally, there are barriers arising from how robots and human workers will need to interact for construction work. Workers in the construction industry may at present lack the digital skills that would help them to operate and maintain RAS. Two factors reinforce this problem. One is the ageing of the construction workforce (see the discussion above); generally, older workers do not have the same digital skills as younger ones. The second is that the splintered nature of the industry (described above) hinders skill acquisition (Delgado et al. 2019). In addition, there is a lack of cultural openness to RAS and new technologies in general in parts of the construction industry, embodied in the small size of many construction firms’ R&D budgets (ibid.) and likely reinforced by a lack of digital skills. In a 2019 survey of construction workers conducted by Volvo Construction Equipment (Volvo CE),[20] the primary concern about automation on construction sites amongst construction workers was about the impacts on safety (Volvo CE, 2019). Nearly a third of construction workers responding to the survey

[20] The survey involved 2219 respondents across the UK and the US, including 205 construction workers. It was conducted in early 2019.

expressed concerns about automation putting their jobs at risk, making it the second most common concern about automation in construction amongst the construction workers surveyed (ibid.).

Wider impacts

Environmental and social impacts

The adoption of RAS in the construction sector has a number of potential environmental benefits.

The construction sector has an important role to play in combating climate change by increasing the energy efficiency of buildings. The benefits of improving energy efficiency were highlighted by the International Energy Agency (IEA) in a 2018 report (IEA, 2018). Improvements in construction automation and prefabrication can bring down the cost of highly energy-efficient components and buildings (Pan et al., 2018). For example, the BERTIM (2016) and ZERO-PLUS (2016) projects, funded by the European Union, use RAS in construction to produce eco-friendly buildings more cheaply and efficiently.

RAS can reduce waste from construction projects (Bock and Linner, 2015). Using RAS, the collection and sorting of waste can be integrated into the off-site prefabrication and on-site assembly processes (Bock and Linner, 2015). Compared to manual labour, RAS can bring about reductions in waste of up to 70% (Cousineau and Miura, 1998). Automation and robotics also can result in an increase in material recycling and a reduction in demolition waste (Pan et al., 2018).

Finally, adopting RAS can reduce the quantity of natural resources used in construction. For example, compared to human labour, construction automation and robotics can make much more efficient use of water resources (Cousineau and Miura, 1998).

RAS adoption is also likely to affect the labour market in the construction sector. Deloitte report that out of 2,607,000 jobs in real estate and construction, 34% are at a high risk, 15.5% at a medium risk and 50.5% are at a low risk (Smith and Bishop, 2016) of being automated. In the construction sector, many current jobs are taxing and dangerous and can involve repetitive work (Richardson et al. 2017). RAS is likely to be used to automate the more physically onerous, dangerous and repetitive tasks, freeing up the workforce to engage with more creative tasks in less physically demanding and dangerous contexts (Richardson et al. 2017). By creating jobs involving working inside and with technology, RAS may make working in the construction sector more attractive to young people (de Laubier et al. 2019). This would help to address the shortage of young people wishing to enter the industry and the ageing of the industry's workforce.

RAS could be used to undertake the most hazardous tasks currently undertaken by humans and hence contribute to a reduction in injuries and fatalities (Castro-Lacouture, 2009). Exoskeletons can prevent common back injuries amongst construction workers (Delgado et al. 2019) by reducing the physical demands placed on these workers. RAS technologies could have positive impacts on the wellbeing of employees (Pan et al. 2018).

Impacts on business resilience

Using robotics and autonomous systems in the prefabrication of building elements could make the construction sector more resilient to extreme weather events which disrupt construction site projects.

As mentioned above, RAS can be used in construction prefabrication (Jeska and Pascha, 2014). Prefabricated modules are also recognized as making construction projects more resilient to adverse weather conditions. In times of climate change and intensified extreme weather, prefabrication has emerged as an alternative method of construction (Fenner et al. 2017). Thunderstorms, extreme heat or cold, hailstorms, lightning, drought and microbursts can create substantial problems which derail a project. Bad weather threatens workers' safety and can cause significant damage to equipment, materials and the construction site itself (Reutter, 2019). Prefabricated construction allows the building of homes efficiently and quickly, reducing the time spent on construction sites from months to weeks and thereby diminishing the potential impact of adverse weather (Fenner et al. 2017). Extreme weather events are increasing not only in frequency but also in severity and duration (Reutter, 2019). Extreme weather was deemed to be the most likely and the third most impactful risk to the global economy in the World Economic Forum (WEF) Global Risks Perception Survey 2019 (WEF, 2019).

Economic opportunities from RAS in energy

The energy sector is a critical sector that supports virtually all other economic activity (Richardson et al. 2017 makes this point about infrastructure in general). It is also a growing sector: GVA in the energy sector increased by around 6% between 2017 and 2018 (Energy UK, 2019). Energy demands are almost certain to increase as the UK's population and economy grow.

The UK's energy sector, then, will need to meet growing demand while existing networks age (Richardson et al. 2017). There is also pressure to change the way in which energy is produced; the UK has committed in law to achieve net zero greenhouse gas emissions by 2050 (UK Government, 2019). Much work in producing and transmitting energy involves hazards (both natural and artificial), and there are large costs associated with mitigating these hazards. Energy systems, because of the strains put on them and their importance, require frequent inspection and maintenance, often in hazardous environments. All of these factors suggest large potential for RAS in this sector.

This section looks at oil and gas extraction, energy production (including from renewable sources), energy transmission, and nuclear energy.

Current RAS landscape

Current adoption and maturity of RAS

RAS has already begun to be deployed in the energy sector, and their use is poised to increase (Innovate UK, 2016).

Oil and gas companies have used remotely operated vehicles (ROVs) for a number of years for subsea inspections (Maslin, 2019). Companies are now trialling the use of autonomous underwater vehicles for such inspections (ibid.); by 2025, BP plans to use marine autonomous systems for all of its subsea inspection (ibid.). Similarly, remotely operated systems are already in use in Sellafield (see e.g. Sellafield Ltd, 2019), and autonomous systems are likely to be introduced soon (given the call for solutions to the "challenges" above). Inspection of powerlines by drones is increasingly prevalent (Bruns, 2019); PwC describe drone use as "well established in the utility industry", citing inspection of powerlines as a key use case (PwC, 2018a).

Selected RAS use cases

- **Inspection, maintenance and repair:** Inspection, maintenance and repair of assets in the energy sector are tasks that could be automated with RAS. In particular, RAS can be used to inspect energy sector assets in environments that are dangerous or difficult for humans to access, of which there are many in the energy sector. These include off-shore oil rigs, off-shore wind farms, and deep-sea oil pipelines. RAS can also be used in conjunction with analytics to perform proactive and preventative maintenance (Richardson et al. 2017).

- **Nuclear energy:** RAS has a number of applications in nuclear energy, which is projected to account for close to half of the UK's energy supply by 2030. The dangers to humans of radiation make RAS especially important in the case of nuclear energy. One important area in which RAS is being applied in nuclear energy is nuclear decommissioning, the process of dismantling retired nuclear power plants, removing the associated waste and reducing the site's radiation levels to safe levels (World Nuclear Association, 2020a). Sellafield, a large nuclear site in the UK, has put out a call for robotic innovation in relation to three challenges (Game Changers, 2019); these are 1) Deployment techniques to allow remote working at height in high hazardous area; 2) Autonomous removal of Special Nuclear Material (SNM) packages from a store to a transport container for export; and, 3) Remote inspection of SNM packages (ibid.).

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

An important driver of RAS adoption in this sector is the promise of safety improvements; much work in this sector is done in hazardous environments. Drones have been used to automate tasks involving work at height in the oil and gas industry (PwC, 2018a); falls from height were the most common cause of fatal workplace injuries in the UK in 2018/19 (HSE, 2019). As described above, RAS can also be used to automate inspection and maintenance in other hazardous or remote contexts, such as offshore oil rigs and offshore wind farms, or deep-sea pipelines. Humans in hazardous or remote environments involves a higher risk of injury or death, and additional costs associated with measures taken to mitigate risks and with compensating workers for the higher risk they face. As mentioned above, BP, one of the largest oil and gas companies in the world, is seeking to automate all of its deep-sea inspection by 2025 (Maslin, 2019).

The use of RAS can significantly reduce the costs and disruption associated with inspection and maintenance. Drones and other RAS allow for the inspection of live assets. RAS can be used to inspect assets while they are still in operation, where normally they would have to be taken offline to be inspected. This reduces costs. For instance, flare stacks – used in oil production to burn off excess natural gas captured during the oil production process[21] (World Bank 2020a) – must be temporarily shut down for normal inspection. Drones can inspect flare stacks while they are live, and this can save over £4 million per day (PwC, 2018a). In addition to such cost savings, inspection of live assets can prevent disruptions to service. It also allows more frequent inspection (Innovate UK, 2016). Drones can also inspect assets more quickly than conventional methods: an underdeck inspection of an oil platform can be done more than ten times more quickly by drone than by the conventional approach (PwC, 2018a). Drones can

[21] While much of the gas collected is used or otherwise dealt with, some has to be burned off 'because of technical, regulatory, or economic constraints' (World Bank, 2020b).

also be used to inspect pipelines and power lines more cheaply than helicopter crews (though this depends on how drones are regulated – see p.48 below).

RAS can also reduce costs and waste and extend assets' lifetime by allowing more frequent and more proactive maintenance of energy sector assets. Frequent inspection by RAS along with Big Data and sophisticated analytics can facilitate the identification of emerging problems, so that they can be addressed at an early stage (Innovate UK, 2016; Richardson et al. 2017). Doing so can prevent more serious problems building up, avoiding the costs and potential downtime associated with major problems. RAS can also spot and fix leaks in pipelines as they form, reducing waste.

Finally, the UK's ageing energy system will need to satisfy growing demand and increasing consumer expectations in the coming years and decades (Richardson et al. 2017). At the same time, there is pressure for the energy system to be more efficient in it uses of scarce natural resources and to shift away from forms of energy that produce greenhouse gas emissions. The cost and efficiency improvements associated with the use of RAS – discussed throughout this section – can help the sector to meet these demands. Further, Remotely Piloted Aircraft Systems (RPAS) are being deployed by the European Maritime Safety Agency (EMSA) to, amongst other functions, monitor emissions of sulphur oxides and carbon dioxide from ships that burn fossil fuels to propel them (EMSA, 2018).

Barriers to RAS adoption

There is a need for safety validation of RAS in energy sector applications, where RAS will often be operating in hazardous, high-stakes environments. The hazardous and complex nature of many energy sector environments makes deploying RAS in the energy sector technically difficult (Robotics in Australia, 2020); RAS will need to be tested extensively in this sort of environment to achieve such validation. There are industry standards that RAS must meet (Innovate UK, 2016). There will also need to be a legal framework for the use of RAS in this sector (ibid.), given the aforementioned high stakes. The issues around research funding and test centres discussed in relation to RAS in infrastructure (see p.61) are also relevant here.[22]

Relatedly, there are cultural barriers to RAS adoption in the energy sector. In much of this sector, decision-makers are cautious and slow to adopt new technologies. Decision-makers in this sector tend to be risk averse (Innovate UK, 2016), and there is the potential for serious consequences if things go wrong in the energy sector.[23] These cultural barriers may be especially important in the nuclear arena (see e.g. Nuclear Decommissioning Authority, 2017). The Nuclear Decommissioning Authority (NDA) Research Board describes how this caution combined with a lack of understanding of RAS leads to "an irrational phobia of automation, non-evidence based assessment of RAS system safety and over-engineering for low probability, low consequence events" at Sellafield and the Atomic Weapons Establishment (ibid.). Government-backed innovation hubs can, however, alleviate this problem by providing opportunities for RAS technologies to be researched and trialled. Such hubs bring together academics and industry experts. Successful trials and demonstrations of RAS technologies can allay fears amongst decision-makers about deploying them. For instance, the National Centre for Nuclear Robotics (NCNR) conducts research into how robotics and other advanced technologies can be used to deal with nuclear waste and was the recipient of £42 million of government funding (NCNR, 2020). The Offshore Robotics for Certification of Assets (ORCA) Hub conducts research to support the goal of automating the offshore energy sector and

[22] Energy supply is typically considered to be part of infrastructure.
[23] Consider, for instance, the Chernobyl disaster or the Gulf of Mexico oil spill.

received £36m (Department for International Trade, 2019) of funding through the Industry Strategic Challenge Fund (ISCF) (ORCA Hub, 2020).

Finally, as in the case of agriculture (see p.39), the uptake of drones is likely to be affected by regulations applied to drone use. In particular, the use of drones for the inspection of assets like pipelines and powerlines is likely to be inhibited if regulations forbidding the flight of drones beyond the user's line-of-sight remain in place (Goldman Sachs, 2016; PwC, 2018a). Beyond-line-of-sight flight is necessary to maximise the cost advantage of drone inspection compared with inspection by a helicopter crew.

Wider impacts

Environmental and social impacts

By making sustainable energy sources including offshore wind, nuclear power and solar power cheaper, safer and more efficient, RAS could greatly reduce the environmental impact of energy production. Adopting RAS to expand the renewable energy industry could help the UK achieve its carbon budgets (Priestley, 2019).

The UK already has the largest installed capacity of offshore wind in the world (Watson, 2019). Under the Offshore Wind Sector Deal, the industries ambition is to quadruple wind power generation in the next decade (Penman, 2020). A large part of the cost of operating and maintaining offshore wind farms comes from inspection and repair missions (Watson, 2019). RAS could fulfil most offshore maintenance tasks at greatly reduced costs, allowing for the expansion of offshore wind production (ibid.). With RAS technology, which allows for the remote maintenance of offshore windfarms, new windfarms can be constructed further from the shore where energy production is higher (ibid.). The MIMRee project, for instance, is working to develop the world's first fully autonomous inspection and repair solution for offshore wind farms (ORE Catapult, 2019).

An expansion of offshore wind power generation aided by the adoption of RAS could regenerate coastal communities (BEIS, 2019). Since most offshore wind operational clusters are on UK coastlines, an expansion in the offshore wind industry could create skilled, fulfilling, well-paid jobs in former fishing villages and ports.

Nuclear power in the UK currently generates around 20% of the country's electricity (World Nuclear Association, 2020b). Adopting RAS for reactor maintenance in the nuclear power industry can extend the life of a nuclear reactor, reduce risks and increase efficiency (Innovate UK, 2016). RAS can also be used for the safer processing of nuclear waste (ibid.). If RAS is integrated into the design of new power stations so that maintenance and inspections become embedded, new reactors could be safer and maintenance costs lower. Furthermore, RAS can be used for the safer decommissioning of old nuclear power stations (ibid.).

Solar power is the third greatest source of renewable energy in the UK (Greenmatch, 2020), generating 6% of the UK's electricity (Ambrose, 2019). The solar power industry could benefit greatly from the adoption of RAS. RAS can be used to manufacture solar panels more cheaply and efficiently (Brumson, 2011). Furthermore, RAS can be used to systematically clean the dust and grime that accumulates on solar panels, increasing energy production. Greenbotics makes a solar-panel-cleaning robot called "CleanFleet" which they claim can boost a project's electricity production by 15% (Woody, 2013).

RAS can be used to clean oil spills quickly and efficiently. The Global Response Group Corporation's AEROS (Airborne Emergency Response to Oil Spills) is a robotic oil spill emergency response, rapid containment and recovery system which can recover up to 90% of spilled oil (Calderone, 2013).

Using RAS in the energy sector could also bring about significant improvements in worker safety. Inspections and repairs of energy infrastructure can be dangerous because, as described above, they are often carried out in hazardous environments. These inspections and repairs can be performed more safely using RAS (Innovate UK, 2016).

Impacts on business resilience

Increasing the capacity of the UK renewable energy sector through the adoption of RAS could make the UK economy more resilient to global shocks which cause oil price fluctuations. By increasing the share of energy that comes from renewables, the UK could become less susceptible to oil price volatility and could build towards complete energy independence (Findlay, 2020).

RAS can also be used to repair energy systems quickly and efficiently and undertake more frequent inspections of energy infrastructure. Better-maintained energy infrastructure is more resilient to extreme weather, natural disasters or man-made damages (Richardson et al. 2017).

Economic opportunities from RAS in food & drink

Food & drink is a sector which can be split between production, preparation and customer-facing applications. Manufacturing aspects of the sector include packaging and preparation of food products, which are then sold to businesses and consumers. Hospitality-focused aspects of the sector include robots which cook and prepare food and drink in restaurants (and similar establishments). RAS can be incorporated at different points along the food & drink supply chain impacting manufacturers and consumer-facing businesses.

Automation within this sector could increase productivity growth in food processing and wholesaling from 1.4 percent to 3.0 percent per annum - increasing food chain GVA by 8.3% above the underlying trend by 2022 (UK Government, 2017b). Changing consumer expectations, changes in the labour supply and increasing maturity of sector-specific RAS provide the incentive and means for widespread adoption of RAS.

Food & drink, when combined with agriculture, forms the larger agri-food sector (Duckett et al. 2018). This sector generates over £108 billion per year and employs 3.9 million employees – the largest manufacturing sector in the UK. This sector faces widespread labour shortages driving the sector towards RAS adoption. There are significant opportunities for efficiency improvements from RAS adoption across the agriculture and food & drink sectors.

Current RAS landscape

Current adoption and maturity of RAS

The variability of food items has caused difficulties for robots to grip and handle them (Paoli, 2020). Whilst this has hampered adoption of RAS in food & drink manufacturing, recent developments in soft robotics are changing this. Adoption of RAS is increasing within food & drink manufacturing with an increasing number of manufacturers incorporating robots into their production – with a 50% increase over the past five years (Ridler, 2019). Most robot applications present within food & drink manufacturing are focused within packaging, product casing and palletisation; there remains untapped potential for RAS to be integrated into production and processing workflows (Paoli, 2020).

New developments in RAS applications have emerged from companies such as Soft Robotics (with their soft mGrip grippers) (Soft Robotics, n.d.) and IBM (who have developed an e-tongue which allows for the sensing of liquids) (Ruch, 2019). Technology advances such as these allow sector-specific RAS applications to enable significant impacts and levels of adoption. As RAS applications mature - with the capacity to automate increasing amounts of tasks within the manufacturing chain - RAS becomes more viable to integrate, and rates of adoption will rise.

Adoption of robotics for hospitality-related aspects of the food & drink supply chain is significantly more limited. Whilst there have been use cases and examples of robot chefs and robot-assisted preparatory robots in the US (Statt, 2018), uptake in the UK has been much sparser. Incorporation of food & drink robots into the operations of restaurants are very limited at this stage. This includes co-bots, such as robotic arms, and automated conveyer belts which can handle multiple components of the food preparation process.

An example of a UK-based supplier who have developed off-the-shelf RAS applications for restaurants is Karakuri (Karakuri, n.d.). Their products, based on robot arms used within factories and manufacturing, are for integration within restaurant kitchens to aid with preparing and processing, while providing consumers increased levels of control over food customisation. While Karakuri have received investment from Ocado and input from chefs such as Heston Blumenthal, the adoption of their robots has not expanded beyond limited use within Ocado’s test kitchens (Katwala, 2020).

As of 2019, there have also been limited examples of restaurants incorporating robotic waitresses (Monk, 2019). The CEO of industry trade body UKHospitality does not see automation having a significant effect on the number of people employed within the (hospitality) sector, due to the sector’s focus on individual tailoring and personalisation of consumer experiences (NatWest Business Hub, 2020b).

Selected RAS use cases

- **Food packaging and manufacturing robots:** RAS can be adopted in the form of food packaging and manufacturing robots (LAC Conveyers & Automation, 2019). These applications can automate picking, packaging, and preparation of food products. Developments in soft robotics have led to advanced grippers which enable quick but gentle handling of fragile food products, such as fruit and vegetables. The automation of these processes reduces worker strain while increasing production line efficiency. As soft robotics develops, the number of processes which can be automated increases.

  RAS can also be used for food processing - applications in meat processing can expedite slaughterhouse production lines (Molteni, 2020)

- **Robot sensing:** RAS applications also include robots with advanced sensors. These sensors can detect odours and identify contaminants and pathogens using human-style taste buds and noses (Edwards, 2020). These robots increase quality and enhance consumer safety by reducing human error in quality assurance.

- **Food & drink preparation robots:** Hospitality RAS applications include food & drink preparation robots - such as robots which flip burgers or mix drinks (Millward, 2018). These applications take the form of automated assembly lines - which handle aspects of the preparation process such as vegetable chopping, meat frying and condiment dispensing - and robot arms which can work alongside existing human capability.

Restaurants incorporating RAS can transform large portions of the consumer experience including the ordering, preparation and serving of food & drink. These robots convenience the consumer by increasing preparation speed while simultaneously increasing efficiency and productivity for the business (Statt, 2018).

- **Robot waiting staff:** Other hospitality-related RAS include robot waiting staff (French, 2020) which can carry food & drink to diners from the kitchen. These robots reduce the labour burden on restaurants, enabling staff to focus on other areas of operation.

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

Changing consumer expectations is a driver leading to increased RAS adoption within the food & drink sector. Consumers are demanding increasing convenience and personalisation in their dining experiences (Statt, 2018) and the incorporation of RAS help to fulfil these changing demands. Consumers' increasing demand for sustainability has led to a focus on reducing waste, which can also be achieved through RAS through increased precision and reduced error (as a result of minimising production errors) (Geijer, 2019).

Increasing cost (and dwindling supply) of labour is a driver for RAS adoption. Cheaper labour incentivizes producers to reduce capital investment to improving efficiency (Atherton, 2017). However, with rising labour costs - due to increases in the national minimum wage, for example - as well as a potential reduction in the EU-migrant labour force in the wake of Brexit, producers are looking towards RAS to improve their productivity. EU nationals comprise around 20 percent of the UK food & drink supply chain – a third of business owners claim their businesses will become unviable without access to EU workers. The industry recognises these labour market changes necessitates upskilling existing employees to move towards increasing digitisation and automation (NatWest Business Hub, 2020a).

Barriers to RAS adoption

Consumer demand for greater sustainability with food packaging manufacture has been increasing due to increased focus on environmental concerns. Trends have resulted in packaging becoming increasingly fragile due to a reduction in plastic use (Demetrakakes, 2020). This trend (which is also present in the logistics industry) requires RAS applications to be able to handle delicate and fragile packaging materials. As the technology of soft robotics (robots capable of handling fragile materials) increases, the significance of this barrier to RAS adoption should decrease.

There is a necessity for sanitation in the food manufacturing process (Demetrakakes, 2020). Machinery used in food & drink-related contexts require regular sanitation and washdowns with highly pressurised and/or caustic liquids. Due to the cost of RAS, plant operators are hesitant to introduce expensive machinery into an environment where they may be damaged from this sanitation process. Recent developments include prototypes which are washdown-safe and can be cleaned using high-pressure sanitation.

As shared with the logistics sector, introducing RAS into food packaging and manufacturing also introduces additional workforce skill requirements. Although RAS can automate simple tasks and replace unskilled labour, the integration of these systems requires engineers, electricians, and robot maintenance specialists (Vincent, 2018). Adopting RAS also requires engagement from existing employees and plant operators to ensure smooth interoperability between the automated and non-automated aspects of warehouse responsibilities (Demetrakakes, 2020). For firms looking to incorporate RAS, they must ensure that they have both the skillset and engagement from their personnel for smooth integration.

In the food manufacturing and processing sector, RAS is viewed as inappropriate in some circumstances because these circumstances require human skill, dexterity and judgement. For instance, the British Meat Processors Association, the biggest trade association for the UK meat and meat products industry, has in a number of publications cited this as a reason why automation is not a complete solution to the labour shortage problems the industry faces (see e.g. British Meat Processors Association, 2019). This reflects both technical challenges and that attitudes in the industry are not conducive to extensive uptake of RAS.

Separate barriers exist for the adoption of hospitality-related RAS. Robots preparing and serving food & drink need to be able to handle flexible and bespoke ordering demands (such as dietary requirements) (NatWest Business Hub, 2020b). This need for flexibility combined with the importance of human interaction within hospitality is a consumer-side barrier preventing the sector from adopting increased levels of RAS.

Wider impacts

Environmental and social impacts

Incorporating RAS into the food & drink sector has the potential to reduce food waste, improve transparency across the food chain, increase safety and shift labour patterns across the supply chain.

Food waste contributes a significant portion of global greenhouse gas emissions. Seven percent of global greenhouse gas emissions is contributed by food waste - with an estimated 1.7 million tonnes wasted in the UK per year (Tatum, 2018). RAS reduce human error across early stages of the manufacturing chain, such as handling, preparing and the weighing of raw ingredients. The reduction in this human error leads to lower rejection rates of food products further along the supply chain and food waste can be greatly reduced (especially when paired with increased efficiency of food processing) (Industry Forum). Introducing RAS for picking and packaging also reduces the time takes for products to reach store shelves, increasing shelf life and reducing food waste (LAC, 2019).

Using RAS for packaging can enable earlier labelling and tracking of food products, increasing food traceability. Greater information for a wider portion of the supply chain can facilitate benefits such as improved information for consumers and increased capacity for manufacturers to mitigate potential safety issues (Duckett et al., 2018).

RAS reduces risk of human contamination in food processing and preparation (LAC, 2019). Cross-contamination of food can be caused by human staff sneezing or coughing near food, or from unhygienic handling of products. The use of robots in food preparation minimises the risk of this occurring. This risk is lessened further as robots capable of withstanding sanitation become more prevalent within the sector (Food Standards Agency, 2018).

RAS in manufacturing minimises health and safety risks (Industry Forum). Manufacturing assembly lines within the sector can involve manual handling and repetitive motion tasks, both activities which can result in worker harm (Smart, 2017). The automation of these tasks with RAS reduces these risk factors.

The sector will experience labour shifts as RAS is increasingly used to solve labour shortages. RAS will likely replace the jobs in food manufacturing that are demanding, dangerous or involve large amounts of routine tasks (Duckett et al., 2018) and instead create positions for higher skilled workers necessary for the maintenance and operation of RAS (such as engineers). The hospitality side of food & drink will also incorporate more automation, with a predicted 25% of routine tasks in the industry to be conducted by robots by 2030 (Martin, 2019). However, the majority of tasks that are predicted to be automated will involve routine manual work such as restocking and cleaning; human-to-human interaction is still considered an important aspect of hospitality, and one which will not be rapidly replaced by applications such as robot waiters.

Impacts on business resilience

The sector’s issues with labour supply must be solved to ensure continued resilience. In January 2018, a survey by the Association of Labour Providers found that 70 percent of food & drink manufacturing companies were suffering from a shortage of low and unskilled labour (LAC, 2019). The problem of labour force and shortages may continue to increase if Brexit were to lead to a fall in immigration into the UK from the EU. Robotisation of these jobs is an important objective for companies looking to mitigate increasing production costs linked to current and future labour shortages (Duckett et al., 2018).

Economic opportunities from RAS in health & social care

Health & social care account for more than 10% of UK GDP (Ramanauskas, 2019). Public spending on healthcare has been continually increasing; to maintain the current trend of healthcare provision - without continually increasing public spending - costs will have to be reduced and services will have to become more operationally efficient. RAS presents an avenue for health & social care to keep up with societal demand.

Examples of RAS use cases can be prevalent (and used within NHS hospitals) or experimental and prototypical. The integration of RAS in this sector improves human capability, worker safety, customer experience and the quality and output of service. Further impact can be obtained with RAS reducing operational costs and increasing productivity.

Current RAS landscape

Current adoption and maturity of RAS

Surgery robots have been used for almost forty years and have developed into a mature application of RAS. Recently, a Cambridge-based robotics firm has designed the ‘Versius’ robot, a robot capable of performing laparoscopic surgery (which requires smaller and more accurate incisions than open surgery). This robot (capable of greater accuracy than previous systems such as the da Vinci surgery robot), is now being trialled at NHS hospitals in Edinburgh and Milton Keynes (CMR Surgical, 2020).

Adoption in the UK is steadily increasing, with more NHS hospitals incorporating robotic surgery into their procedures. There are examples of recent use at hospitals in London (The London Clinic, n.d.), Essex (Mid and South Essex NHS Foundation Trust, 2017) and Scotland (Summers, 2019). As modern surgery robots continue to be developed, they will continue to become smaller, cheaper, and more versatile (Royal College of Surgeons, 2018). As these robots become more affordable and accessible, RAS adoption in this field will also increase – current trials of CMR robots are additional examples of increasing prevalence (CMR Surgical, 2020).

Adoption and maturity of RAS in social care, such as robot nurses or RAS-assisted care devices, is more limited in comparison. Examples of robot social care applications exist as prototypes or have only been administered on a limited basis within their country of origin (with many these prototypes developed by Japanese firms). However, trials are currently testing Pepper robots (Booth, 2020) and exoskeleton co-bots (which are worn along the lower back to help carers move objects and people) (Pyke, 2020) within UK care homes.

UK-developed devices such as JUVA (Chiron, n.d.) and GenieConnect exist, but they are either in early-stage development or prototype stages. Maturity and adoption of these robotic nurses and social-care specific RAS applications remains weak in the UK.

Mature RAS applications, such as autonomous vehicles transporting materials or disinfecting hospital surfaces and rooms, exist in the sector. Autonomous vehicles are a well-researched and well-funded area of RAS in the UK, with a research centre for connected and autonomous vehicles established by the Department for Transport and Department for Business, Energy & Industrial Strategy (GOV.UK, n.d.). Despite the maturity of this technology, evidence for adoption within medical and social care contexts is limited. There is evidence of few hospitals installing disinfectant robots (Pinkstone, 2020) and transport vehicles (Brown, 2015).

Despite current evidence of RAS adoption across the sector, future uptake and adoption will be dependent on the success of initial trials and prototypes, and the ease of replicability these new inventions have across the sector.

Selected RAS use cases

- **Robot surgery:** Robot-assisted surgeries have existed since the 1980s (Lechky, 1985), and their use has become more prevalent as technology has increased, with robots now used for a variety of medical procedures such as heart and gastrointestinal surgeries. The benefits of these robots include reducing the fatigue of operating surgeons, improving recovery times for patients (through the usage of minimal access procedures), and improving career length for surgeons (due to the comfort and efficiency provided). Over six million surgeries worldwide have been performed by American-developed da Vinci surgery robots (Utley, n.d.) since its introduction in 2000; this figure includes procedures which have been carried out in the UK from as early as 2004 (Guy’s and St Thomas’ NHS Foundation Trust, n.d.).

- **Robot nursing:** Multiple examples of robotic nursing and social care use cases improve the experience of patients requiring long term care. Robots can reduce strain on caregivers and nurses, as well as provide new forms of care for patients. Examples include (Luca Robotics, n.d.):

  Pepper, a Japanese-developed robot nurse which allows patients to schedule appointments as well as monitoring patient vitals (SoftBank Robotics, n.d.).

  Paro, a robotic seal used to administer animal therapy for patients, especially for those in long-term care and those suffering with dementia (PARO Robots, n.d.).

  Robear, a robotic bear which can be used to help lift patients, reducing strain on nurses and caregivers (Dredge, 2015).

  Adoption of robotic nurses and robot-assisted care is limited in the UK although robotic projects such as UK-based GenieConnect (GenieConnect, n.d.) continue to raise high levels of investment; this suggests that potential future market opportunity exists.

- **Autonomous vehicles and disinfectant robots:** Autonomous vehicles which can transport supplies, food, and hazardous waste, have been incorporated into at least one NHS hospital (Brown, 2015). Other examples include disinfectant robots, which can disinfect rooms without the need of human staff (Martin, 2016). These autonomous robots improve operating efficiencies by supplementing hospital staff responsibilities, and increase worker safety by reducing exposure to contaminants and hazardous materials.
- **Drones:** Drones are also being trialled to deliver medical supplies to the Isle of Wight and islands in the Scottish Highlands. (Skyports, n.d.) (University of Southampton, 2020)

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

To match the increasing demand for health & social care, public spending on health (as a percentage of national income) is projected to increase to over 12% of national income by 2067 (Ramanauskas, 2019). This increasing demand (and associated spending) leads to pressure for reducing costs - RAS is a possible route to obtain these cost savings.

The time and cost savings achieved from automation can be as high as £12.5bn per year for NHS staff in time savings (Ramanauskas, 2019). In addition to this, there is potential for savings of £5.9bn per year for social care staff, and multi-million savings in specific areas: pathology, mental health medication, and cardiovascular diagnostics.

An ageing population also places additional strain on health & social care, leading to robotics manufacturers releasing innovations (such as robotic nurses) which assist with palliative care. The 19% of UK population which are above pension age (in 2016) stands to increase to 23.1% by 2066; increasing demand for long-term social care will also increase the adoption of RAS in these areas (Ramanauskas, 2019).

The need for health & social care is exacerbated by a current shortage of healthcare workers in the UK. By 2030, the NHS workforce gap could reach almost 250,000 (from its current level of around 100,000). Additionally, one in 10 social worker and one in 11 care worker roles are currently unfilled, and an estimated 650,000 to 950,000 new adult social care jobs will be needed by 2035 (Macdonald, 2020).

Key drivers pushing RAS adoption in health & social care are the need for reducing costs, a population which is ageing and a workforce which is diminishing. RAS can increase time and cost savings and fill workforce shortages which look to increase in coming years.

Barriers to RAS adoption

The cost of robots, especially surgery robots, is a barrier for RAS adoption in the health & social care sector. For example, the cost of acquiring and installing a da Vinci surgery robot is £2 million, with additional costs of £3000 per procedure (Med-Tech Innovation, 2018). However, these costs are falling and new business models (such as monthly rentals) are emerging, making RAS increasingly accessible for the healthcare sector. As the introduction of cheaper and more accessible alternatives enter the market, this barrier will become less impactful.

Previously slow entrance of competitors has also been partly caused by restrictive patents held by the creators of the da Vinci system (Rassweiler et al., 2017). The expiration of these patents in 2019 have allowed the creation and development of cheaper alternatives, such as the Versius or German ‘MicroSure’ systems. This barrier to entry may reduce as the number of competitors and alternatives increases.

Negative viewpoints and lack of pull from professionals and patients (Cresswell et al., 2018) also impedes RAS adoption. Integration of medical robots have been met with negative emotions, caused by poor publicity, pop culture and general misinformation. Patients may lack trust in robots to carry out sensitive health-related procedures and professionals view incorporation of robots as threats to their positions. Limited levels of exposure and a lack of pull from patients and professionals discourages adoption of RAS.

In addition, RAS also require specific technical and digital skills, necessitating the need for additional skills training for doctors and other healthcare workers. For example, while robotic surgical systems have already been adopted for various procedures, there has been a lag in the development of a comprehensive training and credentialing framework (Sridhar et. al., 2017).

RAS integration also has ethical and legal challenges (Cresswell et al., 2018). A lack of clear and established liability rules contributes to unease when adopting new technologies and negative public attitude. A need for legislation to cover potential liability, without stifling innovation, will assuage these concerns and encourage further uptake.

Adoption of RAS is affected by the ease of which technology providers can deliver new solutions for the NHS (Ramanauskas, 2019). Technology providers often experience poor procurement practices, difficulty with interoperability with existing NHS systems and scalability between different NHS trusts. For the NHS to take advantage of RAS, their procurement practices will need to be adjusted to facilitate greater uptake. The NHS are currently in the process of reducing these barriers which should have a positive effect on RAS adoption.

Wider impacts

Environmental and social impacts

RAS has the potential to transform the health & social care landscape. They can improve medical diagnosis, undertake complex surgeries, and help face the challenges relating to an aging population. However, there are social concerns over the effect of RAS on jobs in this sector and whether RAS will lead to lack of human contact.

The application of robotics in healthcare could lead to vast improvements in patient outcomes (Dolic et al. 2019). For example, robotic systems can improve the accuracy of diagnosis - computer-aided diagnosis for colonoscopy can detect polyps with over 95% accuracy (Mori et al., 2017). RAS can also be used to improve precision in surgical interventions and microrobots can make minimally invasive surgery possible (Nelson et al., 2010). Moreover, recent estimates by Nepogodiev et. al. (2019) suggest that that at least 4.2 million people worldwide die within 30 days of surgery each year, more than from all causes related to HIV, malaria, and tuberculosis combined (2.97 million deaths).

Robotics and autonomous systems can also address the growing demand for long-term care across the UK, which is exacerbated by an ageing population (Tan and Taeihagh, 2020). Adopting RAS in long-term care can relieve the pressure on nursing homes and carers. Robots and autonomous systems enhance mobility, administer medication, provide companionship to older people and help them maintain independence at home (Draper and Sorell, 2017).

Introducing RAS in healthcare could have employment consequences. A PwC survey of healthcare professionals revealed that several medical specialities, starting with anaesthesiology and surgery, are at risk of being replaced by robots within the next 10-20 years (Suarez, 2018). Concerns have also been voiced over the potential loss of human contact if health & social care workers are replaced by robots. Social interactions and human touch are deemed vital in easing loneliness and preserving well-being (Tan and Taeihagh, 2020).

RAS can also complement existing healthcare workers' responsibilities (Tan and Taeihagh, 2020). Auxiliary robots, such as the Moxi robot by Diligent Robotics, can perform routine jobs (like restocking and cleaning) so that nurses and other care workers can spend more time providing personalised care. The focus for human employees will likely shift towards care giving roles and away from repetitive tasks (Suarez, 2018).

Impacts on business resilience

Adopting RAS can improve the resilience of health & social care systems by improving the ability of healthcare systems to withstand surges in demand, labour shortages and COVID-19.

RAS can supplement the hospital workforce and help cope with surges in healthcare utilisation (Simeone, 2015). A typical healthcare facility depends on the availability and sufficiency of staff (Achour and Price, 2010) and unprecedented surges in demand (e.g. after a natural disaster) can result in staff shortages. A healthcare robot can work throughout (barring maintenance and other periods of downtime) peaks in healthcare demand and can be idle when demand is low. This grants healthcare institutions more operational flexibility and resilience.

RAS can make healthcare systems less susceptible to labour shortages. A briefing by the King's Fund, the Health Foundation and the Nuffield Trust estimated that NHS staff shortages could reach just under 250,000 by 2030 (The King's Fund, 2018).

Finally, RAS makes it possible for healthcare workers to treat patients from a safe distance, making healthcare systems more resilient to COVID-19. Autonomous robotic systems allow for surgical interventions while lowering virus transmission risk to both staff and patients (DiMaio et al., 2020). The UK-RAS network has also recently announced a new Medical Robotics Challenge for Contagious Diseases seeking new RAS innovations to combat contagious diseases (UK-RAS Network, 2020).

Economic opportunities from RAS in infrastructure

The infrastructure sector is difficult to define. A distinction can be made between so-called "economic" infrastructure and "social" infrastructure. Social infrastructure, like schools and hospitals, "primarily provides social services" (Atolia et al. 2017). Economic infrastructure supports the general function of the economy (ibid.), and includes transport networks (such as roads, railways, and ports (ibid.)), energy supply, water supply, telecommunications, and systems for waste and sewerage. This section is concerned only with economic infrastructure. This study treated energy separately in its qualitative analysis (see the qualitative energy sector section above, starting at p.46). Without adequate infrastructure, an economy cannot function optimally (see e.g. World Bank, 1994). A number of studies confirm empirically that infrastructure investment increases GDP (see e.g. National Infrastructure Commission, 2017). Infrastructure is, therefore, a crucial sector.

As in the case of the UK's energy networks, the UK's infrastructure networks are set to face increasing demand because of a growing population, increasing urbanisation and increasing consumer expectations (Richardson et al. 2017). Infrastructure networks, in part because of the heavy demands placed on them, need frequent inspection and maintenance interventions. RAS can be used to do this inspection and maintenance more frequently, more proactively and with less disruption. It also offers safety improvements in an industry where there are a number of hazards.

Infrastructure investment by the UK government was £18.9 billion in 2016, accounting for 36% of total government investment (ONS, 2018b). Alongside this, private investment in infrastructure was £10.3 billion (ibid.). Infrastructure is a hugely valuable sector, and RAS applications have the potential to be transformative. As with the energy sector, RAS can enable live maintenance within hazardous environments reducing potential disruption. The size of the sector and potential benefits are compelling reasons for increased RAS uptake. PwC estimates the total addressable market for drones in the infrastructure sector globally is more than $45 billion (PwC, 2016).

Current RAS landscape

Current adoption and maturity of RAS

The deployment of RAS in infrastructure has already begun, but the level of adoption and the maturity of technology varies between different application areas. The infrastructure area is broad one, and it can be useful to consider different sub-sectors in turn.

In the utilities industry, drone use was described as “well established” in 2018 (PwC, 2018a). Currently, drones are most commonly used in inspecting “long, linear assets” such as powerlines and in mapping and monitoring dams and sub-stations (ibid.). Integration with data analytics software and cloud software along with improvements in payloads promise to increase the opportunities associated with drone use in this sub-sector (ibid.).

Robots used to monitor and repair pipes present large opportunities for firms in the utilities industry. Prototypes for such robots now exist and are beginning to be trialled. For instance, Severn Trent Water is trialling a robot called “Lighthouse” that is designed to travel passively through water pipes and to detect and record the location of leaks as it does so (Caffoor, 2019). It is purportedly ten times more sensitive to leaks than current solutions (ibid.). Meanwhile, in the UK a prototype for a gas pipe inspection robot that is 3D printable and could be wirelessly recharged was developed in 2017 (Purnell et al. 2018).

Both the transport and utilities (sub-)sectors stand to benefit from the use of climbing robots for inspection and repairs to assets at height, such as towers, masts and bridges. Prototypes for climbing robots have existed for more than five years (Liu et al. 2014).

Prototypes for RAS applications in transport networks have been developed. A drone equipped with a 3D asphalt printer combines innovations from teams at University College London and the University of Leeds (Purnell et al. 2018). The drone has a vision system which allows it to detect cracks in road surfaces, which it then fills in with asphalt it 3D prints (ibid.). Other applications of drones in transport infrastructure are being developed; see below.

In telecommunications, drones are beginning to be used for routine inspection and maintenance of assets such as masts and antennae (PwC, 2017). T-Mobile has successfully trialled the inspection of antenna masts at a stadium in Utrecht in the Netherlands (ibid.). Trials are beginning for other uses of drones in the telecoms industry; Facebook had begun trials in its project to deploy a fleet of solar-powered drones that provided internet access in locations where it was otherwise unavailable (Satariano, 2018). In 2018, it abandoned plans to build the drones itself; in one of the two test flights, the drone sustained serious damage (ibid.).

Selected RAS use cases

RAS has a number of applications in inspection, repair and maintenance of infrastructure networks. Their uses in building infrastructure assets are discussed in the qualitative construction sector section above (see p.42). They include prefabrication for cheaper and lower-risk construction of structures and their parts, the automation of production processes from the design stage through to the delivery stage, the use of drones for quicker and cheaper site surveying, and the use of exoskeletons to reduce the physical demands on workers. Each box below describes use cases in three constituent sub-sectors of infrastructure: transport, utilities and telecommunications:

- **Selected use cases in utilities:** One important application of RAS in utilities is so-called "fire and forget" robots. Infrastructure networks feature extensive pipelines, carrying water, waste and gas. "Fire and forget" robots are deployed in these pipelines and reside there indefinitely (Richardson et al. 2017). When there, these robots can inspect the pipes and repair any issues they identify (ibid.). The continuous inspection and repair allow for proactive or preventative maintenance, which can prevent larger problems from building up. "Fire and forget" robots in water and gas pipelines can also be used to measure and report usage for billing and analysis purposes (ibid.).

  Drones can be used by utilities companies to inspect and repair assets. This is particularly attractive for assets such as powerlines (PwC, 2018a), which can be dangerous for humans to inspect and whose linear shape (ibid.) means drones can gather lots of information about them quickly.

- **Selected use cases in transport infrastructure:** A widely touted use case of RAS in transport infrastructure is swarms of drones that inspect and repair road surfaces. Drones that can detect small cracks and repair them using 3D printing before they grow and become potholes are being developed (Purnell et al. 2018; see above).

  Drones can also be used to inspect and maintain transport infrastructure - including, roads, railways and bridges - more generally; PwC (2017) estimate that the total addressable value of "drone powered solutions" in the maintenance of transport infrastructure is approximately $4 billion.

  The process of asset inventory can be automated by drones. Drones can be used to catalogue assets - for instance in a railyard (ibid.) - and detect damage to them; this is otherwise a time- and labour-intensive process (ibid.)

- **Selected use cases in telecoms:** RAS can also be used to inspect and repair assets such as telephone masts and antennae at height. This could be done by climbing robots (see e.g. Liu et al. 2014) or by drones. As described above, working at height is the single biggest cause of fatal workplace injuries in the UK. Inspection of assets at height by drones or climbing robots is a use case that also exists in transport infrastructure (consider bridges, for example), and utilities.

  Drones can also be used by the telecoms industry in network optimisation (PwC, 2016). Drones can be used to survey the landscape and identify the optimal heights, frequencies and locations of towers and antennae given the obstacles to signal that they detect (ibid.). In the future it is expected that drones will be used to broadcast signal, to provide internet access and radio and television signal to consumers (ibid.). PwC estimated (ibid.) that the value of the total addressable market for drones in the telecoms industry globally was over $6 billion.

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

Inspection, maintenance and repair of infrastructure assets by RAS would offer cost savings. Researchers at Imperial College London estimate that RAS adoption in the infrastructure sector could cut maintenance costs by 20-40% and increase asset utilisation by as much as 20% (Imperial College London Centre of Excellence on Infrastructure Robotics Ecosystems, 2020).[24]

Another driver of RAS adoption in the infrastructure sector is safety improvements. As described above, RAS can be used to automate the inspection and maintenance of bridges, masts and other vertical structures (Richardson et al. 2017). This reduces the need for humans to work at height to perform these tasks,[25] so that they are less exposed to the associated dangers. This driver applies across the different infrastructure industries.

RAS adoption in infrastructure promises to reduce disruption. At present, roads frequently have to be excavated in order to allow access to water mains for maintenance and roads are often closed to allow the repair of potholes. According to a 2010 article in The Telegraph, roadworks cause 36% of London's traffic delays, at a cost to businesses of $1.3 billion (Johnson, 2010; Demaitre, 2018). The cost to the UK from road closures because of road excavations is estimated to be around £5.5 billion per year (Caffoor, 2019). The deployment of 'fire and forget' robots in water mains would allow for preventative maintenance and maintenance in situ, reducing the frequency at which excavations to make repairs would be necessary (Demaitre, 2018).[26] Fewer excavations would imply fewer road closures, saving time and money.

Barriers to RAS adoption

As in the case of RAS adoption in the energy sector, RAS adoption in the infrastructure sector is subject to technical challenges. In the infrastructure sector, RAS will operate in complex and often cramped environments where error could carry severe costs (Liu et al. 2014). For these reasons, the technical demands on RAS that are designed to be deployed in the infrastructure sector are high. Particular challenges include co-operation, perception and movement in what are complex and sometimes dynamic environments (Robotics in Australia, 2020).

Another connected barrier to RAS adoption in the infrastructure sector is the need for regulatory frameworks (ibid.; Marvin et al. 2018). Because of the importance of the services this sector provides and because of the potential costs and consequences of error, this concern is especially prevalent for this sector (as well as for the energy sector). Like the energy sector, the infrastructure will require relatively extensive safety validation before RAS is

[24] The increase in asset utilisation will primarily be because of the ability of RAS to inspect and perform maintenance and repairs on 'live' assets, as described in the qualitative energy sector section above.
[25] Again, it is likely that human interventions at height would be needed sometimes, but less frequently than is true now.
[26] It is likely that excavations would remain necessary on occasion, for large repairs or overhauls.

deployed (ibid.). This is a barrier in itself and it raises the costs of developing RAS for the infrastructure sector.

The use of drones in infrastructure may be inhibited by regulation on drones' use; see the discussion in the "Barriers to RAS adoption" subsection in the qualitative energy sector section.

Finally, RAS adoption in the infrastructure sector may be constrained by inadequacies in the research and testing associated with it. In a UK-RAS Network White Paper, Richardson et al. (2017) describe current test facilities for infrastructure robotics in the UK as "small-scale, fragmented and uncoordinated" (ibid.), and call for collaboration between industry and universities in the development of test facilities. There is also a need for collaboration between firms within the water, gas and electricity industries, who each stand to benefit from funding and developing RAS solutions.[27] Increased funding for research into infrastructure robotics would benefit adoption; infrastructure robotics at present is the subject of a small portion of the robotics research funded by the UK government (ibid.).

Wider impacts

Environmental and social impacts

Adopting RAS could transform the way infrastructure is built and maintained, making these processes cleaner, safer and less disruptive.

Using specialised robots in infrastructure maintenance can have significant environmental benefits. For example, robots used in infrastructure construction use advanced technologies to reduce waste (Richardson et al. 2017). Further, using RAS in the pro-active maintenance of pipe networks could help to conserve fresh water and prevent the leakage of sewage from pipes into ecosystems (ibid.).

Adopting robots for infrastructure maintenance would also have social benefits, such as an improvement in the safety of workers who would no longer need to perform dangerous activities (ibid.). The application of RAS in infrastructure maintenance would also result in less social disruption. Repairs to tarmac, rail networks, gas or water mains, cables, sewers and streetlights can disrupt daily life for millions of people in the UK (Middleton, 2017). Most disruptions are caused by activities required to provide human operatives with safe access to infrastructure (e.g. digging trenches to access pipes, building gantries to access overhead cables or closing roads to protect those working on live carriageways). RAS can often access infrastructure assets without such preparatory activities, and their use can therefore avoid the associated disruption. Further, it may be[28] that up to one third of excavations conducted by water utilities do not give access to the fault, either because the pipe was not where the excavation was made or because the fault was not in fact in the section of pipe that had been identified (Caffoor, 2019).

The adoption of RAS in the infrastructure industry has the potential to create new jobs in designing, manufacturing, commissioning and maintaining the robots. The trend towards robotics will likely increase the demand for high-skilled workers in infrastructure (ibid.). In contrast, many of the jobs that exist in the infrastructure sector are dangerous and difficult and involve repetitive tasks (ibid.). RAS is likely to augment human labour in relation to such work:

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[27] A positive example can be found in the recent collaboration between a group of utilities companies, who are working with the CAA on beyond-visual-line-of-sight flight of drones for inspection and maintenance (Jenkinson, 2019).

[28] Evidence for this is anecdotal (Caffoor, 2019).

much of this work will be automated[29] but human operators will be required for the RAS systems deployed for these tasks.

Impacts on business resilience

In the ways already described, the use of RAS in infrastructure can allow more pro-active, predictive maintenance. This could make infrastructure networks more resilient to shocks by "nipping problems in the bud" (Richardson et al. 2017) and thereby preventing the build-up of major problems. For instance, Richardson et al. (ibid.) envisage "fire and forget" robots detecting and repairing emerging pipe defects while they are at an early stage before they generate more serious problems, such as sinkholes arising from leakage.

The ability to inspect assets while they are "live" (discussed above), for instance through "fire and forget" robots "living" in pipes, reduces the need for system downtimes while repairs are made. Meanwhile, RAS can also reduce the disruption to transport networks caused by closures to allow for safer access by workers to infrastructure assets under ground or at height. These two improvements make for a more stable infrastructure system in which services are disrupted less frequently.

Economic opportunities from RAS in logistics

Logistics contributes 10% of UK non-financial business economy GVA, employing 2.7 million (FTA, 2019). The logistics sector has grown each year since at least 2014, with demand increasing further due to increases in e-commerce. RAS investment from firms such as Ocado and Amazon are transforming logistics operations (Vincent, 2018) through large-scale warehouse automation. As large firms incorporate RAS deeper into their operations, continuing uptake of RAS appears highly likely.

The transport and logistics sectors' contribution to the economy in 2019 was £124 bn in GVA, this includes £12.9bn in warehousing and cargo alone (FTA, 2019). The introduction of automation in the form of drones into these sectors can result in a £2.8bn in cost savings and an 8.4% increase in multi-factor productivity by 2030 (PricewaterhouseCoopers, 2018).

The logistics sector includes transport applications, warehouse automation, picking and packaging. Logistics and transport are often grouped as a single sector for the purposes of economic statistic reporting (such as GVA). For this section, the analysis excludes transport where possible.[30]

Current RAS landscape

Current adoption and maturity of RAS

In 2018, the UK warehouse automation market was worth almost £1.7 billion[31] and this was forecasted to have a five-year CAGR of 11% (from 2018 to 2023) (Scriven, 2019). Amazon has heavily invested in warehouse automation, installing over 200,000 mobile robots at UK sites such as Dunstable, Doncaster and Tilbury.

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[29] As already discussed, humans are likely to be required for large repairs or overhauls.
[30] However, sometimes information and statistics are available only for the logistics and transport sectors together.
[31] Source reports dollar value of almost $1.5 billion: this figure is converted using exchange rate of GBP:USD (1.213) at time of article publication

Other adopters of warehouse automation include ASOS, Ocado, and John Lewis. Ocado's Andover warehouse (before its recent destruction (BBC News, 2019)) was planned to be able to process up to 3.5 million items due to the capabilities provided by RAS (Vincent, 2018) – a second similar warehouse is located in Erith (Verdict_AI, 2019). The planned rebuild will upgrade its fleet of robots – RAS adoption is seen as vital and a key differentiator for companies using warehouse logistics.

RAS in logistics has been further shaped by the increasing dexterity and capability of robotic arms - through the advancement of soft robotics. Prototypes and experiments, such as Ocado's SOMA project (related to soft robotics) (Ocado Group, 2019), and AI-enabled robotic pickers from firms such as Californian AI (Vincent, 2020), have demonstrated capability to handle soft items (such as food). Automated picking and packaging are poised to be increasingly adopted by the logistics sector as the technology continues to mature.

There will be an estimated number of 11,000 drones in the transport and logistics by 2030, representing roughly 14% of the total number of drones in the UK by 2030 (PricewaterhouseCoopers, 2018). It is predicted that drones will be responsible for the delivery of 80% of all items. However, it is worth noting that challenges such as regulations on airspace, package weights, and the low margins in the industry remain, as well as negative public opinion towards drone usage (PricewaterhouseCoopers, 2019). Given these challenges, drone delivery over the medium term is likely to be more feasible for deliveries of large numbers of small items within a short radius, where speed is of utmost importance, or where traditional delivery methods face challenges (e.g. having to use ferries).

Selected RAS use cases

- **Warehouse logistics**: RAS is extensively used as part of warehouse logistics, improving the efficiency of simple warehouse activities, such as lifting, picking, and sorting stored items (Vincent, 2018). In RAS-equipped warehouses, robots controlled by a central computer can automate large parts of warehouses, greatly increasing warehouse efficiency and productivity. Humans typically can perform 350 and 600 grabs (picks) per hour whereas a robot can achieve performance as high as 1,100 (Halliwell, 2019).

  Warehouse-RAS still requires human interaction to help bypass technological bottlenecks. These robots are limited in their capacity with unpacking bulk deliveries, moving pallets and handling delicate and irregularly shaped items (such as bags of oranges). The automation of a large part of manual tasks still results in a reduction in worker strain, fewer injuries, lower operating costs and increased accuracy (Monroy, 2020)

- **Packaging automation:** Another part of the logistics chain which can benefit from RAS relates to the automation of the packaging process. Packaging robots have been integrated into supply lines for several years, and significantly before the current wave of smart robotics. However, customer demand for greater stock keeping unit (SKU) complexity and need for finer handling have allowed technological advancements in robotics to fulfil further packaging demands. Technological development in RAS has resulted in the creation of picking and packaging robots which can handle small and delicate items, allowing them to package a wider variety of items (some of which require delicate handling) (Banker, 2018).

- **Micro-fulfilment Centres:** These applications of RAS can also be applied as part of Micro-fulfilment Centres, in which automation is integrated into the back room of a retail store. RAS integrated in this manner can improve productivity ten-fold, increasing picks from 60 per hour to 600 (Halliwell, 2019).

- **Drones:** RAS can also be used for delivery aspects of logistics. Large retail and logistics companies are investing in drones for different aspects of logistics, such as 'last mile' delivery and warehouse operations (PricewaterhouseCoopers, 2018). These drones will be able to perform tasks such as conducting real time stock checks and form a complete system alongside other forms of RAS designed for picking and packaging.
- **Exoskeletons:** Robotic exoskeletons can be used to reduce worker strain by assisting with heavy loads. These exoskeletons may be powered with motors which can increase a worker's physical strength, allowing them to carry heavier weights. These exoskeletons, by reducing fatigue, can also allow for aging workforces to remain effective (Best, 2019).

Factors influencing adoption: Drivers & barriers

Drivers of RAS adoption

UK warehousing suffers from labour shortages, and these may be further exacerbated by Brexit (Halliwell, 2019). 64% of the UK's transport and storage businesses struggle to fill vacancies and EU workers currently constitute 13% of the entire logistics workforce (Global Cold Chain News, 2020). The need to address labour shortages is a major driver for RAS adoption across the logistics sector.

Advancement of RAS technology capability in this sector is also a driver for increased adoption. Recent technology can fully automate warehouse processes – such as lifting, picking, and sorting – using independently working robots controlled from a central point (Halliwell, 2019). These collaborative robots – alongside exoskeletons – enhance existing worker capability. Advancing technology drives adoption by increasing the scope of what RAS can be used for.

Increasing consumer demand for online commerce will also increase the need for warehouse operations - e-commerce sales have increased from £513.5 billion in 2014 to £688.4 billion in 2018 (ONS, 2018c). Matching this increased consumer demand requires online retailers to have increased efficiency or capacity across their warehouse logistics operations. However, this increase in demand may be attributed to COVID-19; the longevity of this demand increase depends on consumer attitudes and development of the current crisis. If demand for online commerce reduces, the demand for warehouse capability will also reduce (and so will the demand for increasingly efficient warehouse operations).

This increasing consumer demand is combined with a greater need for faster (and more convenient) home delivery (Joerss et al., 2016). From a large-scale consumer survey (conducted before September 2016 with 4,700 respondents in China, Germany and the US), almost 25% of respondents stated that they are willing to pay significant premiums for the privilege of same-day or instant delivery. However, respondents in the survey were still relatively price sensitive (with price remaining the key criteria in consumer delivery preference). The incorporation of drones (and other autonomous vehicles) allows firms to take capitalise on these changing consumer demands without incurring the additional labour cost needed.

For developed countries, the cost of labour continues to increase. As technology becomes increasingly affordable, the opportunity cost for logistics and delivery firms to switch to autonomous vehicles and drones decreases (Joerss et al., 2016). As this opportunity cost decreases, incentives for firms to use RAS will increase, which will encourage greater rates of adoption across the logistics sector.

Adoption of drones is also driven by advances in battery technology. The invention of lithium metal batteries resulted in increased drone flight time (70% longer) compared to previous lithium-ion powered times (Pappalardo, 2019). As drone flight time increases, the amount of delivery and logistics operations which can be fulfilled by drone usage also increases.

Barriers to RAS adoption

Increased demand for increasing variety of goods (and packaging) have resulted in RAS adoption becoming limited by technological progression. Consumer demands and greater environmental consumer consciousness has resulted in product manufacturers using less plastics (resulting in thinner and more fragile packaging) (Demetrakakes, 2020). This is compounded as RAS applications will also need to be able to interact with several different products as part of its operations. As soft robotic packaging solutions have not yet been fully developed, and adopted by the logistics sector, RAS has struggled to cope with increasingly greater packaging demands. As soft robotics continue to mature, this barrier will lessen, and adoption will further increase.

RAS also introduces additional workforce skill requirements – as shared with RAS applications in the Food & drink sectors. Although RAS can automate simple tasks and unskilled labour, the integration of these systems requires engineers, electricians and robot maintenance specialists (Vincent, 2018). Adopting RAS requires engagement from existing employees and plant operators to ensure smooth interoperability between automated and non-automated aspects (Demetrakakes, 2020). For firms looking to incorporate RAS, they must ensure that they have both the skillset and engagement from their personnel for a smooth integration.

The incorporation of drones into the UK economy depends on the UK's regulatory environment. Regulation and rules relating to air space and operation can influence how successful drone usage will be. The UK government are committed to providing an agile regulatory landscape to keep pace with technological development and the creation of new opportunities (Parliament UK, 2020; PricewaterhouseCoopers, 2018). The significance of this barrier will depend on whether regulation progresses in pace with commercial and technological development. Deploying drones is therefore dependent on safety validation; issues regarding where drones can land, where they take off from and how their safety risks are managed need to be answered to assuage regulatory and public concern.

Public opinion on drones are a barrier against increasing adoption. A UK survey showed that less than a third of the UK public (31%) felt positive towards drone technology – with almost half undecided (PricewaterhouseCoopers, 2019). A lack of understanding of technology and regulation may be reasons for low public trust and positivity towards drones. Additionally, public opposition towards drones changes depending on their usage. Search and rescue, observing fires and emergencies and tracking criminals were the most popular uses of drones with package delivery the second most opposed use (behind flying taxis). Negative public opinion towards drones may represent a significant barrier for RAS adoption in the logistics sector as attitude change for delivery-specific usage may lag behind positive attitude shifts towards drones more generally.

Wider impacts

Environmental and social impacts

The introduction of RAS in logistics has the potential to reduce the carbon footprint of storage, improve workplace safety, alter shopping patterns, and impact the labour market.

Automation increases storage density, hence reducing the carbon footprint of warehouse storage as less energy is needed for lighting and heating (Nisudan, 2020). In traditional warehouse designs, a large percentage of a warehouse's square footage is used to access aisles. With high-density deep lane storage systems, access aisles are no longer needed, increasing the number of slots available per square foot (iGPS, 2019).

Adopting RAS in hazardous environments reduces work-related injuries and fatalities in logistics (Innovate UK, 2016). Warehouses and storage buildings can be dangerous environments to work in. In 2010/11 there were 157 major injuries to workers in warehousing and storage reported to the Health and Safety Executive (Croner-I, 2020) – there were also 622 reports of serious injury or near misses at Amazon's UK warehouses between 2017 and 2019 (annual figures increasing year on year) (BBC News, 2020). Using RAS to undertake hazardous tasks can reduce the risk of injury. Exoskeletons can also be worn by warehouse workers to help them lift heavy loads with less strain (DHL, 2016).

RAS may also lead to a reduction in worker safety if increased capability causes workers to overexert themselves. RAS in Amazon warehouses has resulted in inflated worker targets because of increased efficiencies gained from RAS integration. Reports state that workers are expected to deliver four times as many items since the introduction of robots, leading to increased strain and injury rate (Hamilton, 2020). Worker safety is therefore affected by how firms use RAS efficiency gains and higher worker capability.

The adoption of RAS in logistics, such as drones and smart warehouses, could transform the job landscape (WEF, 2016) by creating jobs. In logistics, the implementation of digital platforms that enable cross-border trade and crowdsourcing of logistics routes could create approximately 4 million jobs worldwide by 2025, equivalent to a net 8.4% increase in the number of people employed in the industry (WEF, 2016).

Finally, the introduction of RAS in logistics will increase the speed of delivery systems. The use of smart warehouses, drones and automatic guided vehicles (AGVs) can reduce delivery times to under a day and in some cases a few hours (Innovate UK, 2016). Faster delivery services will alter the way consumers shop and accelerate the e-commerce revolution and the trend towards online shopping (DHL, 2016).

Impacts on business resilience

Supply chain resilience is crucial to economic activity (Nisudan, 2020). The logistics sector faces labour shortages, with this being exacerbated by COVID-19 and any reduction in immigration from the EU that may follow Brexit. The adoption of RAS in logistics can improve the resilience of businesses in this sector to these labour shortages. Pick and place technologies such as automated guided vehicles (AGVs), robotic picking, and automated storage and retrieval (ASRS) all mechanise manually intensive processes, reducing labour requirements and human error rates, increasing warehouse productivity (Nisudan, 2020).

Higher levels of automation in logistics could result in greater operational flexibility and resilience to fluctuations in demand. RAS can work longer hours (when demand is high) and be left idle when it is low. During peak times, such as the Christmas season, idle capacity can be easily unlocked without adding large numbers of part-time warehouse employees (Dekhne, 2019).

Furthermore, RAS allows for remote interaction in logistics systems, minimising human contact and hence improving resilience to COVID-19 and other future pandemics.

Quantitative evidence of RAS adoption across sectors

This section provides the results of a quantitative assessment of the economic opportunities of RAS across selected UK sectors. This section first discusses current trends of RAS adoption at the UK-wide level. It then presents estimates of the economic opportunity for selected sectors, given current estimates of future adoption. The section ends with a discussion on the size of the automation gap – that is the gap between the level of automation estimated to be achieved given current adoption trends, and the potential level of automation that could be achieved. In light of this gap, the section ends with a brief discussion on the feasibility of policy interventions to facilitate further RAS uptake in selected sectors.

The central aim of the quantitative analysis was to provide comparable estimates of the potential opportunity across UK sectors, rather than precise forecasts of the uptake and corresponding benefits in any one sector. The estimates should therefore be interpreted in this light. Further, the following points should also be kept in mind when interpreting estimates provided throughout this section:

- Quantitative results presented in this study are based on current estimates of future RAS adoption; i.e. they are estimates given current adoption trends. In practice, adoption may differ from these estimates due to a wide range of factors, not least the evolving nature of RAS itself and the government's own public policy choices.

- In practice, adoption may differ from these estimates due to a wide range of factors. The extent to which benefits can be delivered over and above the results presented in this study depend, in addition to advances in robot technology themselves, on the level to which uptake of robotics can be facilitated over and above current uptake forecasts, for example by mitigating barriers to uptake in key sectors.

- As with any estimates of future economic potential, a number of assumptions had to be made in order to estimate future uptake of RAS across UK sectors and to translate estimated growth into economic benefits. Utmost care was taken to ensure assumptions chosen are sensible, in order to derive the most robust and fair estimates of benefits. Nevertheless, the usual limitations and uncertainty present in any estimation of future adoption potential remain.

- It is further important to note that estimated impacts show the potential size of the economic impact relative to baseline estimates of value added, employment needs, and labour productivity (see methodological annex). The results do not make any claims about the overall growth of value added itself. That is, the estimated impacts may be in addition to growth in value added under the baseline (i.e. sectors would grow more as a result of RAS uptake), or part of it (i.e. growth due to RAS is already captured in baseline sectoral growth, and sectors would grow less without RAS uptake). Whether RAS provides additional growth depends on whether productivity impacts of RAS are on top of typical advances in technology already captured in the baselines.

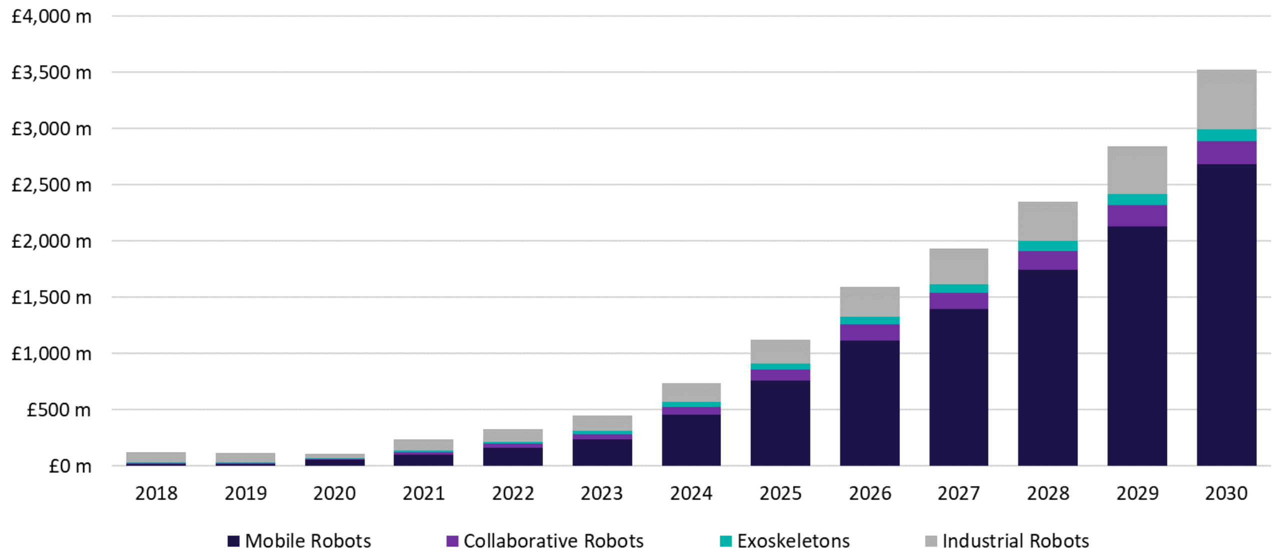
A detailed methodological discussion, including assumptions made and caveats of the analysis, is provided in the methodological note accompanying this study.

Estimated future RAS adoption: economy-wide estimates

Analysis undertaken for this study estimates, based on ABI Research (2020) robot shipments forecasts, that the total UK robots market will grow at a compound annual growth rate of more than 40% per annum between 2020 and 2030, reaching an estimated market size of almost £3.5 billion by 2030.

A significant proportion of this growth is expected to be driven by the rise in mobile robots. Data for mobile robot shipments was not directly available from ABI Research. However, if UK shipments follow a similar trend to the European market as a whole, the mobile robot segment is poised to experience the most drastic growth; from an estimated level of around 1,500 shipments per annum in 2020 to over 90,000 annual shipments by 2030.

Estimated total UK robot market, by 2030, size based on current trends



Note: Converted to Sterling using the 2018 Bank of England exchange rate. Data for mobile robots estimated, by London Economics, from estimated shipments of mobile robots and global unit revenue.

Source: London Economics analysis of ABI Research (2020a)

Quantitative estimates of RAS uptake used in this study:

One of the key challenges for the modelling was the derivation of estimates of RAS uptake for the selected sectors. Potential uptake is uncertain and depends on a variety of factors. While forecasts for RAS uptake are available at the UK level, no (known) UK forecasts were available for the selected sectors. Therefore, estimates of UK RAS forecasts at the sector level were derived by combining ABI Research (2020a) forecasts for the UK as a whole with ABI Research (2020a) sectoral forecasts at the global level.

ABI Research has long-standing experience in the robotics sector their estimates are derived on robust quantitative assessment from both top-down and bottom-up approaches, which are further informed and refined by, a qualitative analysis of the technological, business, and political drivers and constraints impacting each sector. Nevertheless, as with any estimation of future uptake, uncertainty surrounding the estimation remains. Moreover, the approach used in this study makes a number of key assumptions (discussed in detail in the methodological note accompanying this report).

Bearing in mind the limited availability of RAS forecasts, and the uncertainty surrounding such forecasts in general, estimates were deemed to present a plausible central case. Further, it should be noted that estimates derived in this study are based on current adoption trends. In practice, adoption may differ from these estimates due to a wide range of factors, not least the evolving nature of RAS itself and the government's own public policy choices. Results should therefore be interpreted as plausible estimates, aiming to represent a central view, given current adoption trends, not as forecasts.

Sectoral RAS adoption trends

The uptake forecasts presented for the economy as a whole appear relatively modest when evaluated in the light of the figures by McKinsey (2013) and, more recently, Oxford Economics (2019). Specifically, while the total UK robot market is estimated to grow at a compound annual growth rate of more than 40% per annum between 2020 and 2030; this rise is from a low base of only 0.6 robots per million hours worked in 2020. As highlighted above, even by 2035 robot density across the economy is estimated to reach only 28.9 robots per million hours worked[32].

As discussed at the beginning of this section, these figures represent estimates of future RAS adoption given current adoption trends. In practice, adoption may differ from these estimates due to a wide range of factors, not least the evolving nature of RAS itself and the government's own public policy choices.

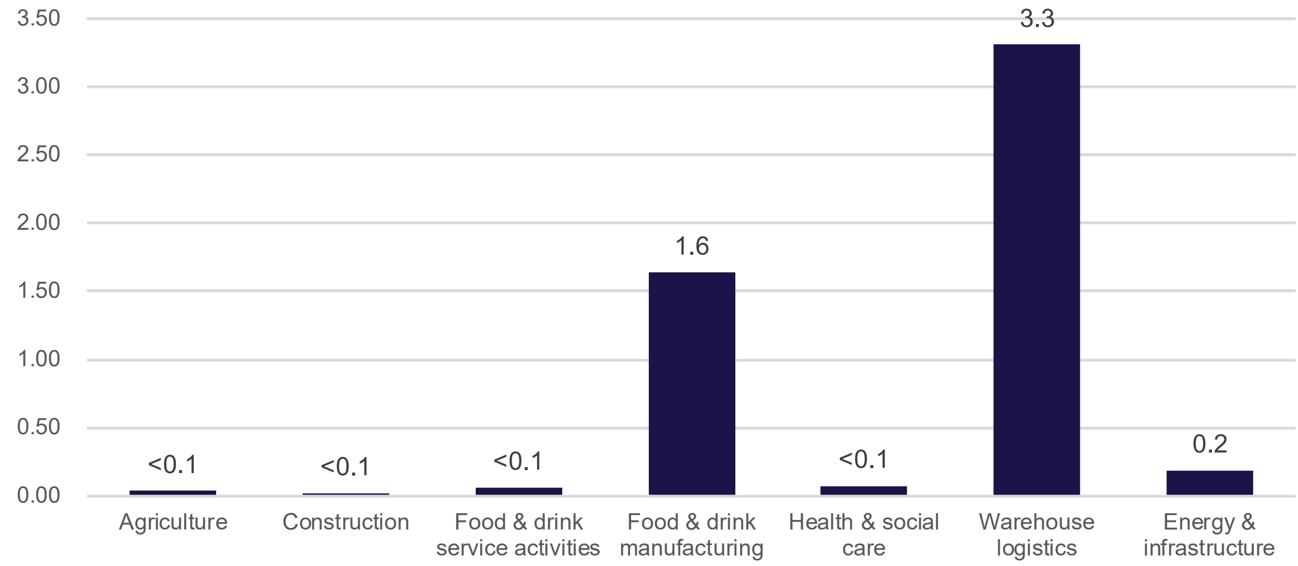
The UK has historically lagged behind other countries in robot uptake - being the only G7 country with a robot density below the world's average, with just 74 units per 10,000 workers (International Federation of Robotics, 2018). The relatively modest future robot density forecast thus suggests that this may continue to be the case with RAS unless further uptake can be encouraged.

At the same time, the economy-wide uptake figures mask significant variation across UK sectors. In particular, it is worth noting that, in the UK, the services sector dominates the UK economy, accounting for approximately 80% of UK gross domestic product (GDP) and employing around 85% the UK workforce. At the same time, jobs in the services sector are more likely to be labour intensive and more difficult to automate through physical robotics systems; with automation in some services sectors, such as finance, primarily driven by digital solutions such as artificial intelligence and robotics process automation.

At present, uptake is much higher in some sectors than others. Uptake is significantly higher in the warehouse logistics and food & drink manufacturing sectors than in the other selected sectors. This is shown in the figure below, which displays estimates of the current robot density (robots per million hours worked) in select sectors.

[32] Baseline aggregate hours worked were estimated based on the average weekly hours worked in a sector (from the ONS) times the number of employees under the baseline scenario. Further details can be found in the methodological note accompanying this report.

Estimated current robot density (robots per million hours worked)

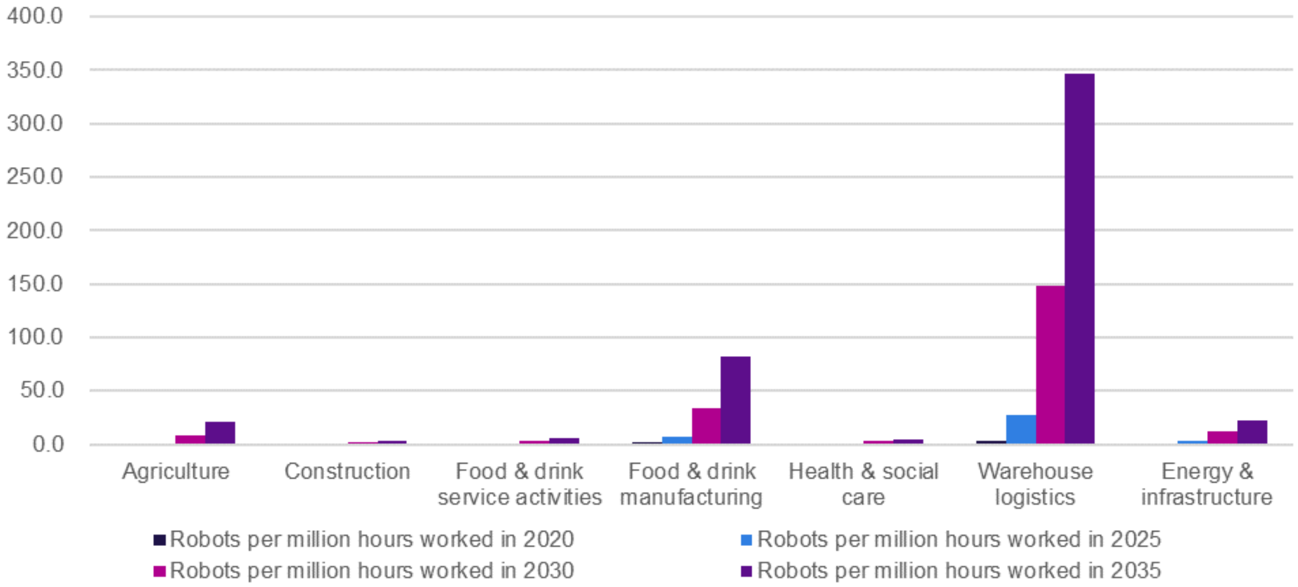


Note: The figure shows estimated number of robots per million hours worked, given estimates of current adoption of RAS across UK sectors.

Source: London Economics' analysis

This concentration of uptake in the warehouse logistics and food & drink manufacturing sectors is expected to continue. The figure below shows, based on current estimates of future adoption, the estimated robot density for a number of select sectors up to 2035. This further suggests that short to medium-term economy-wide impacts may be concentrated in the warehouse logistics sector, and, to a lesser extent, in food & drink manufacturing.

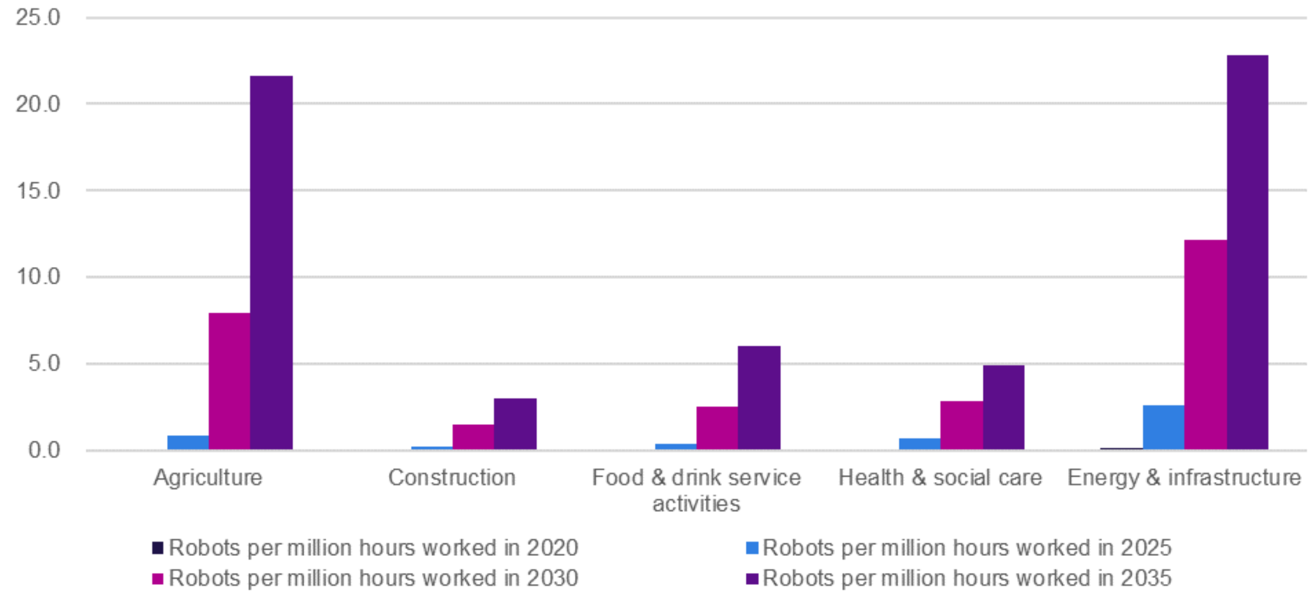
Estimated future robot density on current trends



Note: The figure shows estimated number of robots per million hours worked under baseline, given estimates of future adoption trends.

Source: London Economics' analysis

Estimated future robot density on current trends (excl. warehouse logistics and food & drink manufacturing)



Note: The figure shows estimated number of robots per million hours worked under baseline, given estimates of future adoption trends.

Source: London Economics' analysis

Estimated productivity impacts across sectors

In order to estimate labour productivity impacts associated with the above described uptake trends, the following productivity assumptions were made.

Productivity estimates were anchored to estimates from the Centre for Economics and Business Research (2017), which found that, in OECD countries between 1993 to 2016, a one-unit increase in robotics density (defined as the number of robots per million hours worked) is associated with a 0.04% increase in labour productivity. To account for the differences of RAS compared to 'traditional' robots (which mostly automate manual and routine tasks) CBER estimates were adjusted to account for differences in the nature of tasks (manual and routine vs. non-routine) across sectors as well as to account for productivity improvements from non-routine task automation.

Further details are provided in the annex at the end of this report. A detailed discussion of the assumptions is provided in the methodological note accompanying this study.

Assumptions: % increase in labour productivity per unit increase in robot density

Sector	Productivity assumption made
Agriculture	0.04%
Construction	0.05%

Energy & infrastructure	0.05%
Food & drink service activities	0.03%
Food & drink manufacturing	0.06%
Health & social care	0.03%
Warehouse logistics	0.07%

Note: The figure shows the assumed % increase in labour productivity per one unit increase in robot density, given estimates of future adoption trends. Source: London Economics' analysis

Given the relatively low estimated levels of future RAS uptake across most selected sectors, the productivity increases, associated with the above-described uptake trends, are estimated to be relatively modest for most sectors. With the exception of warehouse logistics and food & drink manufacturing, labour productivity increases are estimated to remain below 1.5%, relative to baseline (see methodological annex), by 2035, reflecting the low levels of adoption in these sectors.

In contrast, warehouse logistics is expected to see significant increases in labour productivity of around 10% by 2030, rising to nearly 25% by 2035.

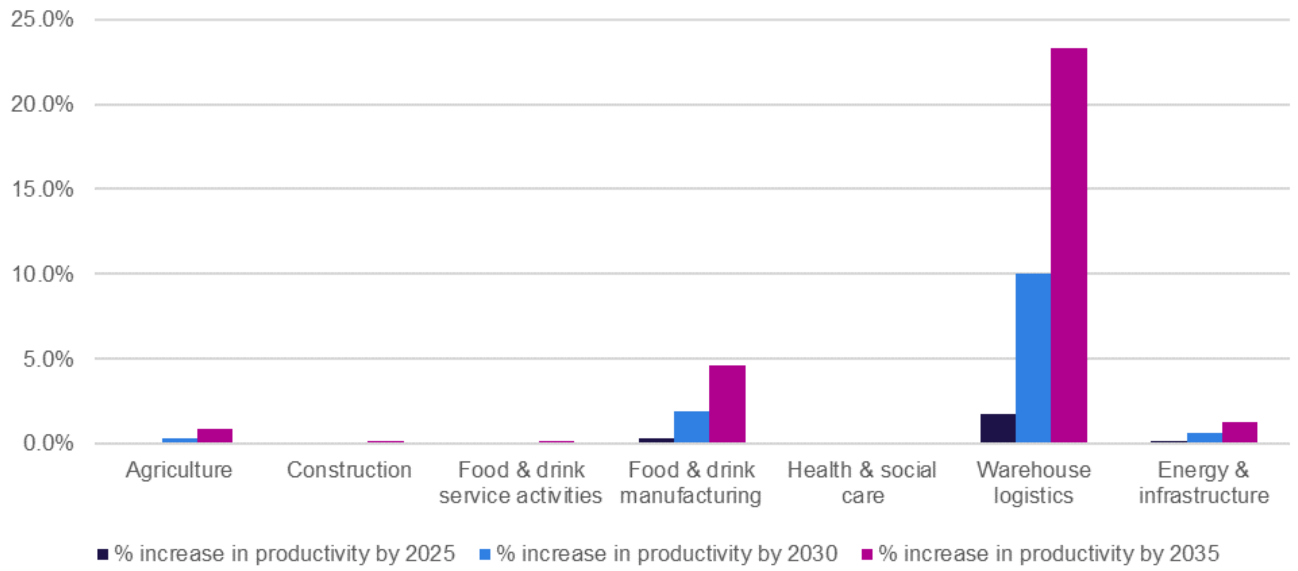
Labour productivity impacts in the food & drink sector are estimated to reach around 5% of baseline labour productivity by 2035. However, the continued importance of industrial robots in the manufacturing sector should be noted when interpreting these results; industrial robots are expected to account for approximately one-third of robot shipments in the food & drinks manufacturing sector by 2035.

The higher impacts in the warehouse logistics manufacturing and food & drink manufacturing sectors in part reflect the higher the higher automation potential in the sector (resulting in higher productivity assumptions being used in the analysis – see table above). However, the scale of the differences mean that the higher impacts mostly reflect the higher estimated levels of future adoption in these sectors.

Interpretation of productivity estimates:

Estimated productivity improvements shown in the charts above refer to the estimated difference in labour productivity in a sector under current trends of RAS adoption relative to baseline levels of labour productivity (see methodological annex). Productivity estimates therefore show the overall productivity improvements that RAS could bring to the sector if adoption followed current trends relative to baseline labour productivity. The higher levels of productivity improvements in the warehouse logistics and food and drink manufacturing sector therefore reflect the higher levels of expected uptake in these sectors; importantly, they are *not* estimates of the productivity benefits RAS could bring to individual firms. Note that other selected sectors would also see higher overall productivity improvements in line with higher levels of RAS adoption in these sectors – though the magnitude of the improvements would be somewhat lower given the lower assumed productivity assumptions made (due to the nature of tasks and automation potential) for these sectors.

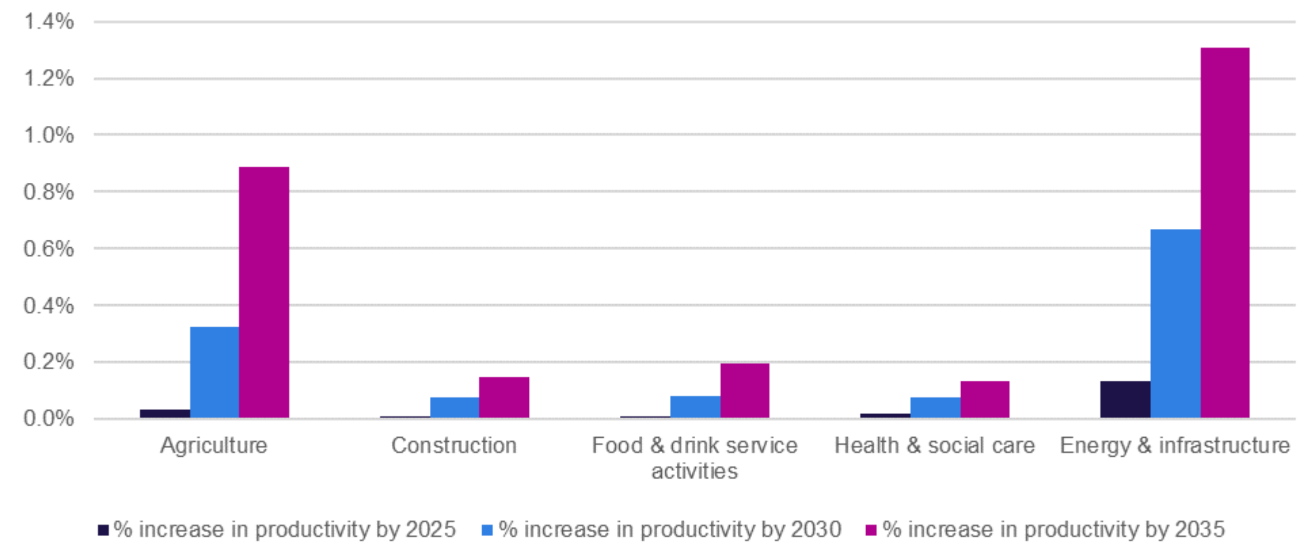
Estimated associated productivity improvements



Note: The figure shows the % increase in labour productivity (value added per worker) relative to baseline, given estimates of future adoption trends and productivity assumptions made.

Source: London Economics' analysis

Estimated associated productivity improvements (excl. warehouse logistics and food & drink manufacturing)



Note: The figure shows the % increase in labour productivity (value added per worker) relative to baseline, given estimates of future adoption trends and productivity assumptions made.

Source: London Economics' analysis

Estimated reduction in labour needs

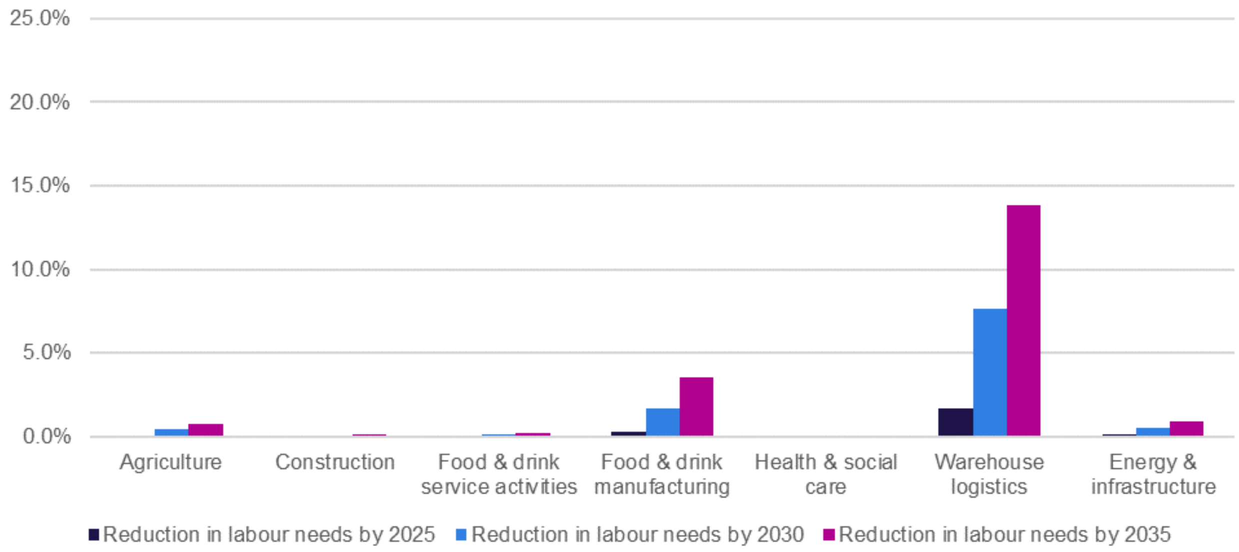
The graph below shows the estimated reduction in labour needs corresponding to the increases in labour productivity presented in the previous section.

> Interpretation of reduction in labour needs estimates:
>
> The estimated reduction in labour needs refers to the proportion of jobs (or tasks), that are currently undertaken by humans, that could be replaced as a result of productivity improvements resulting from higher levels of RAS adoption given current trends.
>
> For the analysis we do not distinguish explicitly between jobs and tasks. If the work undertaken by one FTE job is automated, we do not specifically model whether this affects all the tasks of one worker or half the tasks of two workers. We therefore use jobs and tasks interchangeably.
>
> Note that the 'reduction in labour needs' refers to jobs (tasks) that could potentially be replaced by RAS given current adoption trends rather than those that necessarily will be replaced – in practice some workers will be re-deployed.

Specifically, it is estimated that productivity improvements from advanced robotics will translate into reduced labour needs of around 14% in the warehouse logistics sector, and around 4% in the food & drink manufacturing sector, by 2035. Other selected sectors are not expected to see significant reductions in labour needs given current estimates of future adoption.

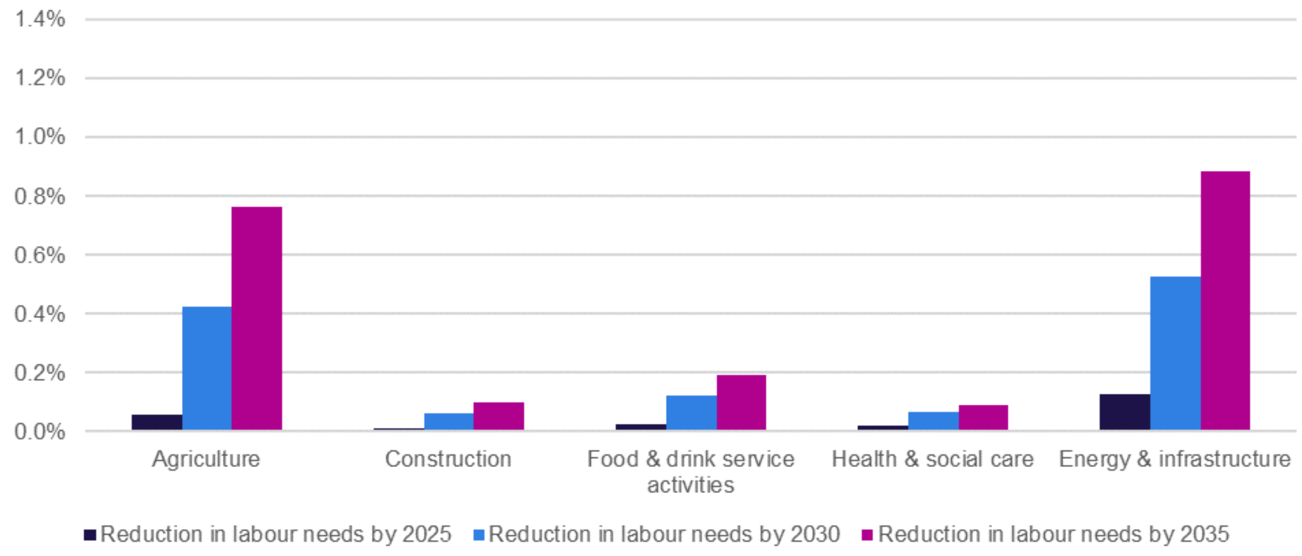
Again, these estimates are reflective of the higher expected levels of automation on current trends in the warehouse logistics sector, and to a lesser extent, the food and drink manufacturing sector. The results therefore suggest that on current trends most selected sectors will not see sufficient levels of automation in order for RAS to help mitigate challenges such as an aging workforce and low levels of productivity.

Estimated reduction in labour needs



Note: The figure shows the % reduction in labour needs (no. of workers) relative to baseline, given estimates of future adoption trends. Source: London Economics' analysis

Estimated reduction in labour needs (excl. warehouse logistics and food & drink manufacturing)



Note: The figure shows the % reduction in labour needs (no. of workers) relative to baseline, given estimates of future adoption trends.

Source: London Economics' analysis

Impacts on value-added

The economic impact in terms of value added will depend on the level of displacement that RAS will bring; that is, what proportion of labour will be re-deployed to perform other tasks, and what proportion of labour will be replaced. Therefore, in order to derive corresponding economic impacts, assumptions of the level of displacement likely to occur have to be made.

However, there is significant uncertainty around the level of displacement likely to occur as a result of RAS uptake. A detailed analysis of the future labour market impacts of RAS was beyond the scope of this study. Therefore, this study sought to use plausible central estimates of the proportion of jobs replaced. Specifically, the analysis uses estimates by PwC (2018b) on the proportion of jobs – or tasks – at high risk of automation in selected sectors in order to derive central estimates of the level of displacement likely to occur.[33] The displacement assumptions made in the central case are shown in the figure below.

Note: The displacement assumptions refer to the proportion of jobs (or tasks) that were previously undertaken by humans that can now be undertaken by RAS. For example, if RAS is estimated to reduce labour needs in a sector by 100,000 jobs and the analysis assumes that 30% of workers are displaced this means that: of the 100,000 jobs that can now be undertaken

[33] While uncertainty on the level of displacement exists PwC estimates were judged plausible. PwC's estimates are based on analysis of a dataset compiled by the OECD that looks in detail at the tasks involved in the jobs of over 200,000 workers across 29 countries (27 from the OECD plus Singapore and Russia) and builds on previous research by both Oxford University (Frey and Osborne, 2013) and the OECD (Arntz and Zierhahn, 2016).

by RAS, 30,000 workers are displaced while the remaining 70,000 would be utilised to perform other tasks.[34]

Assumptions: % of workers displaced & re-deployed

Sector	% of workers re-deployed	% of workers displaced
Agriculture	70%	30%
Construction	62%	38%
Energy & infrastructure	61%	39%
Food & drink service activities	76%	24%
Food & drink manufacturing	55%	45%
Health & social care	79%	21%
Warehouse logistics	58%	42%

Note: The figure shows the assumed proportion of workers that are re-deployed to other tasks of at least a similar value-add. Assumptions are based on the potential rates of job automation across sectors from PwC (2018b).

Source: London Economics' analysis

The estimated increases in value added, given these displacement assumptions, is shown in the graphs overleaf. Based on this analysis, the **total economic impact, across all selected sectors,** of uptake of RAS given current trends is estimated to be in the region of **£6.4 billion** by 2035.

Given the significantly higher estimated adoption of RAS in **warehouse logistics**, the warehouse logistics sector is expected to see the most sizeable increase in value-added of approximately **14% (£4.4 billion)** of baseline value-added by 2035.

Similarly, the impact of advanced robotics in the **food & drink manufacturing** sector is estimated to reach around **3% (£0.9 billion)** of baseline value-added by 2035.[35]

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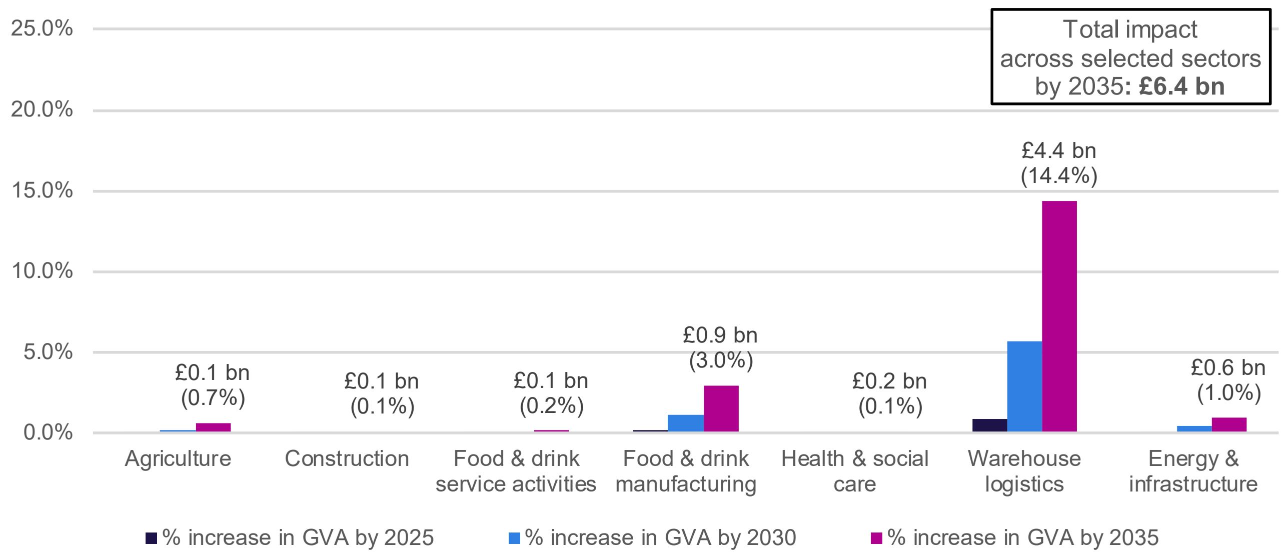
[34] It should further be noted that the analysis did not make any assumptions about whether re-deployment is within the same company, sector or across sectors. However, the analysis assumed that the proportion of tasks or jobs created within an industry would be of a similar value than those displaced. In practice some workers will likely be re-deployed within the same companies, others may be made redundant but take up jobs in the same industry, while others move across sectors. Similarly, the tasks performed by workers re-deployed may not be of the same value. A detailed analysis of the labour market impacts of RAS was beyond the scope of this study, though a brief discussion of these issues is provided in the theoretical assessment of RAS section (Section 2).

[35] Note due to their continued importance in this segment, industrial robots were included in the estimation of robot density, and therefore impact, in the food & drink manufacturing sector. The expected comparatively larger role of industrial robots should therefore be kept in mind when interpreting the results.

Given the relatively lower levels of estimated future RAS uptake, impacts in the other selected sectors are estimated to be more modest when compared to the warehouse logistics and food & drink manufacturing segments; at least under current adoption trends.

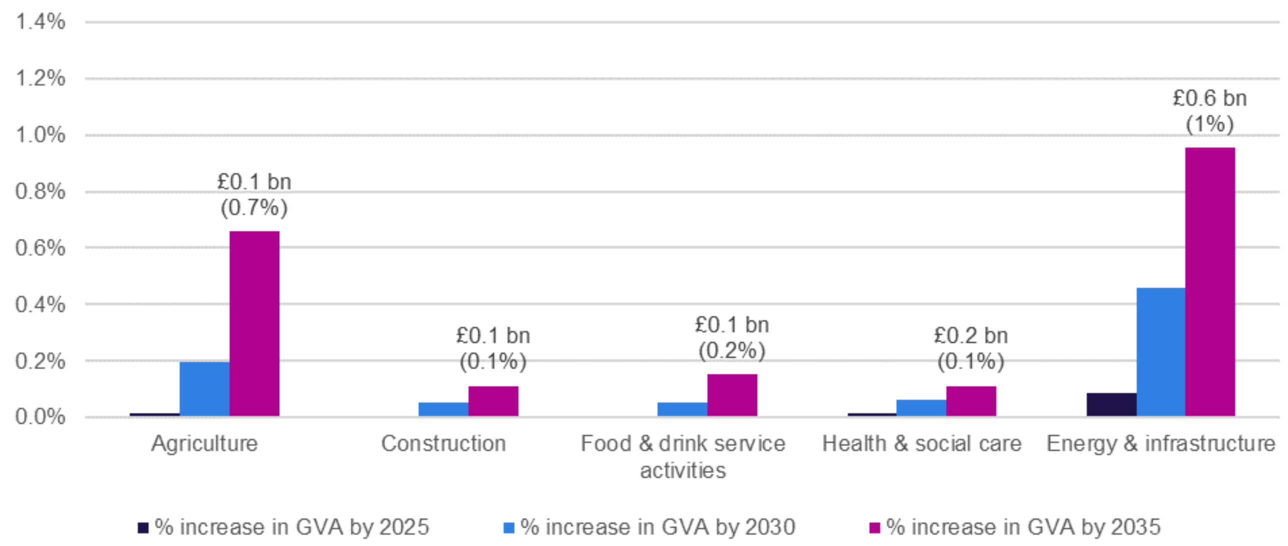
Estimated increase in value added



Note: The figure shows the % increase in gross value added relative to baseline, given estimates of future adoption trends and displacement assumptions made.

Source: London Economics' analysis

Estimated increase in value added (excl. warehouse logistics and food & drink manufacturing)



Note: The figure shows the % increase in gross value added relative to baseline, given estimates of future adoption trends and displacement assumptions made.

Source: London Economics' analysis

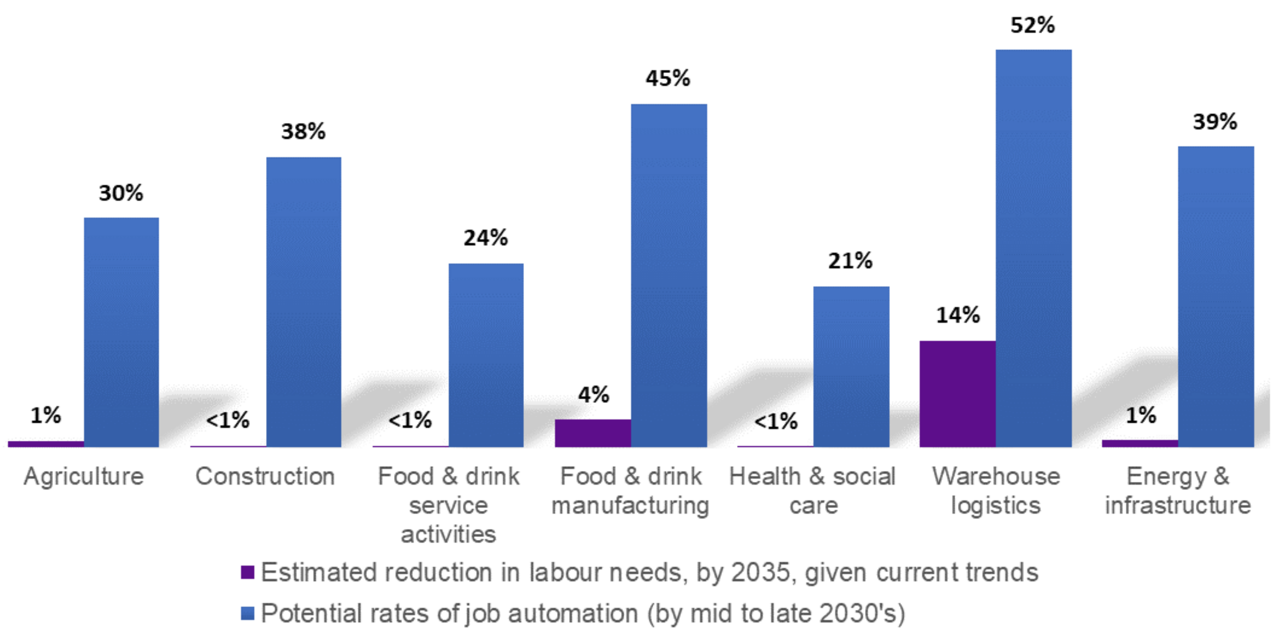
The size of the automation gap

As the previous sections made clear, most of the sectors selected for this study are unlikely to see significant levels of robotics automation if future adoption is similar to the trends described. This raises the question, for policy makers, whether interventions may raise future uptake beyond these levels, and if so what the impact of these interventions might be.

While a thorough evaluation of the impact of various policy interventions is beyond the scope of this study, this section seeks to facilitate a better understanding of the gap between current estimates of future adoption and the potential rates of automation across selected sectors.

The figure below compares estimated levels of automation (by the mid to late 2030's), given current adoption trends, with the potential rates of automation in each sector (based on PwC, 2018b). This analysis makes clear that the gap between estimated future automation trends and potential automation is sizeable.

Estimated vs. potential rates of automation across sectors



Note: The figure compares the estimated reduction in labour needs by 2035, given current estimates of future RAS adoption, and the potential rates of job automation in each selected sector. The potential rates of job automation across sectors is based on PwC (2018b).

Source: London Economics' analysis

Estimated vs. potential rates of automation across sectors:

The comparison of estimated vs. potential rates of automation is based on a comparison of the proportion of jobs that could be automated given current trends and the proportion of jobs that could feasibly be automated if digital technologies were adopted fully. Specifically, the analysis compares:

- The estimated reduction in labour needs (by 2035) that could be achieved given current trends. This refers to the proportion of jobs (or tasks), that are currently undertaken by humans, that could be replaced as a result of productivity improvements from RAS if adoption follows current trends. Note that this refers to jobs (tasks) that could be replaced by RAS given current adoption trends rather than those that will be replaced – in practice some workers will be re-deployed.

- The potential rates of job automation (by mid to late 2030's) that could be achieved from automation (based on PwC, 2018b). The potential rates of job automation give estimates of the relative automatability of jobs (i.e. the proportion of jobs – or tasks – at high risk of automation) based on the technical feasibility of automation.

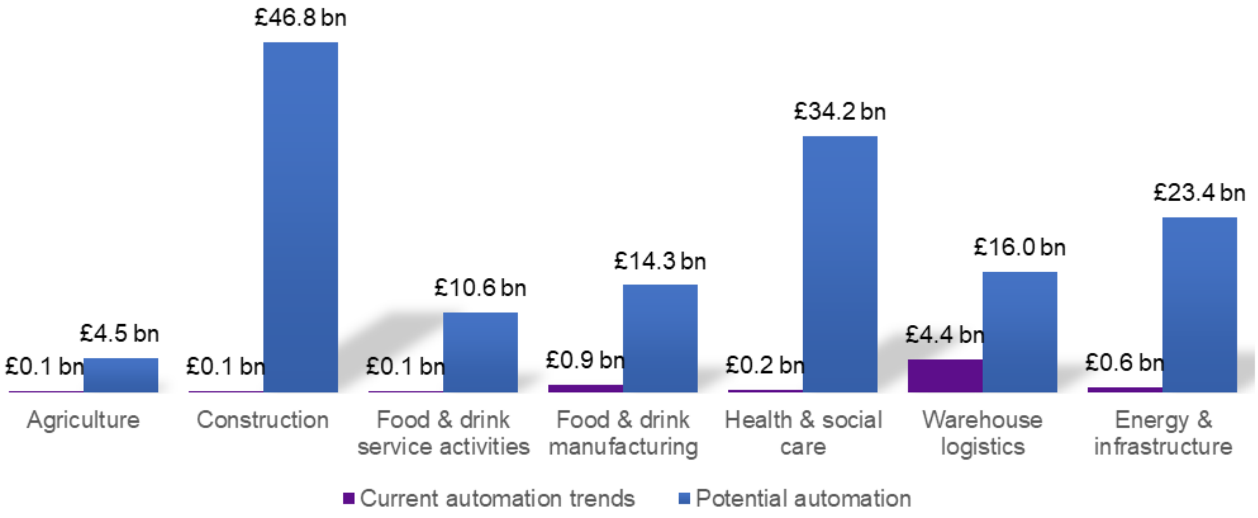
Note, estimates of the automation potential capture also automation through non-physical technologies such as AI. The level of automation that could be achieved from RAS alone is therefore likely to be less than the full automation potential. Nevertheless, the comparison provides a useful indication of the magnitude of automation that may be achieved given current trends and the level of automation that is technically feasible.

Moreover, while tasks could technically be automated, it is not necessarily feasible to automate all these tasks in practice (e.g. because of economic, legal, regulatory, organisational or other constraints – see PwC, 2018b for further discussion).

The size of the prize

The figure below provides, based on the potential rates of automation across sectors shown in the previous figure, estimates of the economic opportunity in each sector. The estimates are based on a simple calculation of 2035 baseline GVA, multiplied by the potential rate of automation from PwC (2018b). They should therefore be seen as rough estimates facilitating a comparison across selected sectors only. For convenience, the estimated GVA impacts under current adoption trends are also provided as a comparison.

The size of the prize: Potential value of GVA that could be attributable to RAS, by 2035, if potential rates of automation were achieved



Note: The figure provides, for each selected sector, a rough estimate of the potential value of GVA that could be attributable to RAS, by 2035, if the potential rates of automation were achieved. These rough estimates are the result of a simple calculation multiplying 2035 baseline GVA by the potential rate of automation from PwC (2018b).

Source: London Economics' analysis

Magnitude of the size of the prize:

Note that the GVA estimates under full automation (the magnitude of the size of the prize in each sector) are based on a simple calculation of 2035 baseline GVA, multiplied by the potential rate of automation from PwC (2018b). They should therefore be seen as rough estimates facilitating a comparison across selected sectors only; in particular it should be noted that:

- Sectors with higher estimated automation potential (i.e. sectors where a higher proportion of tasks could feasibly be automated) will have higher economic impacts.
- At the same time, the impact is also dependent on the size of the sector: Sectors that are smaller in size will have lower estimated impacts, while larger sectors will have larger impacts.

Therefore, sectors with a high proportion of automatable tasks but a small sector size will see smaller impacts. In contrast, large sectors with a relatively modest proportion of automatable tasks may see larger impacts simply due to the scale of the sector.

The following points are worth highlighting in particular:

- The comparison suggests that up to 38% of tasks in the **construction** sector could be automated, equivalent to an estimated £45 billion of 2035 construction sector GVA. As discussed previously, opportunities in the construction sector range from off-site prefabrication of components and entire structures, to the demolition of buildings, in site surveying and mapping, as well as supporting workers lifting heavy items by utilising powered exoskeletons. However, current trends suggest that RAS adoption in the construction sector will remain low, with a less than 1% reduction in labour needs by 2035, equivalent to only around £0.1 billion of construction GVA.
- Similarly, significant opportunities for RAS adoption exist in the **health & social care** sector. While only around 21% of tasks in the industry could feasibly be automated by 2035, the size of the sector means that automation on this scale would translate to nearly £35 billion of GVA. However, current adoption trends indicate that less than 1% of health & social care tasks (equivalent to around £0.2 billion of GVA) are expected to be automated over this period. While economic impacts in the sector may remain small, RAS adoption can also generate human impacts - for example, surgical robots improving the accuracy of diagnosis and reducing negative outcomes for patients.
- The comparison suggests that up to 52% of tasks in the **warehouse logistics** sector could technically be automated by 2035, equivalent to an estimated £16 billion of GVA. Under current trends, however, RAS adoption is expected to result in a reduction in labour needs of 14%, equivalent to an estimated £4.4 billion of GVA. Therefore, while the economic impact of RAS in this sector is expected to be significant, it is less than one third of the impact that could be achieved if its automation potential was reached.
- The comparison suggests that up to 39% of tasks in the **energy & infrastructure** sector could technically be automated by 2035, equivalent to an estimated £23 billion of GVA. Under current trends, however, RAS adoption is expected to result in a reduction in labour needs of just 1%, equivalent to an estimated £0.6 billion of GVA. This indicates a significantly lower economic impact of RAS than could be achieved if its automation potential was reached. It is worth noting that no official definition of the energy & infrastructure sectors exists. Therefore, impacts will vary depending on the definition

used[36]. The sector also has overlaps and synergies with the construction sector – meaning that some impacts counted as part of the construction sector could also be classified as infrastructure impacts.

- In the **agriculture** sector up to 30% of tasks could technically be automated by 2035, equivalent to an estimated £4.5 billion of GVA. Under current trends, however, RAS adoption is expected to result in a reduction in labour needs of just 1%, equivalent to an estimated £0.1 billion of GVA. This also indicates a significantly lower economic impact of RAS than could be achieved if its automation potential was reached. However, as with health & social care, the agriculture sector – and the food & drinks sector – is of significant wider importance to the UK.
- In the **food & drink manufacturing** sector up to 45% of tasks could technically be automated by 2035, equivalent to an estimated £14.3 billion of GVA. Under current trends, RAS adoption is expected to result in a reduction in labour needs of 4%, equivalent to an estimated £0.9 billion of GVA. Therefore, while the economic impact of RAS in this sector is expected to be significant relative to other sectors, it is a small fraction of the impact that could be achieved if its automation potential was reached. Moreover, combining the potential impact across the agriculture, food & drink services, and food & drink manufacturing sectors, suggests that the total impact of automation in **food & drink** could be up to nearly £30 billion if its automation potential were to be reached by 2035.

The feasibility of policy interventions for addressing the automation gap

Despite only being a rough approximation, the analysis in the preceding section nevertheless highlights the sizeable opportunity that RAS provides even for sectors where future adoption is estimated to be relatively small. However, whether, and to what extent, these additional benefits can be realised depends on whether, and how much, adoption of RAS over and above current trend estimates can be facilitated.

Whether, and to what extent, policy interventions may be fruitful in raising the level of adoption in a sector depends, at least to some extent, on the nature of the barriers. Sectors where barriers are mostly related to issues that are more readily addressable by policy, such as regulation, are more likely to benefit from policy interventions than sectors in which barriers are less readily addressable by policy, such as significant structural barriers.

A detailed analysis of challenges and barriers faced was not part of the study scope. However, the importance of the nature of barriers for RAS uptake means that this report would not be complete without at least some discussion on the barriers faced in selected sectors. Therefore, we provide here a brief analysis of the extent to which identified barriers in selected sectors (as discussed in the qualitative chapter) may be addressable through policy interventions:

- **Agriculture:** Barriers to RAS adoption in the agriculture sector include those that are policy-addressable and those that are not. Policy can address the identified barriers relating to farmers' inability to make use of RAS technology. Specifically, policy interventions improving rural broadband and 4G and 5G access as well as digital skills

[36] Note the sector was assumed to be equivalent to the electricity, gas, steam (D) and water supply, sewerage and waste management (E) sectors – see methodological annex.

could be put in place. While low margins faced by many UK farms are difficult to address with policy, a potential policy solution to this barrier could be the provision of loans on favourable terms to farms seeking to purchase or rent RAS. Policy could also be used to address the lack of coordination of RAS research in agriculture. However, policy cannot feasibly address the small size of UK farms and the unpredictability of UK weather, both identified as barriers to RAS adoption as they prevent the achievement of economies of scale and create technical challenges respectively (see the qualitative assessment of the economic opportunities from RAS in agriculture above for more details).

- **Construction:** A key barrier to RAS adoption in the construction sector was identified to be the technical complexity of tasks and environments in this sector. While this technological barrier is not directly addressable via policy (in that policy cannot change the fact that there is technical complexity in this sector), it likely will be mitigated as technology becomes more advanced. Policy makers could help mitigate the barrier indirectly by providing support for RAS researchers and developers seeking to further develop the ability of RAS to perform complex tasks in complex environments. Policy interventions could also be used to address the labour market barriers to RAS adoption in the construction sector. Specifically, training to improve digital skills and funding for apprenticeships could help to address the shortage of digital skills as well as mitigate the ageing workforce demographics in the sector. It has been suggested (see e.g. de Laubier et al. 2019) that increased use of RAS can make working in the construction industry more attractive to young people, and so adoption of RAS may itself help mitigate the ageing workforce demographics. However, in the construction sector a key barrier to RAS adoption is the structure of the sector. The UK construction sector is characterised by a large number of small firms with small budgets for new technologies (Delgado et al. 2019). The large initial investments needed to adopt RAS thus present a specific barrier to RAS adoption in the sector as RAS investments may be deemed infeasible by many smaller firms. It will be difficult for policy to remove this barrier.

- **Energy and infrastructure**: The technical challenges involved in the use of RAS in the energy & infrastructure sectors are important. Policy cannot remove these by fiat, but it can support the proper networks and funding of research and development aimed at solving these challenges. While, again, policy cannot simply eliminate cultural risk aversion and a high standard of validation in the energy & infrastructure sectors, government can support innovation hubs that provide “proving grounds” for RAS technology. The UK government is already doing this, as described in the qualitative energy sector section.

- **Food & drink**: Barriers to RAS adoption in the food & drink sector are largely technical and include the need for soft robotics capable of handling fragile packaging, the need for robots that can withstand sanitisation procedures and the need for robots to be able to interact with customers and accommodate custom orders and dietary requirements. Policy measures that can address this are likely to be limited to those supporting testing and research into solutions to the relevant problems.

- **Health & social care**: In health & social care, a number of important barriers to RAS adoption are difficult to address with policy. For instance, the ethical concerns around the use of RAS cannot be removed by policy, though information campaigns aimed at eliminating misconceptions about RAS and highlighting their potential benefits could help to assuage them. The cost of RAS is also difficult to address by policy beyond providing support for the development of cheaper RAS solutions. However, training to provide medical and social care staff with the necessary technical and digital skills can be facilitated.

- **Logistics**: With respect to logistics, a number of the barriers to adoption are readily addressed by policy. Drone regulations can be liberalised so as to keep pace with developments in drone technology. The skill requirements and need for engagement and "buy-in" by staff with RAS could plausibly be addressed by informational campaigns and increased funding for education and training. The technical challenges around interoperability and the need for greater flexibility should lessen as technology advances; plausible policy interventions to address are limited to supporting research into and development of new RAS technologies.

Bibliography

ABI Research (2020a). Commercial and Industrial Robotics. Available at: https://www.abiresearch.com/market-research/product/7777986-commercial-and-industrial-robotics/

ABI Research (2020b). Commercial and Industrial Robotics – ABI Research Sample. Available at: https://0d6ea3a143112fa73580-03f08f5fc1c22419d3b64e44df494fa7.ssl.cf1.rackcdn.com/eblast/deliverables/ABI-Research-Sample-MD-2020.xlsm

Acemoglu, D. and Restrepo, P. (2017). Secular Stagnation? The Effect of Aging on Economic Growth in the Age of Automation, American Economic Review, P&P, 107(5): 174–79.

Acemoglu, D. and Restrepo, P. (2019a). Demographics and Automation. Available at https://economics.mit.edu/files/16788.

Acemoglu, D. and Restrepo, P. (2019b). Automation and New Tasks: How Technology Displaces and Reinstates Labor, Journal of Economic Perspectives—Volume 33, Number 2—Spring 2019—Pages 3–30

Acemoglu, D., Lelarge, C., and Restrepo, P. (2020). Competing with Robots: Firm-Level Evidence from France, AEA Papers and Proceedings 2020, 110: 383-388.

Achour, N. and Price, A.D., (2010). Resilience strategies of healthcare facilities: present and future. International Journal of Disaster Resilience in the Built Environment.

Agri-EPI Centre (2020a). Agri-Tech Centres of Agricultural Innovation. Available at https://agri-epicentre.com/about/agri-tech-centres-of-agricultural-innovation/.

Agri-EPI Centre (2020b). South West Dairy Development Centre. Available at https://agri-epicentre.com/solutions/livestock-dairy/south-west-dairy-development-centre/.

Ambrose, J. (2019) Renewable electricity overtakes fossil fuels in UK for first time, The Guardian. Published 14th October 2019. Available at https://www.theguardian.com/business/2019/oct/14/renewable-electricity-overtakes-fossil-fuels-in-uk-for-first-time.

Arntz, M., T. Gregory and U. Zierahn (2016), The Risk of Automation for Jobs in OECD Countries: A Comparative Analysis, OECD Social, Employment and Migration Working Papers, No. 189, OECD Publishing, Paris, https://doi.org/10.1787/5jlz9h56dvq7-en.

Atherton, M. (2017, September 25). Food manufacturers lose £400M as productivity falls. Foodmanufacture.Co.Uk. https://www.foodmanufacture.co.uk/Article/2017/09/25/Food-and-drink-productivity-falls-as-labour-costs-rise

Atolia, M., Bin, G.L., Ricardo, M., and Melina, G. (2017). Investing in Public Infrastructure: Roads or Schools?, International Monetary Fund Working Paper WP/17/105. Available at https://www.imf.org/en/Publications/WP/Issues/2017/05/04/Investing-in-Public-Infrastructure-Roads-or-Schools-44865.

Autodesk (2020). What are the benefits of BIM?. Available at https://www.autodesk.com/solutions/bim/benefits-of-bim.

Autor, D.H. (2015). Why Are There Still So Many Jobs? The History and Future of Workplace Automation. *Journal of Economic Perspectives* Volume 29, Number 3, Summary 2015, pp.3-30.

Balafoutis A, et al. (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability 9(8):1339.

Bank of England (2020). Monetary Policy Report. May 2020

Banker, S. (2018, October 4). Robots With ‘Hands’ That Pick And Pack Delicate Products At Incredibly High Speeds. Forbes. https://www.forbes.com/sites/stevebanker/2018/10/04/robots-with-hands-that-pick-and-pack-delicate-products-at-incredibly-high-speeds/

Barclays (2018). #FarmtheFuture – Inspiring the next generation. Available at https://www.barclays.co.uk/business-banking/business-insight/farmthefuture/.

Bass, F. M. (1969). A New Product Growth Model for Consumer Durables. Management Science 15: pp. 215-227

BBC (2020). BBC Briefing: Housing. 26 February 2020. Available at http://news.files.bbci.co.uk/include/newsspec/pdfs/bbc-briefing-housing-newsspec-26534.pdf.

BBC News. (2019). Ocado warehouse set to be rebuilt after fire. Published 10th December 2019. Available at https://www.bbc.com/news/uk-england-hampshire-50727440

BBC News. (2020, February 18). ‘Hundreds injured at Amazon UK warehouses’. BBC News. https://www.bbc.com/news/business-51539329

BERTIM (2016). Building Energy Renovation through Timber Prefabricated Modules. http://www.bertim.eu/index.php?limitstart=63&lang=en.

Best, J. (2019). Robotic exoskeletons: Coming to a factory, warehouse or army near you, soon. ZDNet. https://www.zdnet.com/article/robotic-exoskeletons-coming-to-a-factory-warehouse-or-army-near-you-soon/

Bock, T. and Linner, T. (2015). Robotic industrialization. Cambridge University Press.

Booth, R. (2020, September 7). Robots to be used in UK care homes to help reduce loneliness. The Guardian. https://www.theguardian.com/society/2020/sep/07/robots-used-uk-care-homes-help-reduce-loneliness

Booth, W. and Adam, K. (2018) Brits don’t want to work on farms – so who will pick fruit after Brexit?, *The Independent*, published 4th August 2018. Available at https://www.independent.co.uk/news/uk/politics/brexit-eu-agriculture-farms-fruit-picking-migrant-workers-labour-shortage-a8469806.html

Boston Consulting Group (2019). Advanced Robotics in the Factory of the Future. 27th March 2019. Available at https://www.bcg.com/publications/2019/advanced-robotics-factory-future.

Boyle (2010). Some forecasts of the diffusion of e-assessment using a model. Innovation Journal. Vol. 15:1-30

British Meat Processors Association (2019). Meat industry labour shortages signal it's time to get serious. 22nd January 2019. Available at https://britishmeatindustry.org/industry-news/meat-industry-labour-shortages-signal-its-time-to-get-serious/.

Broadbent, E., Stafford, R. and MacDonald, B., (2009). Acceptance of healthcare robots for the older population: Review and future directions. International journal of social robotics, 1(4), p.319.

Brooks, K. (October 15th 2018) How robots are changing logistics Current by Distrelec https://www.distrelec.de/current/en/robotics/how-robots-are-changing-logistics/

Brown, A. (2015, April 20). South Glasgow Hospital spends £1.3million on fleet of ROBOT NHS staff. Express UK. https://www.express.co.uk/life-style/science-technology/571593/NHS-South-Glasgow-University-Hospital-Robots-Porters-Droids-Cost

Brumson, B. (2011). A Look at Robots in Alternative Energy for the Robotic Industries Association. Published 12th August 2011. Available at https://www.robotics.org/content-detail.cfm/Industrial-Robotics-Industry-Insights/Robotics-in-Alternative-Energy/content_id/3168.

Bruns, I. (2019). Drones for Power Line Inspections, Utility Products. Published 1st January 2019. Available at https://www.utilityproducts.com/line-construction-maintenance/article/16003823/drones-for-power-line-inspections.

Caffoor, I. Robotics and Autonomous Systems (RAS) for buried pipe infrastructure and water operations, Twenty65 report. Available at https://pipebots.ac.uk/wp-content/uploads/2019/03/robotics-report-web-4.pdf.

Calderone, L. (2013). Using Robots to Clean Oil Spills, RoboticsTomorrow. Published 12th January 2013. Available at https://www.roboticstomorrow.com/article/2013/12/using-robots-to-clean-oil-spills/215/.

Carthey J, de Leval MR, Reason JT (2001) Institutional resilience in healthcare systems BMJ Quality & Safety;10:29-32.

Castro-Lacouture, D. (2009). Springer Handbook of Automation, Springer, Berlin, pp. 1063-1078

Chandrasekaran and Tellis (2007). A Critical Review of Marketing Research on Diffusion of New Products

Cheeseman, J. (2017). Manufacturing the future of robotics: The state of the UK robotics industry. Available at: https://www.factoryandhandlingsolutions.co.uk/articles/manufacturing-the-future-of-robotics-the-state-of-the-uk-robotics-industry/

Chiron. (n.d.). Chiron—Care at Home using Intelligent Robotic Omni-functional Nodes. Retrieved 24 August 2020, from https://chiron.org.uk/

Civil Aviation Authority (2020a). Large unmanned aircraft. Available at https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Large-unmanned-aircraft/.

Civil Aviation Authority (2020b). Unmanned aircraft and drones. Available at https://www.caa.co.uk/Consumers/Unmanned-aircraft-and-drones/.

Civil Aviation Authority (2020c). Regulations relating to the commercial use of small drones. Available at https://www.caa.co.uk/Commercial-industry/Aircraft/Unmanned-aircraft/Small-drones/Regulations-relating-to-the-commercial-use-of-small-drones/.

Civil Engineering Contractors' Association (2018). The social benefits of infrastructure investment. Available at https://www.ceca.co.uk/wp-content/uploads/2018/12/Cebr-CECA-report-The-Social-Benefits-of-Infrastructure-Investment-FINAL-December-2018-compressed-2.pdf

CMR Surgical. (2020, February 20). 'Transformative' surgical robot begins first NHS procedures. CMR Surgical. https://cmrsurgical.com/transformative-surgical-robot-begins-first-nhs-procedures/

Colombo, M. G., Piva, E., Quas, A., & Rossi-Lamastra, C. (2016). How high-tech entrepreneurial ventures cope with the global crisis: Changes in product innovation and internationalization strategies. Industry and Innovation, 23(7), 647–671.

Cortese, D. (2018). The Construction Robots are Coming, The B1M. Published 29th May 2018. Available at https://www.theb1m.com/video/the-construction-robots-are-coming.

Costello, K. (2020, May 13). Gartner Says Global IT Spending to Decline 8% in 2020 Due to Impact of COVID-19. Available at https://www.gartner.com/en/newsroom/press-releases/2020-05-13-gartner-says-global-it-spending-to-decline-8-percent-in-2020-due-to-impact-of-covid19

Country Land and Business Association (CLA) UK will need a new land army to feed the nation says CLA. 20 March 2020 https://www.cla.org.uk/%E2%80%98uk-will-need-new-land-army-feed-nation-says-cla

Cousineau, L. and Miura, N. (1998). Construction robots: the search for new building technology in Japan. ASCE Publications.

Cousins, S. (2019). The rise of construction robotics, Construction Manager. Published 28th May 2019. Available at https://www.constructionmanagermagazine.com/rise-construction-robotics/.

Cresswell, K., Cunningham-Burley, S., & Sheikh, A. (2018). Health Care Robotics: Qualitative Exploration of Key Challenges and Future Directions. Journal of Medical Internet Research, 20(7), e10410. https://doi.org/10.2196/10410

Croner-i (February 17th 2020) Managing health and safety in warehouses https://app.croneri.co.uk/feature-articles/managing-health-and-safety-warehouses?product=133

Dasgupta, S. (2019, October 13). What is Remotely Operated Underwater Vehicle (ROV)? Retrieved from Marine Insight : https://www.marineinsight.com/tech/what-is-remotely-operated-underwater-vehicle-rov

Davis, N. (2016, January 19). What is the fourth industrial revolution? Retrieved from World Economic Forum : https://www.weforum.org/agenda/2016/01/what-is-the-fourth-industrial-revolution

de Laubier, R. et al. The Offsite Revolution in Consulting, Boston Consulting Group. Available at https://www.bcg.com/en-gb/publications/2019/offsite-revolution-construction

Dekhne, A. et al. (April 24th 2019) Automation in logistics: Big opportunity, bigger uncertainty McKinsey & Company https://www.mckinsey.com/industries/travel-logistics-and-transport-infrastructure/our-insights/automation-in-logistics-big-opportunity-bigger-uncertainty

Delgado, J.M.D., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M., and Owolabi, H. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption, Journal of Building Engineering 26. Available online from 12th July 2019. Available at https://uwe-repository.worktribe.com/output/1491964/robotics-and-automated-systems-in-construction-understanding-industry-specific-challenges-for-adoption.

Deloitte. (2020). Robotic Process Automation. Retrieved from Deloitte: https://www2.deloitte.com/uk/en/pages/innovation/solutions/robotic-process-automation.html

Demaitre, E. (2018). Infrastructure Robots Rise to Meet Urgent Needs, Robotics Business Review. Published 4th July 2018. Available at https://www.roboticsbusinessreview.com/construction/infrastructure-robots-meet-urgent-needs/.

Demetrakakes, P. (2020, May 1). Food Industry Struggles with Barriers to Automation. Food Processing. https://www.foodprocessing.com/articles/2020/food-industry-struggles-with-barriers-to-automation/

Department for Business, Energy & Industrial Strategy. (2019, March 7). Press release: Offshore wind energy revolution to provide a third of all UK electricity by 2030. Retrieved from gov.uk: https://www.gov.uk/government/news/offshore-wind-energy-revolution-to-provide-a-third-of-all-uk-electricity-by-2030

Department for Business, Energy and Industrial Strategy (2020). 2018 UK Greenhouse Gas Emissions, Final Figures.

Department for Business, Innovation & Skills. (2013, October 9). Eight great technologies: infographics. Retrieved from gov.uk: https://www.gov.uk/government/publications/eight-great-technologies-infographics

Department for Environment, Food & Rural Affairs (2016). Agricultural labour in England and the UK. Farm Structure Survey 2016. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/771494/FSS2013-labour-statsnotice-17jan19.pdf.

Department for Environment, Food & Rural Affairs (2020). Total Income from Farming in the United Kingdom, first estimate for 2019. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/884101/agricaccounts-tiffstatsnotice-07may20i.pdf.

Department for International Trade (2019). Robotic Solutions. Available at http://www.race.ukaea.uk/wp-content/uploads/2019/08/DIT-Robotics-Proposition.pdf.

DHL (2016). Robotics in logistics: A DPDHL perspective on implications and use cases for the logistics industry. https://www.dhl.com/content/dam/downloads/g0/about_us/logistics_insights/dhl_trendreport_robotics.pdf

DiMaio, S. et al. (2020) Robotics, Autonomous Systems and AI for Nonurgent/Nonemergent Healthcare Delivery During and After the COVID-19 Pandemic. Frontiers https://www.frontiersin.org/research-topics/14462/robotics-autonomous-systems-and-ai-for-nonurgentnonemergent-healthcare-delivery-during-and-after-the

Dolic, Z., Castro, R., Moarcas, A. (2019). Robots in healthcare: a solution or a problem?, European Parliament, Luxembourg, 2019. https://www.statewatch.org/media/documents/news/2019/may/ep-analysis-robots-health.pdf

Dredge, S. (2015, February 27). Robear: The bear-shaped nursing robot who'll look after you when you get old. The Guardian. https://www.theguardian.com/technology/2015/feb/27/robear-bear-shaped-nursing-care-robot

Duckett, T., et al. (2018). Agricultural Robotics: The Future of Robotic Agriculture, UK-RAS Network White Paper. Available at https://www.ukras.org/wp-content/uploads/2018/10/UK_RAS_wp_Agri_web-res_single.pdf.

Edmund, C. (Jan 15th 2020) These are the top risks facing the world in 2020 World Economic Forum https://www.weforum.org/agenda/2020/01/top-global-risks-report-climate-change-cyberattacks-economic-political/

Edwards, D. (2020, January 23). Top 5 Food Industry Technology Advances In 2019. Robotics & Automation News. https://roboticsandautomationnews.com/2020/01/23/top-5-food-industry-technology-advances-in-2019/28932/.

Encyclopedia.com. (2020, September 5). Mobile Robotics. Retrieved from Encyclopedia.com: https://www.encyclopedia.com/computing/dictionaries-thesauruses-pictures-and-press-releases/mobile-robotics

Energy UK (2019). Energy in the UK, 2019. Available at https://www.energy-uk.org.uk/publication.html?task=file.download&id=7233.

Epicor. (2020). What is Industry 4.0. Retrieved from Epicor: https://www.epicor.com/en-uk/resource-center/articles/what-is-industry-4-0

European Commission (2018). Drones in agriculture. Available at https://ec.europa.eu/growth/tools-databases/dem/monitor/sites/default/files/Drones_vf.pdf.

European Maritime Safety Agency (EMSA) (2018). RPAS Service Portfolio: Ship Emission Monitoring, press release. Published 22nd September 2017; updated 21st August 2018. Available at http://www.emsa.europa.eu/operations/rpas/items.html?cid=352&id=3116.

Evans, R. et al. (2013). Adoption of site-specific variable rate sprinkler irrigation systems. Irrig. Sci. 31(4):871–87.

Exoskeleton Report. (n.d.). What is an exoskeleton? Retrieved from Exoskeleton Report: https://exoskeletonreport.com/what-is-an-exoskeleton/

FarmingUK (2020). More than 4 in 10 farmers don't have adequate broadband. Available at https://www.farminguk.com/news/more-than-4-in-10-farmers-don-t-have-adequate-broadband_54753.html.

Fenner, A.E. et al. (2017). A review of prefabrication benefits for sustainable and resilient coastal areas, Proceedings of the 6th International Network of Tropical Architecture Conference, Tropical Storms as a Setting for Adaptive Development and Architecture, Gainesville, FL, USA (pp. 1-3).

Findlay, K. (2020) Is Renewable Energy the Definition of Resilience?, REN21.Publishwed 3rd June 2020. Available at https://www.ren21.net/renewable-energy-resilient/.

Finger, R. et al. (2019). Precision farming at the nexus of agricultural production and the environment.

Food Standards Agency (December 11th 2018) Food hygiene for your business https://www.food.gov.uk/business-guidance/food-hygiene-for-your-business

Freeman, R.B., Ganguli, I., and Handel, M.J. (2020). Within-Occupation Changes Dominate Changes in What Workers Do: A Shift-Share Decomposition, 2005–2015, AEA Papers and Proceedings 2020, 110: 394–399

French, P. (2020, June 3). Dutch restaurants recruit robot waiters as Covid-19 restrictions ease. https://www.thedrinksbusiness.com/2020/06/dutch-restaurants-recruit-robot-waiters-as-covid-19-restrictions-ease/

Frey, C.B. and M.A. Osborne (2013). The Future of Employment: How Susceptible are Jobs to Computerisation?. University of Oxford

FTA. (2019). FTA Logistics Report 2019. 88.

Game Changers (2019). 'Delivering Change Through Robotics at Sellafield'. Available at https://www.gamechangers.technology/challenges/delivering-change-through-robotics/.

Geijer, T. (2019, April 30). Food tech: Technology in the food industry. ING Think. https://think.ing.com/reports/food-tech-technology-in-the-food-industry/

GenieConnect. (n.d.). Meet GenieConnect. Service Robotics Limited. Retrieved 24 August 2020, from https://www.genieconnect.co.uk/

Gerrard, N. (2018). Revealed: How UK's construction workforce is ageing, Construction Manager. Published 19th June 2018. Available at https://www.constructionmanagermagazine.com/revealed-how-uks-construction-workforce-ageing/.

Giles, C. (2020). Post-Brexit migration regime forecast to hit UK growth, Financial Times. Published 6th March 2020. Available at https://www.ft.com/content/76f1e376-5efc-11ea-b0ab-339c2307bcd4.

Global Cold Chain News. (2020, February 19). Logistics faces growing labour crisis. https://www.globalcoldchainnews.com/logistics-faces-growing-labour-crisis/

Golder, P. N., Mitra, G., D. (2018). Handbook of Research on New Product Development: Edward Elgar Publishing

Goldman Sachs (2016). Technology Driving Innovation: Drones. Available at https://www.goldmansachs.com/insights/technology-driving-innovation/drones/.

GOV.UK. (n.d.). Centre for Connected and Autonomous Vehicles. GOV.UK. Retrieved 24 August 2020, from https://www.gov.uk/government/organisations/centre-for-connected-and-autonomous-vehicles

Government Office for Science (2016). Future of an Ageing Population. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816458/future-of-an-ageing-population.pdf.

Grant, A. et al. (2020) The economic and environmental impacts of UK offshore wind development: The importance of local content. Energy: 117436.

Greenmatch (2020) UK Solar Capacity: Is the Future of Solar Cloudy?. Published 20th July 2020. Available at https://www.greenmatch.co.uk/blog/2019/09/uk-solar-capacity.

Guy's and St Thomas' NHS Foundation Trust. (n.d.). Robotic-assisted surgery at Guy's Hospital. Retrieved 24 August 2020, from https://www.guysandstthomas.nhs.uk/Home.aspx

Hall, W., & Pesenti, J. (2017). Growing the Artificial Intelligence Industry in the UK. UK Government. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652097/Growing_the_artificial_intelligence_industry_in_the_UK.pdf

Halliwell, J. (2019, March 22). Can robots solve the labour shortage in UK warehousing? The Grocer. https://www.thegrocer.co.uk/supply-chain/can-robots-solve-the-labour-shortage-in-uk-warehousing/591518.article

Hamilton, I. A. (2020, September 30). Explosive Amazon warehouse data suggests serious injuries have been on the rise for years and robots have made the job more dangerous. Business Insider. https://www.businessinsider.com/explosive-reveal-amazon-warehouse-injuries-report-2020-9

Harper Adams University (2017). 'Harvest completed at world-first project to farm a crop exclusively with robots'. Published 8th September 2017. Available at https://www.harper-adams.ac.uk/news/203144/harvest-completed-at-worldfirst-project-to-farm-a-crop-exclusively-with-robots.

Harvey, F. (2014). Robot farmers are the future of agriculture, says government, The Guardian. Published 9th January 2014. Available at https://www.theguardian.com/environment/2014/jan/09/robots-farm-future.

Hassan, Ahmed A, et al. (2020) Renewable Energy for Robots and Robots for Renewable Energy – A Review. Robotica, vol. 38, no. 9, pp. 1576–1604.

Health and Safety Executive (2019). Workplace fatal injuries in Great Britain, 2019. Published 3rd July 2019. Available at https://www.hse.gov.uk/statistics/pdf/fatalinjuries.pdf.

Henriques, M. (2019). The ageing crisis threatening farming, BBC. Available at https://www.bbc.com/future/bespoke/follow-the-food/the-ageing-crisis-threatening-farming/.

Heyden, T. (2015). The cows that queue up to milk themselves, BBC News. Published 7th May 2015. Available at https://www.bbc.co.uk/news/magazine-32610257.

Ho, C. and Lee, N. (July 18th, 2019) The future of transport resilience. The Resilience Shift https://www.resilienceshift.org/the-future-of-transport-resilience/

Hopp, W. J. (2004). Ten most influential papers of management science's first fifty years. Management Sci., Vol. 50:1763–1893

House of Commons (2017). Feeding the nation: labour constraints. Environment, Food and Rural Affairs Committee. Available at https://publications.parliament.uk/pa/cm201617/cmselect/cmenvfru/1009/1009.pdf.

House of Commons Library (June 4th 2020) NHS staff from overseas: statistics https://commonslibrary.parliament.uk/research-briefings/cbp-7783/

IEA (2018). Energy Efficiency 2018. Published October 2018. Available at https://www.iea.org/reports/energy-efficiency-2018.

iGPS (January 31st, 2019) Deep Lane Storage: When to Choose High-Density Automated Warehouse Storage https://igps.net/blog/2019/01/31/deep-lane-storage-when-to-choose-high-density-automated-warehouse-storage/

Imperial College London Centre of Excellence on Infrastructure Robotics Ecosystems (2020). Research. Available at https://www.imperial.ac.uk/infrastructure-robotics/research/.

Industry Forum UK Strategy for Robotics and Autonomous Systems https://www.industryforum.co.uk/resources/articles/uk-strategy-for-robotics-and-autonomous-systems/

Innovate UK (2016). The UK Landscape for Robotics and Autonomous Systems 2015. Available at https://admin.ktn-uk.co.uk/app/uploads/2020/03/The-UK-Landscape-for-Robotics-Autonomous-Systems_15-02-16.pdf.

International Federation of Robotics (2018). IFR Press Releases, Frankfurt, Feb 07, 2018. Available at: https://ifr.org/ifr-press-releases/news/robot-density-rises-globally#:~:text=As%20the%20only%20G7%20country,to%20modernize%20and%20increase%20productivity.

International Federation of Robotics (2019). Executive Summary World Robotics 2019 Industrial Robots. Available at: https://ifr.org/downloads/press2018/Executive%20Summary%20WR%202019%20Industrial%20Robots.pdf

Jenkinson, L. (2019). Pioneering drone project trials are a resounding success, Energy Information Centre press release. Available at https://www.ukeic.com/media/pioneering-drone-project-trials-are-a-resounding-success

Jeska, S., & Pascha, K. S. (2014). Emergent Timber Technologies: Materials, Structures, Engineering, Projects. Birkhäuser.

Joerss, M., Schröder, J., Neuhaus, F., Klink, C., & Mann, F. (2016). Parcel delivery: The future of last mile. McKinsey. https://www.mckinsey.com/~/media/mckinsey/industries/travel%20transport%20and%20logistics/our%20insights/how%20customer%20demands%20are%20reshaping%20last%20mile%20delivery/parcel_delivery_the_future_of_last_mile.ashx

Johnson, B. (2010). The roadworks scam that costs Londoners £1 billion every year, The Telegraph. Published 11th January 2010. Available at https://www.telegraph.co.uk/politics/0/roadworks-scam-costs-londoners-1-billion-every-year/.

Karakuri. (n.d.). About Karakuri. Karakuri. Retrieved 2 September 2020, from https://karakuri.com/about-us/

Katwala, A. (2020, February 19). Heston Blumenthal wants robots to make your boring lunch. Wired UK. https://www.wired.co.uk/article/heston-karakuri

King, I. (2019). Britain's 'productivity puzzle' bugs economy, Sky News. Published 9th January 2019. Available at https://news.sky.com/story/britains-productivity-puzzle-bugs-economy-11602847.

The King's Fund (2018). Staffing shortfall of almost 250,000 by 2030 is major risk to NHS long-term plan, experts warn. Press release, 15th November 2018. Available at https://www.kingsfund.org.uk/press/press-releases/staffing-shortfall-major-risk-nhs-long-term-plan.

Knell, T. (2019, September 7). What are automated guided vehicle systems? Definition & advantages. Retrieved from maschinen markt international: https://www.maschinenmarkt.international/what-are-automated-guided-vehicle-systems-definition-advantages-a-861015/

Koch, M., Manuylov, I. and Smolka, M. (2019), Robots and firms, CESifo Working Paper 7608.

L&Q (2019). L&Q acts to address construction industry's image problem following startling new research. Published 8th February 2019. Available at https://www.lqgroup.org.uk/about/media-centre/news/details/164.

LAC Conveyers & Automation. (2019). Robotics and automation in the food industry and its future. https://www.lacconveyors.co.uk/robotics-and-automation-in-the-food-industry/

Law Society. (2019). Technology, Access to Justice and the Rule of Law: Is technology the key to unlocking access to justice innovation?

Lechky, O. (1985, November 12). World's first surgical robot in B.C. The Medical Post. https://www.brianday.ca/imagez/1051_28738.pdf

Lexico. (2020a). Rover. Retrieved from Lexico powered by Oxford: https://www.lexico.com/definition/rover

Lexico. (2020b). Internet of Things. Retrieved from Lexico powered by Oxford: https://www.lexico.com/definition/internet_of_things

Lin, B.B., (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience, 61(3), pp.183-193.

Lindsay, F. (2020) With No EU Workers Coming, The U.K. Agriculture Sector Is In Trouble Forbes. Published 24th March 2020.

Liu, D.K., Dissanayake, G., Valls Miro, J., and Waldron, K.J. (2014). Infrastructure Robotics: Research Challenges and Opportunities, conference paper for the 31st International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014).

Logistics UK (October 14th 2019) HGV driver shortage climbs to 59,000 https://logistics.org.uk/media/press-releases/2019/october-2019/hgv-driver-shortage-climbs-to-59-000#:~:text=The%20shortage%20of%20HGV%20drivers,a%20recent%20report%20by%20FTA.

Lowenberg-DeBoer, J. et al. (2020). Economics of robots and automation in field crop production, Precision Agric. 21, 278–299

Luca Robotics. (n.d.). Robot surgeons and AI nurses: The future of the NHS? Retrieved 4 June 2020, from https://www.lucarobotics.com/blog/robots-in-the-nhs

Macdonald, M. (2020). The health & social care workforce gap. https://commonslibrary.parliament.uk/social-policy/health/the-health-and-social-care-workforce-gap/

Mahajan, V., Muller, E., and Bass, F. (1995). Diffusion of new products: Empirical generalizations and managerial uses. Marketing Science. 14 (3): G79–G88.

Martin, F. (March 8th 2019). What Robots Mean For The Future Of The Hospitality Industry Houston Public Media https://www.houstonpublicmedia.org/articles/shows/bauer-business-focus/2019/03/08/324596/what-robots-mean-for-the-future-of-the-hospitality-industry/

Martin, S. (2016, November 25). Hospitals bringing ROBOTS to kill off superbugs and save lives. Express UK. https://www.express.co.uk/news/science/736600/robots-superbug-NHS-infection-xenex

Marvin, S. et al. (2018). Urban Robotics and Automation: Critical Challenges, International Experiments and Transferable Lessons for the UK, UK-RAS Network White Paper. Available at https://www.ukras.org/wp-content/uploads/2018/09/UK_RAS_wp_Urban_010618_print.pdf

Maslin, E. (2019). Imaging the Future, Offshore Engineer. Published 31st January 2019. Available at https://www.oedigital.com/news/462367-imaging-the-future.

Matthews, K. (2019). 5 Ways Robotics Will Disrupt the Construction Industry in 2019, Robotics Business Review. Published 23rd January 2019. Available at https://www.roboticsbusinessreview.com/news/5-ways-robotics-will-disrupt-construction-industry-in-2019/.

McKinsey (2013). Disruptive technologies: Advances that will transform life, business, and the global economy

McKinsey Global Institute (2019), 'Notes from the AI frontier: Tackling Europe's gap in digital and AI'. Discussion Paper, February 2019. Available at https://www.mckinsey.com/~/media/mckinsey/featured%20insights/artificial%20intelligence/tackling%20europes%20gap%20in%20digital%20and%20ai/mgi-tackling-europes-gap-in-digital-and-ai-feb-2019-vf.ashx.

McLaughlin, A., and Mineau, P. (1995). The impact of agricultural practices on biodiversity, Agriculture, Ecosystems & Environment, 55(3), 201-212.

Meade N., Islam T. (2006). Modelling and forecasting the diffusion of innovation—a 25-year review. Int Forecasting. Vol. 22(3):519–45

Med-Tech Innovation. (2018, September 5). New robotic surgical system hopes to rival da Vinci in the UK. Med-Tech Innovation | Latest News for the Medical Device Industry. https://www.med-technews.com/api/content/15371632-b0f3-11e8-8a98-120e7ad5cf50/

MHI. (2020, September 11). Glossary . Retrieved from Material Handling Industry of America - Glossary: https://www.mhi.org/glossary?fq=title-first-letter%3Aa-c&page=2&sort=title-sort%20asc%2Ccompany-sort%20asc

Mid and South Essex NHS Foundation Trust. (2017). Robotic Surgery—Helping the Surgeon to Help You. https://www.meht.nhs.uk/news/news-archive/2017-news-archive/robotic-surgery-helping-the-surgeon-to-help-you/

Middleton, C. (2017). How robots could help fix the UK's failing infrastructure, The Robot Engineer. Available at https://chrismiddleton.company/the-robot-engineer/.

Millward, D. (2018, October 19). The rise of the robot butler – fad or the future of hotel room service? The Telegraph. https://www.telegraph.co.uk/travel/hotels/articles/hotel-robot-room-service/

Molteni, M. (2020, May 25). Covid-19 Makes the Case for More Meatpacking Robots. Wired. https://www.wired.com/story/covid-19-makes-the-case-for-more-meatpacking-robots/

Monk, Z. (2019, August 5). London restaurant chain becomes first in the UK to hire robotic waitress. Foodservice Equipment Journal. https://www.foodserviceequipmentjournal.com/london-restaurant-chain-becomes-first-in-the-uk-to-hire-robotic-waitress/

Monroy, C. (2020, June 23). What is warehouse automation? - 6 River Systems. https://6river.com/what-is-warehouse-automation/

Mori, Y., Kudo, S. E., Berzin, T. M., Misawa, M., & Takeda, K. (2017). Computer-aided diagnosis for colonoscopy. Endoscopy, 49(8), 813.

MTC (2017). Robotics and Automation, i3P Discovery Project poster. Available at http://www.the-mtc.org/our-projects/i3p-programme.

Murphy et al. (May 20th 2020). Robots have demonstrated their crucial role in pandemics - and how they can help for years to come World Economic Forum (WEF) in collaboration with The Conversation https://www.weforum.org/agenda/2020/05/robots-coronavirus-crisis/

National Centre for Nuclear Robotics (2020). National Centre for Nuclear Robotics. Available at https://www.ncnr.org.uk/.

National Farmers' Union (2020). Government must make rural broadband and mobile coverage a priority, says NFU. Available at https://www.nfuonline.com/cross-sector/rural-affairs/broadband-and-mobile/broadband-news/government-must-make-rural-broadband-and-mobile-coverage-a-priority-says-nfu/.

National Infrastructure Commission (2017). Economic Growth and Demand for Infrastructure Services, discussion paper. Available at https://www.nic.org.uk/wp-content/uploads/2906219-NIC-Technical-Paper-Economic-Driver-v1_0A-WEBACCESSIBLE.pdf.

NatWest Business Hub. (2020a, July 21). NatWest Business Hub | Food sector faces skills and labour shortage. https://natwestbusinesshub.com/articles/food-and-drink-sector-faces-labour-shortage

NatWest Business Hub. (2020b, July 21). NatWest Business Hub | Should hospitality workers fear the rise of automation? https://natwestbusinesshub.com/articles/should-hospitality-workers-fear-the-rise-of-automation

Nelson, B. J., Kaliakatsos, I. K., & Abbott, J. J. (2010). Microrobots for minimally invasive medicine. Annual review of biomedical engineering, 12, 55-85.

Nepogodiev et. al. (2019). Global burden of postoperative death. The Lancet. Vol. 393, issue 10170. https://doi.org/10.1016/S0140-6736(18)33139-8

Nisudan, N. (2020) Building Supply Chain Resilience – The Current Trends BoxLogic https://www.box-logic.co.uk/building-supply-chain-resilience-the-current-trends/

Nuclear Decommissioning Authority (2017). Review of NDA's Approach to Robotics and Autonomous Systems (RAS), Output of NDA Research Board NDARB027, Issue 1. Published April 2017. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/609714/NDARB027_Output_of_NDA_Research_Board_-_Review_of_NDA_s_approach_to_robotics_and_autonomous_systems__RAS_.pdf.

Ocado Group. (2019, June 12). How Ocado and SOMA Consortium Partners made major breakthroughs in robotic manipulation. Ocado Group. https://www.ocadogroup.com/technology/blog/how-ocado-and-soma-consortium-partners-made-major-breakthroughs-robotic

OECD (2020). Labour productivity and utilisation (indicator). Available at https://data.oecd.org/lprdty/labour-productivity-and-utilisation.htm.

Office for National Statistics (2020). GDP monthly estimate, UK: May 2020. Available at: https://www.ons.gov.uk/economy/grossdomesticproductgdp/bulletins/gdpmonthlyestimateuk/may2020

Offshore Robotics for Certification of Assets (ORCA) Hub (2020). ORCA Robotics – Vision. Available at https://orcahub.org/about-us/vision.

ONS (2015). What is the productivity puzzle?. Published 7th July 2015. Available at https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/labourproductivity/articles/whatistheproductivitypuzzle/2015-07-07.

ONS (2018a). Labour in the agriculture industry, UK: February 2018. Last updated 6th February 2018. Available at https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/internationalmigration/articles/labourintheagricultureindustry/2018-02-06.

ONS (2018b). Developing new statistics of infrastructure: August 2018, last updated 21st August 2018. Available at https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/developingnewmeasuresofinfrastructureinvestment/august2018.

ONS (2018c). Living longer: how our population is changing and why it matters. Last updated 13th August 2018. Available at https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/ageing/articles/livinglongerhowourpopulationischangingandwhyitmatters/2018-08-13.

ONS. (2019, November 29). E-commerce and ICT activity—Office for National Statistics. https://www.ons.gov.uk/businessindustryandtrade/itandinternetindustry/datasets/ictactivityofukbusinessesecommerceandictactivity

ONS (2020a). Output per Worker: Whole Economy SA: Index 2016=100: UK data series. Released 7th July 2020. Available at https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/labourproductivity/timeseries/a4ym/prdy.

ONS (2020b). GDP output approach – low-level aggregates dataset, series KL9D. Released 12th August 2020. Available at https://www.ons.gov.uk/economy/grossdomesticproductgdp/datasets/ukgdpolowlevelaggregates

ORE Catapult (2019) Multi-Platform Inspection, Maintenance and Repair in Extreme Environments. Published 28th May 2019. Available at https://ore.catapult.org.uk/stories/mimree/.

Oxford Economics (2019). How Robots Change the World. Available at https://www.oxfordeconomics.com/recent-releases/how-robots-change-the-world.

Pan, M., et al. (2018). A framework of indicators for assessing construction automation and robotics in the sustainability context. Journal of Cleaner Production 182: 82-95.

Paoli, A. (2020, June 10). Food manufacture 4.0 – automation and robotics at the service of food manufacturing. New Food Magazine. https://www.newfoodmagazine.com/article/111886/food-manufacture-4-0-automation-and-robotics-at-the-service-of-food-manufacturing/

Pappalardo, J. (2019, April 16). Lithium-Ion Batteries Aren't Good Enough for Electric Flight. But Maybe Lithium-Metal Is. Popular Mechanics. https://www.popularmechanics.com/flight/drones/a27155551/battery-boeing/

Parliament UK. (2020, March 13). Commercial and recreational drone use in the UK: Government Response the Committee's Twenty-Second Report of 2017–19—Science and Technology Committee—House of Commons. https://publications.parliament.uk/pa/cm5801/cmselect/cmsctech/270/27002.htm

PARO Robots. (n.d.). PARO Therapeutic Robot. Retrieved 24 August 2020, from http://www.parorobots.com/

Parsley, D. 'UK housebuilders missed Government target of 300,000 new homes a year, despite more new homes'. iNews, published 6th February 2020 and updated 10th July 2020. Available at https://inews.co.uk/news/business/uk-housebuilders-missed-government-target-new-homes-394719.

Penman, H. (2020). announces plans to quadruple offshore wind power by 2030, evwind.es. Published 6th August 2020. Available at https://www.evwind.es/2020/08/06/uk-government-announces-plans-to-quadruple-offshore-wind-power-by-2030/76323.

Perrault, R., Shoham, Y., Brynjolfsson, E., Clark, J., Etchemendy, J., Grosz, B., Lyons, T., Manyika, J., Mishra, S. and Niebles, J.C. (2019). The AI Index 2019 Annual Report, AI Index Steering Committee, Human-Centered AI Institute, Stanford University, Stanford, CA, December 2019.

Pinkstone, J. (2020, July 20). Hospitals in Derby and Burton start using UV disinfection ROBOTS | Daily Mail Online. Mail Online. https://www.dailymail.co.uk/sciencetech/article-8540593/Hospitals-Derby-Burton-start-using-UV-disinfection-ROBOTS.html

Priestley, S., (2019). UK Carbon Budgets, House of Commons Library Briefing Paper, Number CBP7555, 9TH July 2019. Available at http://researchbriefings.files.parliament.uk/documents/CBP-7555/CBP-7555.pdf.

Purnell, P., et al. (2018). Self-Repairing Cities Mid-Term Report 2018. Available at https://selfrepairingcities.com/outputs/reports-presentations/mid-term-report-2018/.

PwC (2016). Clarity from above – PwC global report on the commercial applications of drone technology. Available at https://pwc.blogs.com/files/clarity-from-above-pwc.pdf.

PwC (2017). Clarity from above: transport infrastructure – The commercial applications of drone technology in the road and rail sectors. Available at https://www.pwc.com/hu/hu/szolgaltatasok/technologiai_tanacsadas/dron/pdf/clarity_from_above_transport_infrastructure.pdf.

PwC (2018a). Skies without limits – The impact of drones on the UK economy. Available at https://www.pwc.co.uk/issues/intelligent-digital/the-impact-of-drones-on-the-uk-economy.html.

PwC (2018b). Will robots really steal our jobs? An international analysis of the potential long term impact of automation.

PwC. (2019). Building trust in drones. Available at https://www.pwc.co.uk/issues/intelligent-digital/drones-and-trust.html.

Pyke, C. (2020, July 22). How a robot 'exoskeleton' will help Hampshire care workers do their job. Hampshirelive. https://www.hampshirelive.news/news/hampshire-news/how-robot-exoskeleton-help-hampshire-4349760

Ramanauskas, B. (2019). Embracing technology in health & social care. TaxPayers' Alliance. https://d3n8a8pro7vhmx.cloudfront.net/taxpayersalliance/pages/16535/attachments/original/1556005812/Embracing_technology_in_health_and_social_care.pdf?1556005812

Rassweiler, J. J., Autorino, R., Klein, J., Mottrie, A., Goezen, A. S., Stolzenburg, J.-U., Rha, K. H., Schurr, M., Kaouk, J., Patel, V., Dasgupta, P., & Liatsikos, E. (2017). Future of robotic surgery in urology. BJU International, 120(6), 822–841. https://doi.org/10.1111/bju.13851

Reed, E. (2018). The Cow-Milking Robots Keeping Small Farms in Business, The Atlantic. Published 11th October 2018. Available at https://www.theatlantic.com/business/archive/2018/10/young-dairy-farmers/567937/.

Reutter, K. (September 2nd 2019) Building Resilience for a New Era of Extreme Weather Events. FMI Quarterly Issue Three https://www.fminet.com/fmi-quarterly/article/2019/09/building-resilience-for-a-new-era-of-extreme-weather-events/.

Rhodes, C. (2019). Construction industry: statistics and policy, House of Commons Library Briefing Paper, Number 01432, 16th December 2019. Available at https://commonslibrary.parliament.uk/research-briefings/sn01432/.

Richardson, R., et al. (2017). Robotics and Autonomous Systems for Resilient Infrastructure, UK-RAS Network White Paper. Available at https://www.ukras.org/wp-content/uploads/2018/09/UK_RAS_wp_infrastructure_final_web.pdf.

Ridler, J. (2019, April 30). Robot adoption grows 50%. Foodmanufacture.Co.Uk. https://www.foodmanufacture.co.uk/Article/2019/04/30/Robot-adoption-grows-50

Robotics in Australia (2020). The future of robotics in infrastructure. Available at http://roboticsinaustralia.com.au/infrastructure/infrastructure-future/.

Rosso, L., & Ferranti, A. (2020, June 26). Consumers will drive urban logistics demand. Property Week. https://www.propertyweek.com/perspectives-summer-2020/consumers-will-drive-urban-logistics-demand/5108714.article

Royal College of Surgeons. (2018). Commission on the Future of Surgery. Royal College of Surgeons. https://www.rcseng.ac.uk/standards-and-research/future-of-surgery/

Ruch, P. (2019, July 5). Hypertaste: An AI-assisted e-tongue for fast and portable fingerprinting of complex liquids. IBM Research Blog. https://www.ibm.com/blogs/research/2019/07/hypertaste-ai-assisted-etongue/

Russell, S., & Norvig, P. (2009). Artificial Intelligence: A Modern Approach (3rd ed.). Upper Saddle River, New Jersey: Prentice Hall.

Sandey, KK., Qureshi, M.A., Mershram, B.D., Agrawal, A.K., and Uprit, S. (2017). Robotics – An Emerging Technology in Dairy Industry, International Journal of Engineering Trends and Technology (IJETT), Volume 43(1). Published 1st January 2017. Available at http://www.iraj.in/journal/journal_file/journal_pdf/2-448-152361955020-23.pdf.

Schranz, M., Umlauft, M., Sende, M., & Elmenreich, W. (2020). Swarm Robotic Behaviors and Current Applications. Frontiers in Robotics and AI, 7, 36.

Scriven, R. (2019, September 19). UK Warehouse Automation Market: Boom or Bust? Interact Analysis. https://www.interactanalysis.com/uk-warehouse-automation-mmarket/

Sellafield Ltd (2019). Pond cleaner ready to make a splash. Published 7th August 2019. Available at https://www.gov.uk/government/news/pond-cleaner-ready-to-make-a-splash.

Sheikh, K. (2020). A Growing Presence on the Farm: Robots, New York Times. Published 13th February 2020. Available at https://nyti.ms/2OQVqV5.

Shibata, T. and Wada, K., (2011). Robot therapy: a new approach for mental healthcare of the elderly–a mini-review. Gerontology, 57(4), pp.378-386.

Simeone, C.L., (2015). Business resilience: Reframing healthcare risk management. Journal of Healthcare Risk Management, 35(2), pp.31-37.

Skyports. (n.d.). NHS Trials. Skyports. Retrieved 28 September 2020, from https://skyports.net/nhs-trials/

Smart, S. (2017, May 1). Hazards in food & beverage manufacturing are found in many workplaces. https://www.ishn.com/articles/106363-hazards-in-food-beverage-manufacturing-are-found-in-many-workplaces?v=preview

Smith, M. and Bishop, G. (2016). Automation transforming UK industries. Deloitte UK https://www2.deloitte.com/uk/en/pages/press-releases/articles/automation-and-industries-analysis.html.

Soft Robotics. (n.d.). MGrip. Soft Robotics. Retrieved 2 September 2020, from https://www.softroboticsinc.com/products/mgrip/

SoftBank Robotics. (n.d.). Pepper the humanoid and programmable robot. Retrieved 24 August 2020, from https://www.softbankrobotics.com/emea/en/pepper

Sridhar et. al. (2017). Training in Robotic Surgery—an Overview. Current Urology Reports, vol. 18,8 (2017): 58. doi:10.1007/s11934-017-0710-y

Srivastava, S. (2020, March 2). SOFT ROBOTICS VS HARD ROBOTICS: HOW ARE THEY DIFFERENT? Retrieved from Analytics Insight : https://www.analyticsinsight.net/soft-robotics-vs-hard-robotics-different/

Statt, N. (2018, July 11). Why you should let a robot cook your next meal. The Verge. https://www.theverge.com/2018/7/11/17550848/future-of-dining-automation-robotics-creator-sf-robot-burgers-ai

Suarez, D. (August 16th 2018) Will AI And Robotics Replace People In Healthcare? PwC https://www.pwc.com/m1/en/media-centre/articles/ai-robotics-considerations-for-healthcare-workforce.html

Summers, L. (2019, December 12). The NHS robots performing major surgery. BBC News. https://www.bbc.com/news/uk-scotland-50745316

Tan, S.Y. and Taeihagh, A. (2020). Governing the adoption of robotics and autonomous systems in long-term care in Singapore. Policy and Society, pp.1-21

Tatum, M. (April 6th 2018). FOOD WASTE: How robots can help reduce supply chain food waste The Grocer https://www.thegrocer.co.uk/food-waste/how-robots-can-help-reduce-supply-chain-food-waste/565540.article

Tech Nation (2020). UK Tech for a Changing World: Tech Nation Report 2020. Available at https://technation.io/report2020/.

The London Clinic. (n.d.). Robotic surgery | The London Clinic. Retrieved 24 August 2020, from https://www.thelondonclinic.co.uk/treatments/robotic-surgery

Thilmany, J. (2019). Exoskeletons for Construction Workers Are Marching On-Site, Constructible. Published 27th February 2019. Available at https://constructible.trimble.com/construction-industry/exoskeletons-for-construction-workers-are-marching-on-site.

Trivedi, D., Rahn, C. D., Kier, W. M., & Walker, I. D. (2008). Soft robotics: Biological inspiration, state of the art, and future research. Applied Bionics and Biomechanics, 5(3), 99-117.

TWI. (2020). WHAT IS AN AUTONOMOUS VEHICLE? Retrieved from TWI: https://www.twi-global.com/technical-knowledge/faqs/what-is-an-autonomous-vehicle

UK Government. (2017a). Industrial Strategy: Building a Britain fit for the future. 256.

UK Government. (2017b). Made Smarter. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/655570/20171027_MadeSmarter_FINAL_DIGITAL.pdf

UK Government (2019). UK becomes first major economy to pass net zero emissions law, from the Department for Business, Energy & Industrial Strategy and the Rt Hon Chris Skidmore MP. Published 27th June 2019. Available at https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law.

UK-RAS Network. (2020). Medical Robotics for Contagious Diseases Challenge 2020. UK-RAS Network. https://www.ukras.org/robotics-week/challenges/medical-robotics-for-contagious-diseases-challenge-2020/

United Nations Food and Agriculture Organisation (2009). Global agriculture towards 2050, How to Feed the World: 2050, High-Level Expert Forum, Rome 12-13 October 2009. Available at http://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf.

University of Hull (2012). Robotic and Information Technologies in UK Dairy Farming, project brochure. Published November 2012. Available at https://orca.cf.ac.uk/40232/1/Robotic%20milking%20project%20brochure.pdf.

University of Southampton. (2020, May 13). Drone successfully completes first delivery of medical equipment to the Isle of Wight. https://www.southampton.ac.uk/news/2020/05/drone-trial-delivery.page

Utley, C. (n.d.). Da Vinci Surgery | Da Vinci Surgical System | Robotic Technology. DaVinci Surgery. Retrieved 24 August 2020, from https://www.davincisurgery.com/da-vinci-systems/about-da-vinci-systems

Varghese, S. (2018). How small robots may kill the tractor and make farming efficient, WIRED UK. Published 11th November 2018. Available at https://www.wired.co.uk/article/farming-robots-small-robot-company-tractors.

Verdict_AI. (2019, May). Inside Ocado: The Automated Warehouses Powering Technology's Dark Horse - Verdict AI | Issue 8 | May 2019. https://verdict-ai.nridigital.com/verdict_ai_may19/ocado_automated_warehouse

Vincent, J. (2018, May 8). Welcome to the automated warehouse of the future. The Verge. https://www.theverge.com/2018/5/8/17331250/automated-warehouses-jobs-ocado-andover-amazon

Vincent, J. (2020, January 29). AI-powered robot pickers will be the next big work revolution in warehouses. The Verge. https://www.theverge.com/2020/1/29/21083313/robot-picking-warehouses-logistics-ai-covariant-stealth

Volvo CE (2019). Advancing automation: Workers worry more about site safety than losing their jobs. Available at https://www.volvoce.com/global/en/news-and-events/news-and-stories/2019/advancing-automation-workers-worry-more-about-site-safety-than-losing-their-jobs/.

Watson, M. (July 16th 2019). Robotics and Autonomous Systems – The Economic Opportunity. Published 16th July 2019. Available at https://ore.catapult.org.uk/blog/robotics-automation-offshore-wind-opportunity/.

WEF (2019). The Global Risks Report 2019. Available at https://www.weforum.org/reports/the-global-risks-report-2019.

Woody, T. (2013) The Key to Cheap Renewable Energy? Robots, The Atlantic. Published 5th November 2013. Available at https://www.theatlantic.com/technology/archive/2013/11/the-key-to-cheap-renewable-energy-robots/281139/

World Bank (1994). World Development Report 1994 – Infrastructure for Development. Available at https://openknowledge.worldbank.org/bitstream/handle/10986/5977/WDR%201994%20-%20%20English.pdf?sequence=2.

World Bank (2020a). Gas Flaring Reduction. Available at https://www.worldbank.org/en/topic/gas-flaring-reduction.

World Bank (2020b). Zero Routine Flaring by 2030. Available at https://www.worldbank.org/en/programs/zero-routine-flaring-by-2030.

World Economic Forum (WEF) White Paper (2016) Digital Transformation of Industries: Societal Implication http://reports.weforum.org/digital-transformation/wp-content/blogs.dir/94/mp/files/pages/files/dti-societal-implications-white-paper.pdf

World Nuclear Association (2020a). Decommissioning Nuclear Facilities. Updated May 2020. Available at https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx.

World Nuclear Association (2020b) Nuclear Power in the United Kingdom. Updated July 2020. Available at https://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom.aspx.

Yale School of the Environment (undated). Cattle Ranching in the Amazon in the Global Forest Atlas. Available at https://globalforestatlas.yale.edu/amazon/land-use/cattle-ranching.

Your Dictionary. (2020). Semiautonomous Vehicle. Retrieved from Your Dictionary: https://www.yourdictionary.com/semiautonomous-vehicle

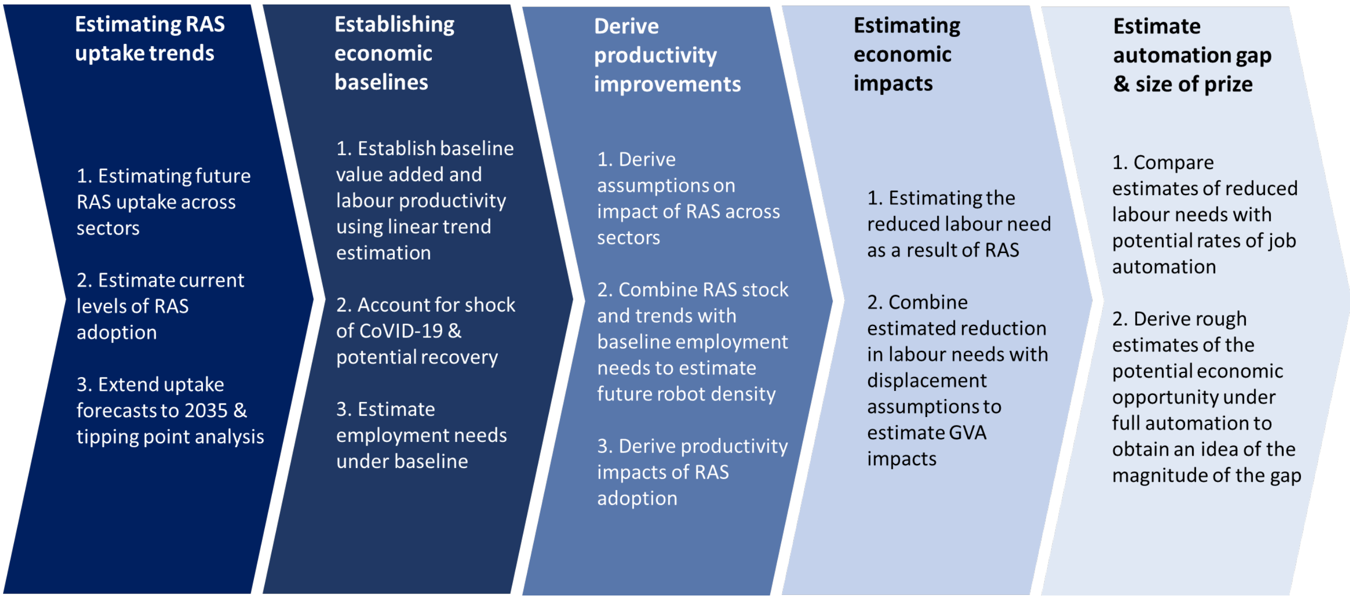
Zeng, Z., Chen, P. J., & Lew, A. A. (2020). From high-touch to high-tech: COVID-19 drives robotics adoption. Tourism Geographies, 1-11.

ZERO-PLUS (2016). Achieving near Zero and Positive Energy Settlements in Europe using Advanced Energy Technology. Available at http://www.zeroplus.org/.

Annex: Overview of methodology

A detailed methodological note accompanying this report describes the modelling approach employed in this study, including the key assumptions, evidence and data sources used; a brief overview is provided here.

Overview of methodology



Source: London Economics' analysis

The analysis used forecasts on future robot shipments, up to 2030, from ABI Research (2020a) as the basis for future trends. No sectoral forecasts were available at the UK level. Therefore, estimates of UK RAS forecasts at the sector level were derived by combining ABI Research forecasts for the UK as a whole with ABI Research sectoral forecasts at the global level.

ABI Research estimates are derived via a quantitative assessment from both top-down (derived from industrial GDP both global and from companies—and industrial automation equipment by vertical market) and bottom-up (based on robotics platform revenue from the major industrial, collaborative, and commercial robotics companies worldwide) approaches. The quantitative analysis was informed by, and further refined by, a qualitative analysis of the technological, business, and political drivers and constraints impacting the sector. Further details are provided in the methodological annex accompanying this report.

Note, in order to estimate i) how far along the adoption path each sector is and when the tipping point in shipments (i.e. the point at which annal shipments reach their peak) is likely to occur, given forecast adoption levels (provided in the methodological note); and, ii) to extend ABI Research forecasts to the period up to 2035, a model of innovation diffusion was utilised to approximate the S-shaped adoption process typical of innovation diffusion.

Shipment estimates were combined with estimates of the existing robot stock in each sector (derived from International Federation of Robotics (2019) and ABI Research (2020a)) in order to derive estimates of future robot density in each sector. These estimates formed the basis for the quantitative analysis. Further details on the methodology ABI Research used to derive these estimates can be found in the methodological note accompanying this study.

In order to derive productivity impacts the analysis used productivity estimates from the Centre for Economics and Business Research (2017), which found that, in OECD countries between 1993 to 2016, a one-unit increase in robotics density (defined as the number of robots per million hours worked) is associated with a 0.04% increase in labour productivity.

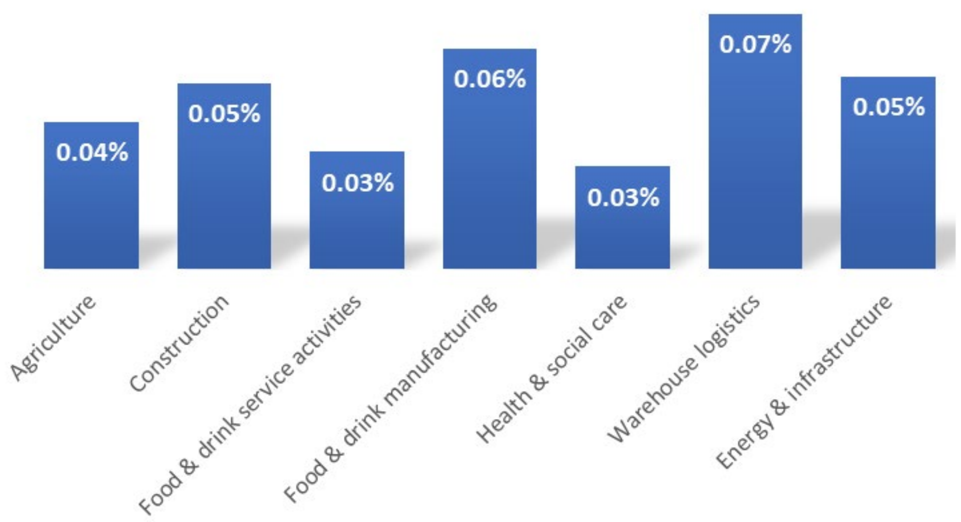
Note that CBER estimates are based on impacts of 'traditional' robots which were mostly industrial robots placed in a manufacturing context. As such, the estimates had to be adjusted to account for differences in impacts in other (non-manufacturing) sectors as well as to account for higher level of automation of non-manual and routine tasks from RAS compared to industrial robots. Therefore, CBER estimates were used as an anchor to derive sector specific productivity assumptions. This was done by first adjusting the CBER estimate by the relative proportion of manual and routine tasks in each sector compared to the food & drink manufacturing sector (in order to adjust the CBER estimate downwards (upwards) in sectors where fewer (more) tasks are manual and routine tasks. Second, the study used the difference (or more precisely the ratio) between the proportion of manual and routine tasks in each selected sector, derived from PIAAC data, and data on the automation potential in each sector, from PwC (2018b), to adjust the productivity anchor in order to account for productivity improvements from non-routine task automation. The resulting productivity assumptions are shown in the figure overleaf.

It should be noted that significant uncertainty surrounds the potential productivity effects that RAS may bring. Productivity impacts depend on a wide range of factors and may vary significantly across sectors or indeed across firms within sectors. As such, the analysis sought to derive assumptions that were plausible; but it is worth reiterating that productivity impacts in practice may differ. PwC estimates were used as these capture the potential rates of job automation that could be achieved from automation (by mid to late 2030's); i.e. they provide estimates of the relative automatability of jobs (i.e. the proportion of jobs – or tasks – at high risk of automation) based on the technical feasibility of automation. While uncertainty on the level of automatability naturally exists PwC estimates were judged plausible. PwC's estimates are based on analysis of a dataset compiled by the OECD that looks in detail at the tasks involved in the jobs of over 200,000 workers across 29 countries (27 from the OECD plus Singapore and Russia) and builds on previous research by both Oxford University (Frey and Osborne, 2013) and the OECD (Arntz and Zierhahn, 2016).

While the analysis sought to derive plausible estimates, it is worth reiterating that productivity impacts in practice may differ. It is further worth noting that PwC estimates capture the automation potential within a sector as a whole. Their estimates also include automation through non-physical technologies such as Artificial Intelligence. Automation from RAS is therefore likely to be less than the automation potential. It could therefore be argued that the chosen scaling factor should be smaller than that implied by the ratio of manual and routine tasks to automation potential. At the same time, however, it is unlikely that 'traditional' robots would have been able to automate all manual and routine tasks in each sector. This would imply that the scaling factor should be larger than the factor used. Which of these effects is stronger in practice is difficult to establish.

To translate productivity improvements into economic impacts (value added) economic baselines for future value added and labour productivity, over the study period, were constructed based on a linear trend estimation. To account for the shock of COVID-19, more recent monthly GVA data for a number of high-level sectors, from the ONS, were used to take account for the economic shock presented by COVID-19. In order to avoid making controversial assumptions about the potential recovery from COVID-19, the Bank of England (2020) plausible economic scenario was used to model the recovery under the baseline. The employment needs implied by the baseline, i.e. the number of employees needed to achieve the GVA baseline given the labour productivity baseline, were derived from the COVID-19 adjusted value added and labour productivity baselines.

Productivity assumptions made: % increase in labour productivity per unit increase in robot density



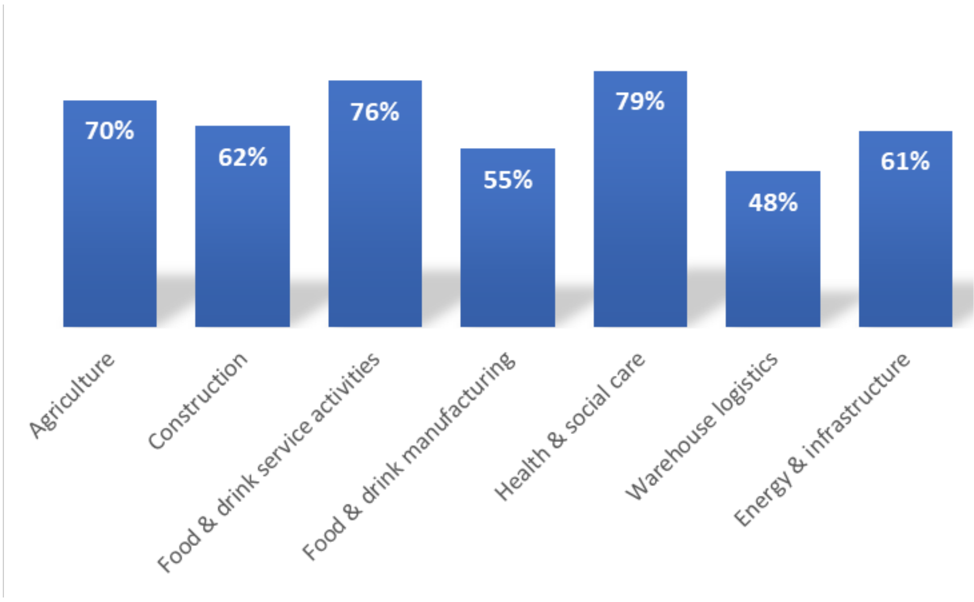
Note: The figure shows the assumed % increase in labour productivity per one unit increase in robot density, given estimates of future adoption trends.

Source: London Economics' analysis

Baselines were then combined with estimated productivity improvements. To this end, the analysis first calculated a proxy for output under the baseline scenario by adding employment costs (calculated as discussed later in this section) to value added. The analysis then calculated the new (reduced) number of workers needed in order for output (proxied by the calculated output proxy) to remain constant, given productivity improvements under given RAS trends and the additional cost of RAS (that is the scenario took the additional cost of acquiring robots, and the corresponding reduction in value-added, into account). This provided estimates of the reduced labour needs given productivity improvements from RAS.

Finally, the economic impact in terms of value added will depend on the level of displacement that RAS will bring; that is, what proportion of labour will be re-deployed to similar or higher value-add tasks, and what proportion of labour will be replaced. Therefore, in order to derive corresponding economic impacts, assumptions of the level of displacement likely to occur had to be made. It is unlikely that all of the labour that is freed-up by the adoption of RAS will be redeployed to similarly productive tasks. This is for two reasons: Firstly, the amount of labour available in the UK is unlikely to grow by as much as required under the baseline. Secondly, labour is not perfectly mobile between jobs, even similarly productive ones (either geographically or in terms of skills). Equally, it is also unlikely that none of the labour freed-up due to RAS is re-deployed. However, there is significant uncertainty around the level of displacement likely to occur. This study uses estimates by PwC (2018b) on the potential rates of job automation across sectors in order to derive central estimates of economic impacts. The displacement assumptions made in the central case are shown in the figure overleaf:

Displacement assumptions made: % of workers re-deployed



Note: The figure shows the assumed proportion of workers that are re-deployed to other tasks of at least a similar value-add. Assumptions are based on the potential rates of job automation across sectors from PwC (2018b).

Source: London Economics' analysis

Finally, in order to provide context to the estimated impacts, the analysis provides a rough analysis of the 'automation gap'; that is, the approximate size of the difference between estimated impacts under current adoption forecasts and potential impacts. To do this, the study first compared estimates of the reduced labour needs with potential rates of job automation across sectors, from PwC (2018b). Second, to obtain an idea of the magnitude of the gap in terms of value, rough estimates of the potential economic opportunity in each sector were derived based on the potential rates of automation. These estimates were based on a simple calculation of 2035 baseline GVA, multiplied by the potential rate of automation from PwC (2018b).

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