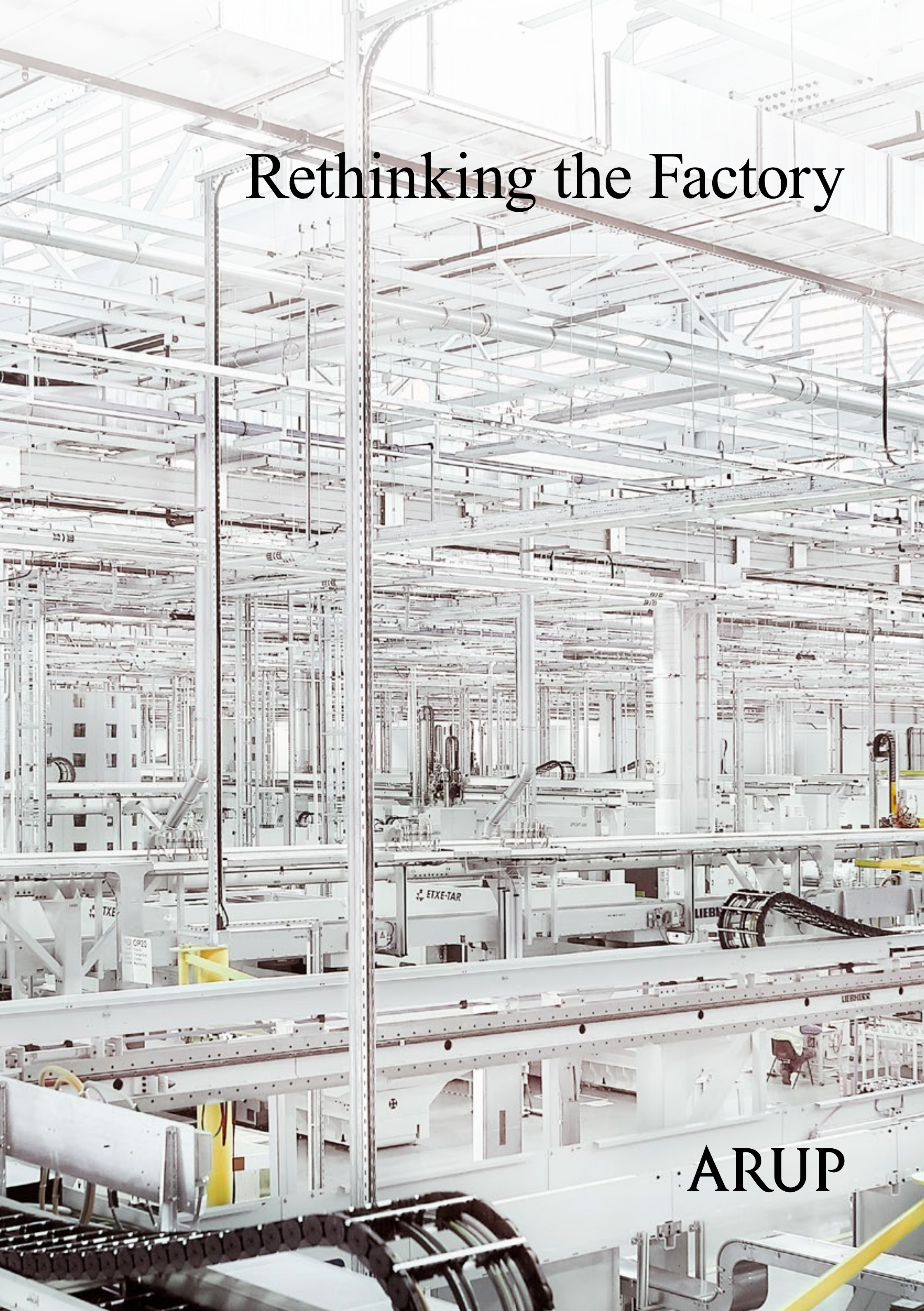
Rethinking the Factory



ARUP

Arup Foresight + Research + Innovation

Foresight + Research + Innovation is Arup's internal think-tank and consultancy which focuses on the future of the built environment and society at large. We help organisations understand trends, explore new ideas, and radically rethink the future of their businesses. We developed the concept of 'foresight by design', which uses innovative design tools and techniques in order to bring new ideas to life, and to engage all stakeholders in meaningful conversations about change.

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SEW
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Key Opportunities

The emerging trends, processes and technologies described in this report will transform the manufacturing landscape. The inevitable shift to leaner, smarter and more flexible forms of production will have a range of impacts on how the factory is designed, how supply chains operate, how people experience changing operational environments and how the future spaces of production will be organised.

The Human Factor(y)

Robotics and automation along with the application of cyber-physical assistance systems[1] will lead to safer and more productive working environments. This integration of technology will also increase the demand for highly skilled workers to operate and maintain machinery and control smart production processes.

The lines between blue- and white-collar workers will continue to blur, with a growing focus on factory environments that facilitate collaboration and innovation along the supply chain and across production lines. As workers' roles continue to adapt and merge, the configuration of factories will have to change to reflect these new working patterns.

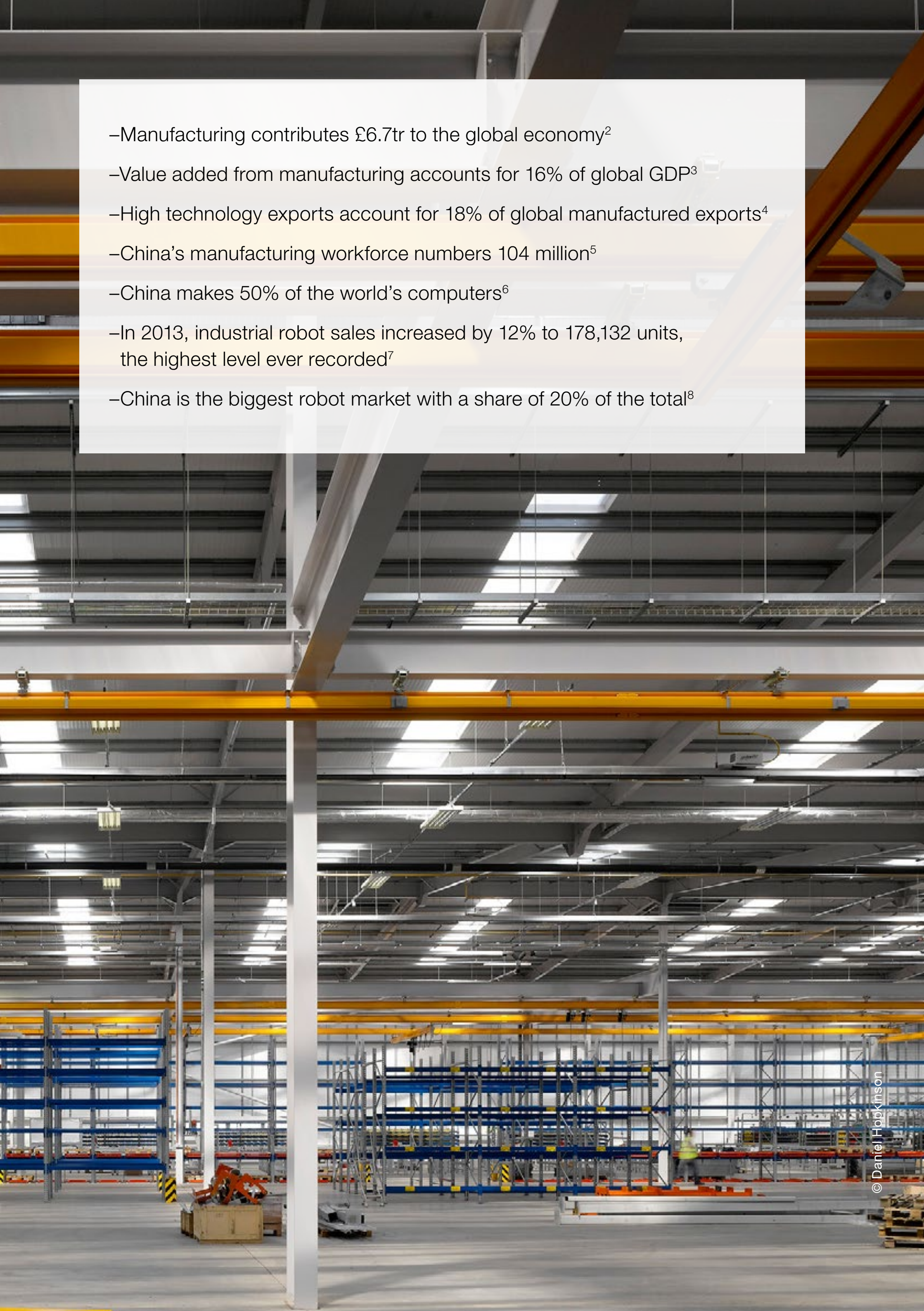
Integrated Design and Production

Smart processes, products and machines will enable the optimisation of production and will require a fine-tuned integration of building and machinery. Sensor-driven production lines and product components will enable factories to react in real-time to changes in the market and supply chain.

The increased use of insights arising from data collection and analytics will allow more rapid and responsive manufacturing, where products and production processes can adapt, perhaps even autonomously, to changing customer demands or market trends.

Left: The atrium at the SEW Eurodrive facility in Wakefield, England, links the factory to the headquarter offices.

- Manufacturing contributes £6.7tr to the global economy[2]
- Value added from manufacturing accounts for 16% of global GDP[3]
- High technology exports account for 18% of global manufactured exports[4]
- China's manufacturing workforce numbers 104 million[5]
- China makes 50% of the world's computers[6]
- In 2013, industrial robot sales increased by 12% to 178,132 units, the highest level ever recorded[7]
- China is the biggest robot market with a share of 20% of the total[8]



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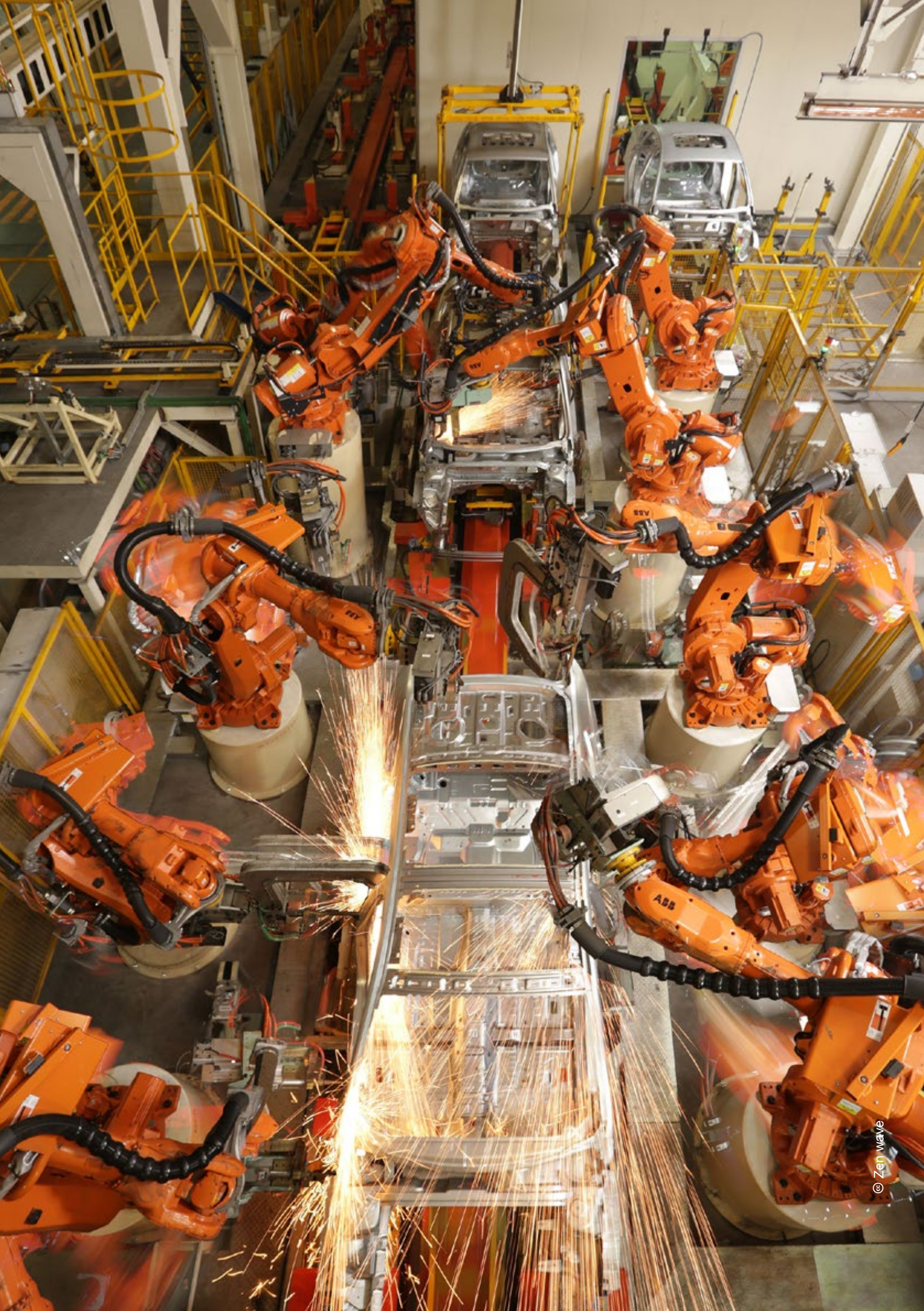
The University of Sheffield Advanced Manufacturing Research Centre with Boeing.

Resilient and Adaptive Spaces

Climate change and resource constraints will require that the construction and operation of factories be both sustainable and resilient. This includes reduced energy, water and material consumption, a shift towards the circular economy, and design and location choices that limit climate related weather risks and reduce transportation needs.

Faster innovation cycles, together with constantly changing market conditions and demand patterns will require flexible and adaptable spaces. Modular and adaptable factory buildings allow companies to quickly set up or expand production capacity, or shift production from one type of product or location to another.

Left: Behind its slick architectural lines, the SEW Eurodrive building incorporates low energy technnologies, including photovoltaic and solar thermal arrays on the roof.



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Introduction

"It's the dawn of the second machine age. To understand why it's unfolding now, we need to understand the nature of technological progress in the era of digital hardware, software, and networks. In particular we need to understand its three key characteristics: that it is exponential, digital and combinatorial."
— Erik Brynjolfsson and Andrew McAfee, The Second Machine Age (2014)

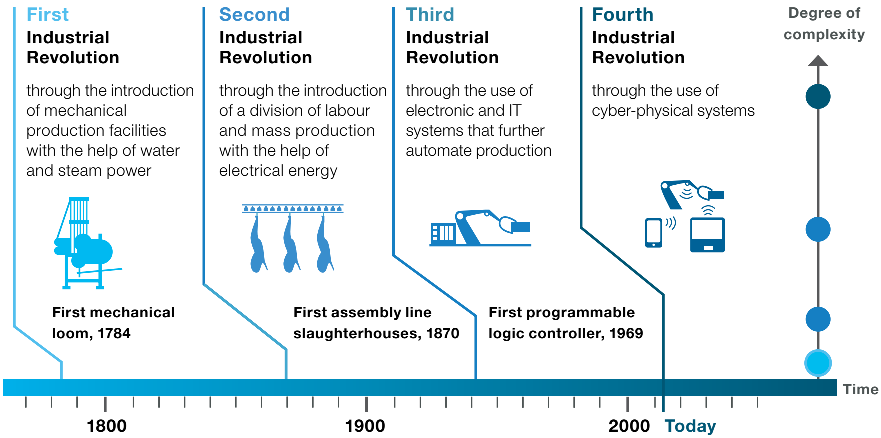
Manufacturing has entered a new age of production. This shift in the design and manufacture of goods is not the result of a single trend, but is driven by a broad range of complex and interconnected factors. These influences range from advances in digital technologies and automation to climate change and market demands. The collective consequence is a shift towards design and innovation processes that are increasingly fast, open, collaborative and responsive.

The economic picture is also changing. Over the past two decades, driven by cheap and plentiful labour, Asia has dominated the global supply of manufactured goods. However, since the onset of the global financial crisis in 2008, demand from advanced economies has slowed, while wages and other costs have risen. This means that in order to continue its manufacturing dominance, Asia will need to expand its own domestic and regional markets while upgrading the competitiveness of its manufacturing sector.[9] Robotics, 3D printing, mass customisation and other trends could also put pressure on Asia's factory model.[10]

As the world of manufacturing changes, the way factories are planned, constructed and operated will also change. They will need to become more flexible and adaptable, achieve better integration between buildings and processes, and be more resilient to economic and environmental shifts.

Left: Changan-Ford's assembly line is equipped with robotic technologies that allow for rapid switching between car models.


S02-A3
© Chrysler Group



Cyber-physical assistance systems are driving the fourth industrial revolution
Source: Siemens, Pictures of the Future, Spring 2013

These future factories will have to operate at higher material and energy efficiencies, while providing safe and healthy working conditions for an increasingly skilled and diverse workforce.

This report explores the future of the factory from three different angles: people, production and space. **'The Human Factor(y)'** looks at the growing impact of technology on the workforce, including automation and the diffusion of cyber-physical assistance systems. **'Seamless Design and Production'** focuses on the growing use of big data, insights and smart machines to optimise production processes and enable greater customisation of complex products. **'Resilient and Adaptive Spaces'** focuses on the physical factory, looking at designs that are resilient to environmental risks as well as sustainable in their construction, operation and end of life disassembly.

We intend the research and insights in this report to act as a catalyst for conversation, helping stakeholders rethink the design and operation of factories. Ultimately, we hope to help facilitate the shift towards a fourth industrial revolution.

Left: More than 1,100 robots have been installed at Chrysler's new body shop in Sterling Heights, Michigan to build the 2015 Chrysler 200.

© Province of British Columbia

The Human Factor(y)

"The full potential of the industrial Internet will be felt when the three primary digital elements – intelligent devices, intelligent systems and intelligent automation – fully merge with the physical machines, facilities, fleets and networks. When this occurs, the benefits of enhanced productivity, lower costs and reduced waste will propagate through the entire industrial economy."

—Peter Evans and Macro Annunziata, GE, Industrial Internet: Pushing the Boundaries of Minds and Machines (2012)

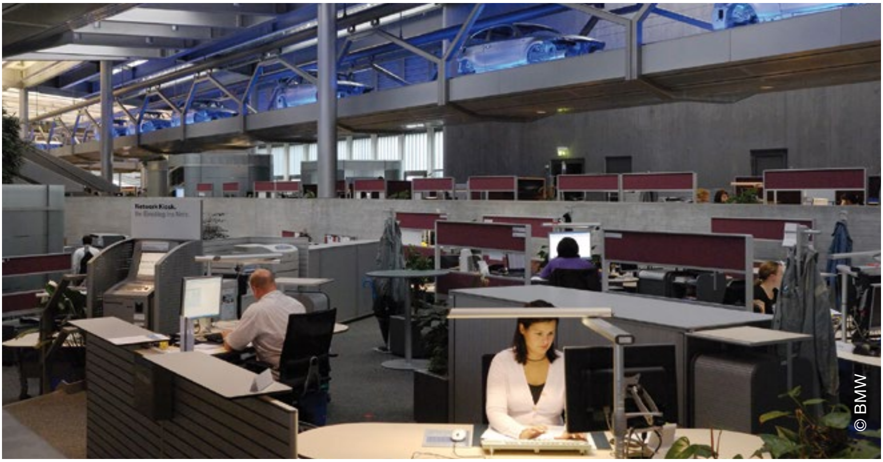
A new relationship between people and machines

Since the 1970's the proportion of German workers employed in the manufacturing sector has dropped by more than half, to about 20%.[11] At the same time, exports of manufactured goods have increased and Germany continues to rank fourth by global manufacturing output.[12] This trend is a reflection of a continued increase in automation within Germany's production lines, allowing the nation to remain competitive despite relatively high labour costs.

Given a steady rate of production, continued advances in both factory automation and robotics reduce the number of people needed to produce goods. While some argue that this trend could make certain workers' positions redundant, proponents assert that it will make workers more productive and relieve them of unpleasant or unsafe jobs. Automation increases reliability and product quality, and often makes it easier to adapt production lines and create flexible production processes. For many organisations in the manufacturing sector, automation is also part of a strategy to deal with the emerging risk of a shrinking and aging labour force, or the ongoing risk of cheaper labour costs in other countries.

Automation increases reliability and product quality, and makes it easier to create flexible production processes

Left: The Husteel Dangjin Steel Plant in South Korea.
The steel industry is a key component of South Korea's economy.



In BMW's Leipzig factory the production and office spaces are combined, transcending traditional blue-collar/white-collar spatial divisions.

In Asia, labour costs are continuing to rise, cutting into the region's competitive advantage. Nevertheless, China's factories are still much cheaper than those in wealthier nations - employees' minimum wages are less than a quarter of their counterparts in the United States.[13]

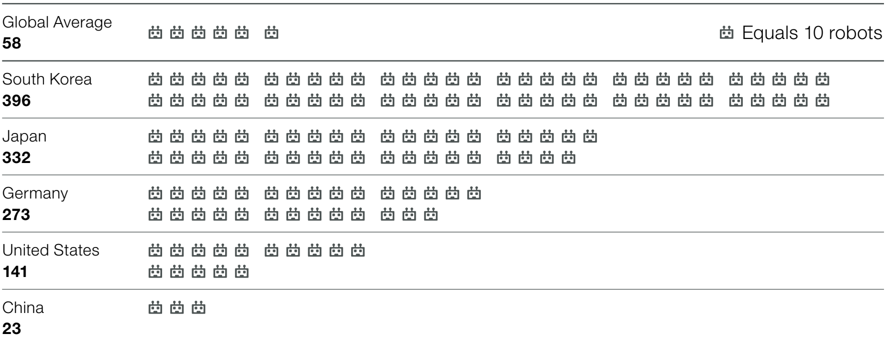
As the global manufacturing hub, rising prices in Asia are reflected in an upwards adjustment of prices worldwide. Average pay in Asia almost doubled between 2000 and 2011, compared to an increase of about 23% worldwide (and a 5% increase in developed countries). The biggest increase was in China, which saw average salaries triple.[14] Lower wage countries like Cambodia and Vietnam are beginning to attract manufacturers, meaning that China - which accounts for half of Asia's output - is embracing greater automation to ensure that local factories remain competitive.

An example of the automation trend, Flextronics, a Singapore-based company with factories in China, initially made small, simple-to-assemble consumer electronics. But as wages, land costs and competition in China began to rise, shrinking margins prompted a focus on more complex, higher priced products. This required investments in automation, more precise manufacturing and increased staff training.

Automation increases reliability and product quality, and makes it easier to create flexible production processes

The Robot Armies

Number of robots per 10,000 workers in the manufacturing sector



China is the largest industrial-robot market in the world, but its level of factory-automation lags behind other countries on a per capita basis.

Source: International Federation of Robotics, World Robotics report (2013)

Higher-priced machines for the aerospace, robotics, automotive, and medical industries now make up 72% of the company's Suzhou output. Flextronics has implemented automated processes wherever it has the potential to reduce labour costs and errors. Automated data about the assembly line is now collected in real-time and there is far more transparency of the supply chain.[15]

Average pay in Asia almost doubled between 2000 and 2011, compared to an increase of about 5% in developed countries

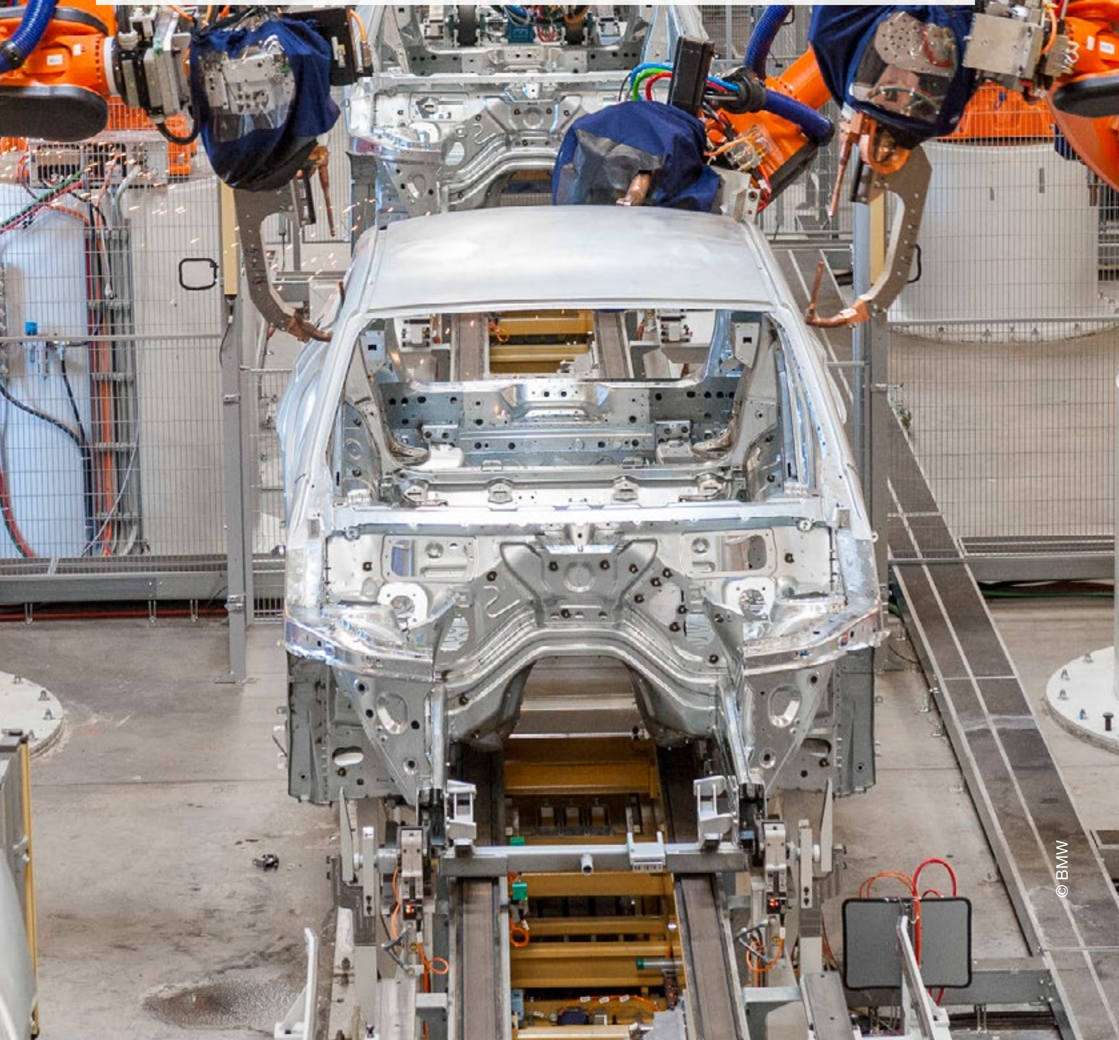
Asia has become the largest market for industrial robotics, with China showing the fastest growth over the past five years.[16] Global demand for industrial robots also continues to grow. The International Federation of Robotics (IFR) expects that between 2014 and 2016 the worldwide sale of robots will increase by an average of 6% per year. By 2016, the annual supply of industrial robots will reach more than 190,000 units.[17] MGI research suggests that 15 to 25% of the tasks of industrial workers in developed countries, and 5 to 15% of those in developing countries, could be automated by 2025.[18]

One significant development in workplace automation is that the factory robot of the future will be able to safely interact and cooperate with its human co-workers. The aim of industrial designers is to combine the ingenuity and versatility of people with the precision and repeatability of robots, enabling

Case Study:

BMW South Carolina Plant

Robots in BMW's Spartanburg, South Carolina plant are challenging the notion that it's too dangerous for robots and humans to work alongside each other. Made by Danish company Universal Robots, the robots help workers with the final door assembly by applying a door sealant to keep sound and water out of the car, a usually arduous task for workers. BMW is also testing more sophisticated final assembly robots that are mobile and capable of collaborating directly with humans. These robots, which should be introduced in the next few years, would be able to hand their human colleague a wrench when needed, and manoeuvre safely around human workers.[26]



© BMW

A Baxter robot retails for around US$25,000 — roughly equivalent to the annual salary of an unskilled worker in the US.

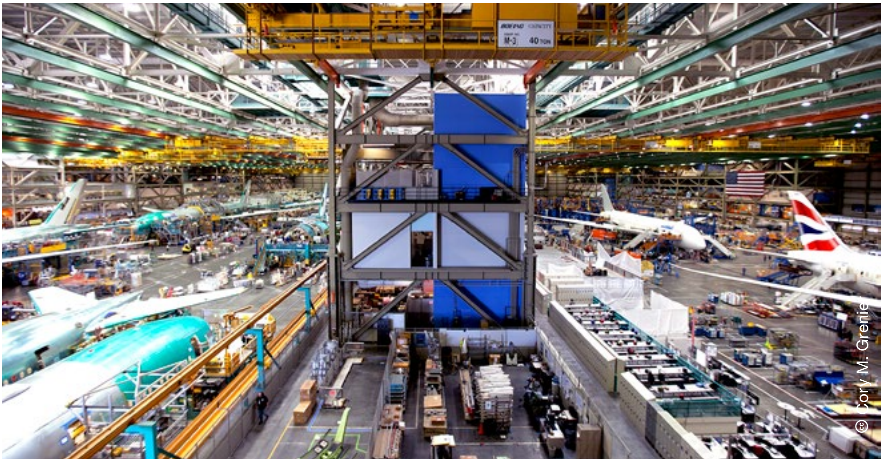
human-machine collaboration in dynamic and reconfigurable manufacturing environments.[19] A world optimised for both humans and robots.

The factory of the future will be optimised for humans and robots working together

For example, Baxter, a robot manufactured by Rethink Robotics, can safely share a workspace with workers due to its variety of smart sensors and cameras. Interacting with Baxter is more like working with a person than operating a traditional industrial robot. Baxter's sensors, including depth sensors as well as cameras in its wrists (allowing it to see with its hands), means it constantly builds and adjusts a mathematical model of the world, allowing it to recognise different objects.

The robot is also intuitive to use, allowing regular factory workers to function as programmers. A factory worker can show the robot a fragment of the task she is asking the robot to perform, and the robot infers the rest of the task. Workers are therefore not in competition with these machines, because they can serve as supervisors.[20] A Baxter retails for around US$25,000 – roughly equivalent to the annual salary of an unskilled worker in the US.

By 2050, 21% of the global population will be 60 years old or older, up from 11% in 2013.[21] This trend is even more notable in developed countries where 32% of people will be

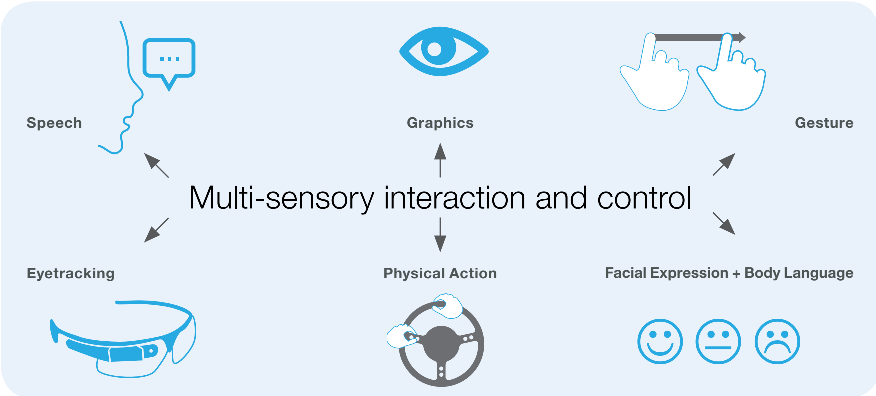


Boeing's Everett Factory is the largest building in the world by volume, covering over 98 acres. It incorporates a store, a theatre, an aviation museum and an education centre.

aged 60 or older by 2050.[22] Within these ageing societies, the supply of working age people will decline as a proportion of the total population, and working age people will have to support more dependents. In less developed regions there will be more young people, providing a larger workforce and growing consumer markets.

In the next few decades, new forms of human enhancement and augmented capabilities may support mental performance and physical mobility, helping to counter the effects of an ageing population.[23] This is already evident today in the growing application of cyber-physical systems (CPS). CPS are "physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core".[24] CPS will transform how people interact with and control the physical world around them. These systems will enable the physical world to merge with the virtual world, allowing factory workers to design products, control processes and manage operations in radically new ways, enabling greater flexibility, productivity and quality.[25]

Combining all Senses:
Getting Rid of Keyboard and Mouse in Factories



Multi-sensory interaction: the impact of cyber-physical systems.
Source: German Research Centre for Artificial Intelligence (2013)

As production lines and machines become more advanced and specialised, companies must also invest more in training and specialised equipment to enable the workforce to manage and operate complex production lines. There will be a heightened need for skilled workers and managers who are adept in the STEM fields (science, technology, engineering and mathematics) as manufacturing shifts to more complex and technological processes. Collectively, this will lead to a shift to safer, more highly skilled jobs in manufacturing.

Integrated and collaborative value chains

Today's knowledge economies are driven by the principles of open innovation and collaboration. Value is created by breaking down silos within and across organisations and enabling dialogue and interaction across different disciplines. These changing boundaries include the increasingly blurred line between blue and white collar workers. As manufacturing becomes more highly skilled and the roles for these workers begin to merge, the configuration of factories will change to reflect this. Many factories are now designed to enable research, development and design teams to work on the same factory floor, enabling enhancements to products

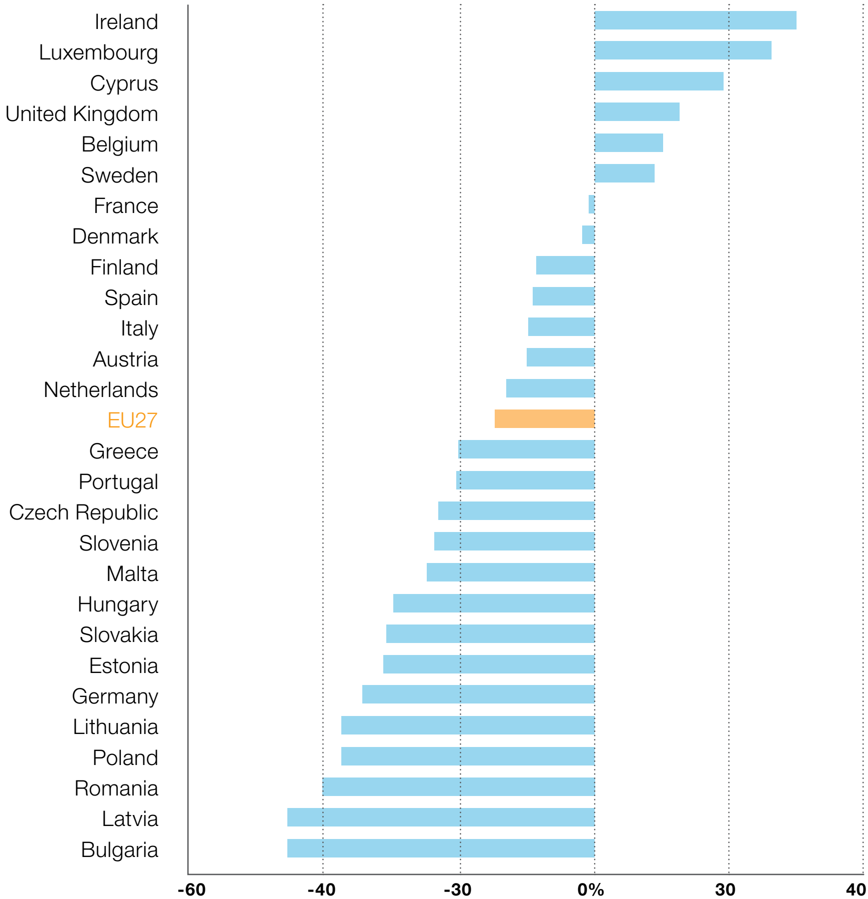
In June 2014, Tesla broke ground on its huge lithium ion battery Gigafactory in Nevada, and expects to begin cell production in 2017.

and processes at the point of production rather than in segregated spaces. With the integration of consumers and external partners and more vertical collaboration within organisations, digital and physical factory spaces must be designed to facilitate greater openness and integration. In such an environment, people, technology and process drive value, while space is a key enabler.

Beyond the walls of the factory there is an increased focus on distributed and e-manufacturing, where physical and virtual networks of suppliers and manufacturers come together to produce a product. These shifts in production and development ecosystems are not new; they are, however, being radically accelerated by a much more sophisticated exchange of people, information and data between the different entities. Manufacturing value chains no longer have clear boundaries or linear pathways. According to the Fraunhofer Institute for Industrial Engineering (IAO), many production processes will run on a decentralised, Internet-based model, networking all steps of the value chain. A digital factory will be used to plan, simulate, and optimise the entire product development and production process.

Digital factories will be used to plan, simulate, and optimise the entire product development and production process

EU labour force developments to 2060



A decade-long decrease in fertility rates is causing a shift in the availability of Europe's labour force. This shift is also influenced by patterns of migration, with high immigration projected for the UK, Spain and Italy, while the Baltic region will experience emigration outflows as well as very low rates of fertility. Most European countries will experience a decrease in the working age population to 2060.

Source: Eurostat, 2015

Case Study: BMW Plant Central Building

BMW's Central Building is the nerve centre for the entire Leipzig complex, acting as the administrative hub in a plant where all production processes — assembly, body shop and paint shop — converge. This design is part of a deliberate strategy to ensure that administrative, engineering and production staff mix more effectively in sharing common spaces and navigable routes throughout a central 'marketplace'.

The production line runs through the Central Building, visible from a variety of angles and levels. Everyone in the building has their own desk, and the lockers and social spaces of the factory workers are also located in this administrative centre. This brings the BMW community closer together in order to share experience and knowledge.[30]

© BMW Group

Workers will require IT and software skills in order to understand and manage more integrated processes and product development pathways. This requirement for specialised skills means that companies will no longer choose locations based on the cheapest wages, but rather will be based in areas where they can find highly skilled workers.[27] Crucially, the global supply of these kinds of workers is not keeping up with demand. According to McKinsey Global Institute, there will be a potential shortage of more than 40 million highly skilled workers by 2020.[28]

Sharing knowledge across the value chain and network is crucial for competitive advantage. Knowledge-sharing of this sort requires strong relationships between manufacturers and suppliers. This is an area in which the Chinese have excelled, and accounts for much of China's leading manufacturing capability, strengths that have allowed China to innovate and develop new products more quickly than other global competitors. In 2012, China was the world's leading exporter of high-tech products, with a combined value of more than $600 billion.[29] The same pattern is being replicated in other parts of the world, where clusters of research and manufacturing facilities enable collective innovation and knowledge exchange

Showroom experiences are part of the larger trend of customers demanding "connected product experiences", rather than just a product

An open and engaging customer experience

Many developed and emerging economies are witnessing a transformation in how people consume products and services. In addition to a shift to more service-based consumption, a democratisation of product design and manufacturing is occurring. The maker movement, 3D printing, open product development platforms, crowd funding and peer-to-peer marketplaces are empowering more people to design, produce and share their own goods than ever before. In response, consumer product companies are integrating these types of experiences into their existing service offerings, enabling the mass customisation of products, or participation in open innovation processes. Faster innovation cycles, coupled with constantly changing market conditions and demand patterns, mean that manufacturers will need a more agile and flexible approach to production, both in terms of the machines deployed, but also in terms of the shape and function of buildings and the skillsets of people working within them.

Case Study:

Volkswagen Autostadt

At Volkswagen’s Autostadt people can enjoy anything from a factory tour to driving the latest SUV along a specially designed off-road course. Picking up your new car at the Autostadt instead of from a dealer is one way of building a strong relationship with the brand and exposing customers to its unique history. The factory area includes a museum, movie theatre, bakery, restaurants, exhibitions, guided tours and a five star hotel.

© VW Group / Lars Landmann

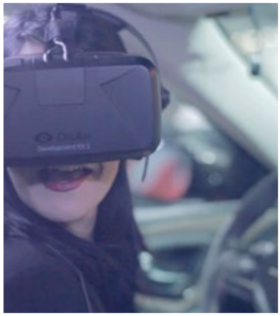
Another aspect of this transformation is a growing opportunity to utilise the factory as a showroom. Many companies have built sophisticated customer experiences around their factories. These showroom experiences are part of the larger trend of customers demanding "connected product experiences", rather than just a product.[31]

In Volkswagen's 'Glass Factory', for example, customers and potential buyers of the Phaeton luxury saloon can watch their car's final assembly process at close hand. The concept of the transparent factory and factory experience will gain increased importance as more people get involved in making things themselves or as they expect closer insight into how products are manufactured, especially at a customised level. The opportunity for factory owners and operators lies in adapting their existing spaces to enable these types of experiences to take place.

Chrysler is taking this idea one step further with a virtual reality experience of its factory floor. Users put on a headset to experience a four-minute, 4D immersive experience of how the 2015 Chrysler 200 is made. Users can interact with the car in real-time via the headset while exploring the three aspects of the car's building process. In the body shop, 18 state-of-the-art framing robots weld the frame of the car together. The next stage is the paint shop, where the car is prepped for its paint job with the help of ostrich feathers before being given its coating. Finally, in the metrology centre, the vehicle's fit and finish is checked and measured.

Brand experiences are not limited to 'fun' consumer products like cars. Saunier Duval, a manufacturer of heating, ventilation and air-conditioning technology, has created a factory tour at its plant in Nantes, France which takes in a 360 degree, 3D cinema show, an interactive display of the company's products and a meal.

These sorts of consumer experiences help differentiate a company's products. To remain competitive and adapt to changing consumer behaviour, companies are finding new concepts and marketing strategies to build brand loyalty. 'Experience marketing' of this kind can also be very useful in creating an image and corporate identity, capitalising on the idea that people "won't remember what you said, but they will always remember how you made them feel."



Top: Volkswagen's Transparent Factory in Dresden, Germany.
Bottom: Chrysler 4D virtual reality experience.

Top: © Volkswagen
Bottom: © Wieden+Kennedy Portland, Stopp, and MPC Creative

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Seamless Design and Production

“This is nothing less than a paradigm shift in industry: the real manufacturing world is converging with the digital manufacturing world to enable organisations to digitally plan and project the entire lifecycle of products and production facilities.”

—Helmuth Ludwig, CEO, Siemens Industry Sector, North America in IndustryWeek (2013)

Rapid and reactive manufacturing

At the end of 2014, the number of mobile-connected devices in existence exceeded the number of people on earth, and by 2018 there will be nearly 1.4 mobile devices per capita.[32] The expanding ‘Internet of Things’ — the connection of a huge range of devices, sensors, and machines to the Web — and the increased collection and analysis of data will have a fundamental impact on the design and operation of factories and manufacturing processes. Embedded sensors and dynamic data collection can now span the entire value chain of a product or component enabling new degrees of transparency and flexibility on production lines.

Intelligence based on big data and advanced analytics creates new opportunities for competitive advantage.

Intelligence based on big data and advanced analytics creates new opportunities for competitive advantage. Analysis of selected data enables companies to reveal customer insights in more detail, identify new product opportunities sooner, and get new product and design variations to market faster. Real-time information allows greater transparency in the supply chain and, and ‘always-on’ monitoring of machinery can prevent potential outages before they happen.[33] Manufacturing and product design can become responsive to external events or changes happening at any point in the supply chain. This can support compressed research, development and production timelines,

Left: The Guangdong Mingzhu Zhenzhuhong Wine Factory in China will use cutting edge automated equipment to improve the traditional wine-making process.

Key Elements of the Industrial Internet

1 Intelligent Machines

Connect the world's machines, facilities, fleets and networks with advanced sensors, controls and software applications

2 Advanced Analytics

Combines the power of physics-based analytics, predictive alogrithms, automation and deep domain expertise

3 People at Work

Connecting people at work or on the move, any time to support more intelligent design, operations, maintenance and higher service quality and safety

Source: GE, Industrial Internet: Pushing the Boundaries of Minds and Machines (2012)

as well as faster responses and adaptation to potential disruptions or changing customer demand. It is estimated that manufacturers can cut product development and assembly costs by as much as 50% and save up to 7% of working capital by integrating big data into their operations.[34]

By 2025, the majority of global consumption will take place in developing countries

One of the biggest opportunities for manufacturers presented by big data is the ability to unearth actionable insights from customer engagement, consumer behaviour and feedback. By 2025, the majority of global consumption will take place in developing countries, while customer demand in established markets is expected to fragment as consumers seek greater product variety. Manufacturers will need to be able to combine data from commercial transactions with data from various web outlets, including social media and mobile devices, in order to better understand, anticipate and meet customer preferences and demands.[35]

Although mass customisation has been the 'next big thing' for decades, relevant technologies are finally sufficiently developed and affordable enough to make it a reality. Interest in customisable products is growing, and according to Forrester Research, Inc., three trends will allow mass customisation to flourish:

“The winners in the global manufacturing arena will be those companies that can adeptly harness big data with manufacturing analytics to uncover customer insight, identify new markets, monitor sensors and collect after sales data.”
—TIBCO Spotfire (2013)

– Supply chain technologies now enable more efficient production, so there is a more efficient flow between customers’ orders and fulfilment on the production side.

– Customer-facing technologies are cheaper and easier to deploy than ever before. The price, and time requirement, for developing customer-facing configurators (which intuitively guides end-users as they build customised products) has dropped significantly in the past few years.

– Technologies allowing customers to design their own products will continue to grow and will become richer.[36]

Additive manufacturing will also make mass customisation easier and more affordable, and in turn, mass customisation will drive the growth of 3D printing. Expenditure on 3D printing is scaling up rapidly, reaching US$412 million in 2013 (an increase of 42% from 2012). In 2014, this investment grew by an estimated further 62%.[37] Additive manufacturing also allows for manufacturing to take place in non-traditional spaces, such as a small office in a city centre. This will allow production to take place closer to the point of use, thereby lowering transport costs and associated emissions.

Case Study: Local Motors 3D Printed Car

The vision behind Local Motors' driveable 3D printed car is that consumers will one day be able to design their own cars online, then have the vehicle printed and delivered to their door. The company plans to set up two new 'micro-factories' and to start selling its cars within 12 to 18 months. The long-term goal is that micro-factories will be located within 100 miles of major urban centres. This will help create local jobs, and will also reduce auto freight and distribution costs by an estimated 97% compared to typical automakers.

Smart and connected machines and products

According to the German Research Centre for Artificial Intelligence, 80% of the innovations seen in the manufacturing sector are ICT-based.[38] Terms like 'Industry 4.0' or the 'Industrial Internet' refer to the convergence of machines and intelligent data. These new ecosystems of connected machines have the potential to increase efficiency, minimise waste, and help the employees operating them make better decisions. GE estimates that the Industrial Internet could eliminate $150 billion of waste and inefficiency across major industries.[39]

Smart products incorporate memory and embedded intelligence, and will be able to coordinate and control manufacturing processes

Along with smart machines and the augmented operator (operators that use virtual tools to control production processes), smart products are one of the central aspects of the fourth industrial revolution.[40] Smart products are grounded in the idea that machines can communicate, learn from one another, and even organise their workflow and throughput without human intervention. These fully integrated systems of hardware and software, enabled by embedded sensors, are reshaping how machines interact with humans, other machines, and manufacturers.[41]

"Future production facilities will be much smarter than today's factories. This intelligence will be made possible by the use of miniaturised processors, storage units, sensors, and transmitters that will be embedded in nearly all conceivable types of machines, unfinished products, and materials, as well as smart tools and new software for structuring data flows. All of these innovations will enable products and machines to communicate with one another and exchange commands. In other words, the factories of the future will optimise and control their manufacturing processes largely by themselves."

—Siemens, Pictures of the Future (2013)

Smart products incorporate memory and embedded intelligence, and will themselves be able to coordinate and control manufacturing processes. The advantages of this approach include completing processing operations on schedule, making optimal use of resources, and reducing warehouse holding stock.

These fully integrated systems of hardware and software, enabled by embedded sensors, are reshaping how machines interact with humans, other machines, and manufacturers

Sustainable resource streams

According to the International Energy Agency, global energy demand is expected to increase 37% by 2040. By this point, the world's energy supply mix is likely to have divided into four nearly equal parts: oil, gas, coal and low-carbon sources.[44] (The current mix is: gas – 24%, coal – 30%, oil – 33%).[45] The availability of alternative fuels, as well as volatile oil prices, could change the way factories operate and could lower costs associated with the transportation of manufactured products.

A focal point of continued factory innovation is reduced energy and material consumption within the manufacturing process. Advances in technology continue to enable lower energy consumption. Recent

Case Study:

Siemens Electronic Works

The Siemens Electronic Works facility in Amberg, Germany, is a 108,000-square-foot high-tech facility where smart machines coordinate the production and global distribution of the company's Simatic control devices. This is "a custom, built-to-order process involving more than 1.6 billion components for over 50,000 annual product variations, for which Siemens sources about 10,000 materials from 250 suppliers to make the plant's 950 different products… The Amberg factory only records about 15 defects per million and enjoys a 99% reliability rate and 100% traceability on its expansive lines." Managing these levels of complexity requires a sophisticated network of technologies that are all integrated into a smarter, more efficient industrial value chain.[43]

© Siemens AG

Case Study: Rolls-Royce, Prince George County

The Rolls-Royce advanced manufacturing and research facility in Prince George County USA is an example of a highly automated modern factory, characterised by a minimum of human interference in the production process. Machines do the initial milling of disks, which later become parts of an aircraft engine, as well as the inspection of the parts' dimensions. Sensors embedded in Rolls Royce engines will track how the engine and its parts are performing, and data is kept on each part for 25 years. While the factory is part of a complex global supply chain, it operates within a local ecosystem of organisational expertise; the facility's proximity to the Commonwealth Centre for Advanced Manufacturing facilitates continuous dialogue with experts and the efficient transfer of innovative ideas.

examples include regenerative braking in conveyor belts, algorithms for improved robot movement and operation, and the use of advanced low-power lasers.

The utilisation of 3D-printing in manufacturing can reduce the amount of waste produced as well as the amount of energy used. Metals manufacturer, Metalysis, in collaboration with engineers from Sheffield University, is using 3D printing to produce titanium car parts. The process uses electrolysis for extracting titanium powder from rutile sand, making it much more affordable and energy-efficient than alternative processes.

Auto manufacturer Tesla is building a "Gigafactory" in Reno, Nevada, which the company claims will generate more power than it consumes. The facility will be the world's largest lithium-ion battery factory, and will use three sources of renewable energy: geothermal, wind and solar. Together these energy sources will produce 20% more energy than the factory will need in order to operate. Through economies of scale, the Gigafactory is expected to drive down the per-kilowatt cost of the company's own lithium-ion car batteries by more than 30% in its first year of production in 2017.[46]

> A focal point of continued factory innovation is reduced energy and material consumption within the manufacturing process

Case Study:

Nestlé Zero-Water Factory

Nestlé's dairy factory in the water stressed state of Jalisco, Mexico, was recently transformed into the company's first 'zero water' manufacturing site. The Cero Agua factory uses fresh cow's milk, which naturally consists of around 88% water, and heats it at low pressure to remove some of its water content. The resulting steam is then condensed, treated and used to clean the evaporating machines. Once the machines have been flushed out, the water is collected, purified and recycled a second time. The water can then be reused for watering gardens or cleaning, thereby eliminating the need to extract groundwater for operational use. The water savings are enough to meet the average daily water consumption of 6,400 people in Mexico.

© Nestec S.A., Vevey, Switzerland

“So often, in the first industrial revolution, factories were dirty. We have these images of factories as gritty buildings with smokestacks — facilities that no families would want in or near their neighbourhoods. This factory is a clean factory. The energy will be clean. The production will be clean.”

—Architect and sustainability leader William McDonough on the design plans for Methods LEED-Platinum factory in Chicago (2014)

McKinsey estimates that, in general, manufacturers across all sub-sectors could reduce the amount of energy they use in production by 20 to 30%. McKinsey’s analysis indicates that manufacturers could also design their products to reduce material use by as much as 30%, while increasing inherent potential for recycling and reuse. Some companies are also starting to explore business models that retain ownership of the materials used in the products they sell. This means that manufacturers could extract additional value from a product by encouraging the consumer to return the product at the end of its useful life.[47]

In a circular economy products are reused to extract their maximum value before being safely and productively returned to the technosphere or biosphere

Historically, industry has been dominated by a one-way, linear model of production and consumption in which goods are manufactured from raw materials, sold, used and then discarded as waste. In a circular economy, rather than entering the waste stream, products are reused to extract their maximum value before being safely and productively returned to the technosphere or biosphere as an input. Resource scarcity and tighter environmental standards will propel this trend forwards, as will new technologies and new patterns of consumer behaviour.[48] New asset management standards, such as ISO 55000, will also draw more from existing assets as proactive lifecycle asset management systems are further developed.

As a result of the volatility of both steel and fuel prices, the Danish shipping division Maersk Line has developed a Cradle to Cradle “Passport” for a fleet of twenty new Triple-E ships. Their longer-term goal is

Case Study: Bio-inspired plastic, self-healing micro metals, self-cleaning glass

Researchers at Harvard University's Wyss Institute for Biologically Inspired Engineering have developed a new material called Shrilk to replicate the strength, durability and versatility of a natural insect cuticle. Insect cuticles are light enough to permit flight, thin enough to accommodate flexibility and strong enough to protect its host without adding weight or bulk. Among other uses, Shrilk could be used to make rubbish bags, packaging and nappies that degrade quickly.[52]

Researchers at the University of Illinois have developed a self-healing system that supports conductivity. The material is filled with tiny microcapsules that burst on impact, releasing the contained liquid metal which seals any gaps in the damaged product. This approach deals with both structural repair and conductivity restoration. It works on a localised level, so only those microcapsules near the damaged area are activated.

A team from Harvard University has developed a transparent, biomimetic coating that toughens ordinary glass giving it self-cleaning properties. The coating offers numerous applications from durable, scratch-resistant lenses for eyeglasses, to self-cleaning windows, improved solar panels or new medical diagnostic devices. The technology was inspired by the carnivorous pitcher plant, which has slippery leaves that trap unsuspecting insects.

© Joanna Aizenberg / James Weaver

to create new ships from those that reach the end of their useful life. The Passport, a first for the shipping industry, records a detailed inventory that can be used to track, locate and recycle the ship's component parts to a higher degree than is currently possible. As a result, the materials – including the 60,000 tonnes of steel per ship – can be sorted and processed more effectively.[49]

Due to concerns about water scarcity, water quality, climatic risks and potential damage to brand value, water efficiency has become an increasingly important factor for manufacturers. Major corporations like Coca-Cola have well-developed strategies at a global level to manage their water footprints, and to address water concerns in the wider community.

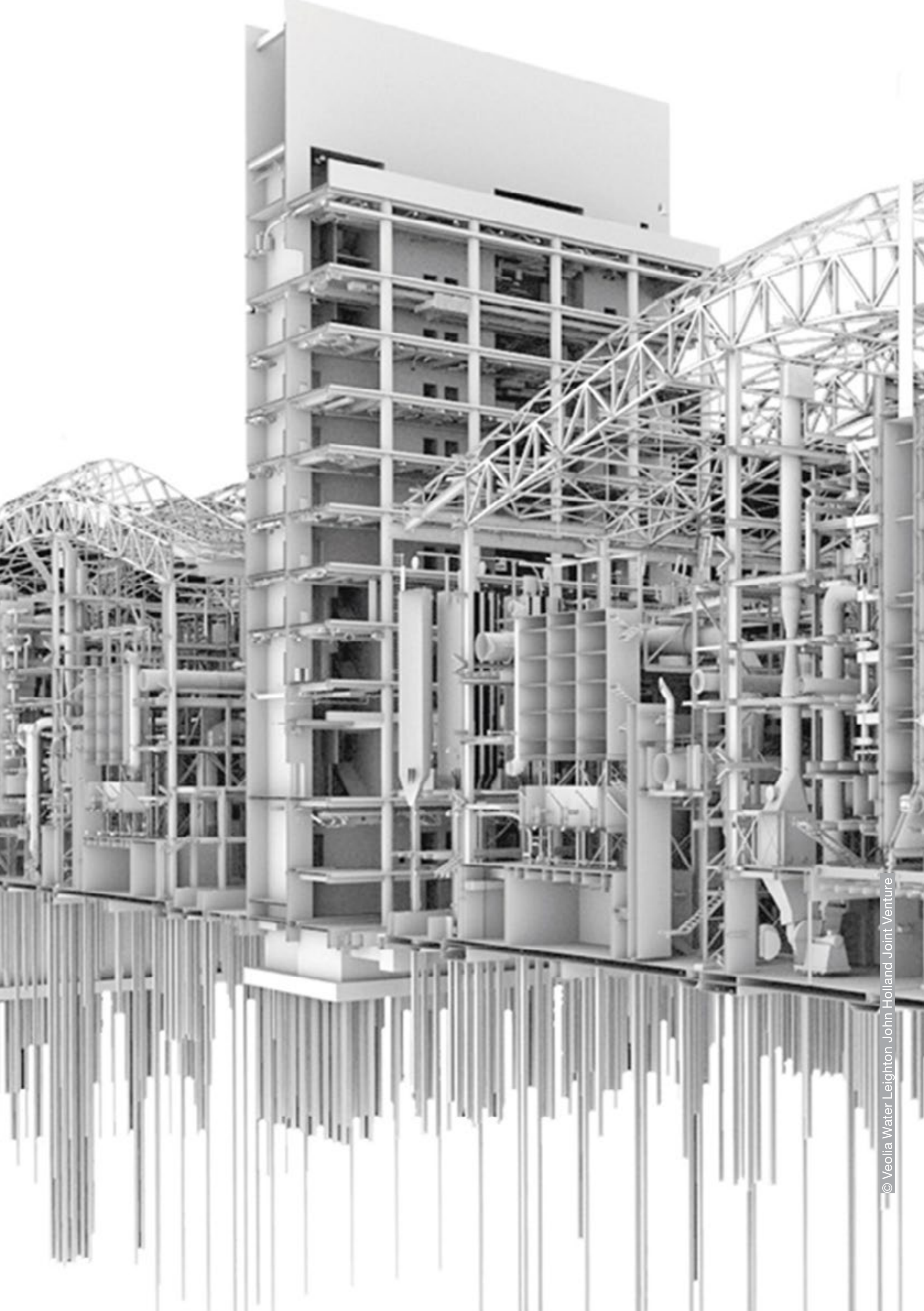
New materials and production

Emissions reductions, resource constraints, rising prices and environmental challenges are major drivers for material innovation and life-cycle considerations. As new and innovative technologies continue to be harnessed in the effort to address these and other global challenges, focus is shifting towards materials that are lighter, stronger, smarter and greener. New materials have the potential to change the future of manufacturing, by improving the production process, increasing product performance, and differentiating products from competitors.

Materials like graphene, which provides revolutionary strength, flexibility and conductivity, could have numerous applications and could support innovative structures. Developments in material science are also dramatically improving the performance of batteries, unlocking much greater potential for electricity storage.[51] A variety of self-healing and self-cleaning materials are being developed, capable of repairing damage without external human intervention. These technologies could potentially extend the lifetimes of manufactured goods and reduce demand for raw materials, as well as improve the inherent safety of materials used in construction.

Top: Additive Manufacturing Steel Node, Arup
Bottom: The design of the Shell Star Pavilion was enabled by advanced digital modelling techniques.

Top: © Davidfotografie
Bottom: © Shellstar Pavilion, Matsys + Riyad Joucka, Hong Kong, 2012, Photo by Dennis Lo


© Veolia Water Leighton John Holland Joint Venture

Resilient and Adaptive Spaces

Designing the digital factory

Factories will need to be significantly more responsive to rapidly changing market dynamics and operational environments in the future. They will need to adapt physically to supply chain disruptions and variations, new product lines, machinery and equipment.

As such, the factory will need to accommodate a range of floor layouts, production systems, equipment configurations and extensions.[53] Most automotive factories today are typically set up to maximise economy of scale for a limited range of vehicle models. In a smart factory, however, the equipment is flexible and readily adapted to manufacture multiple models within the same factory.[54]

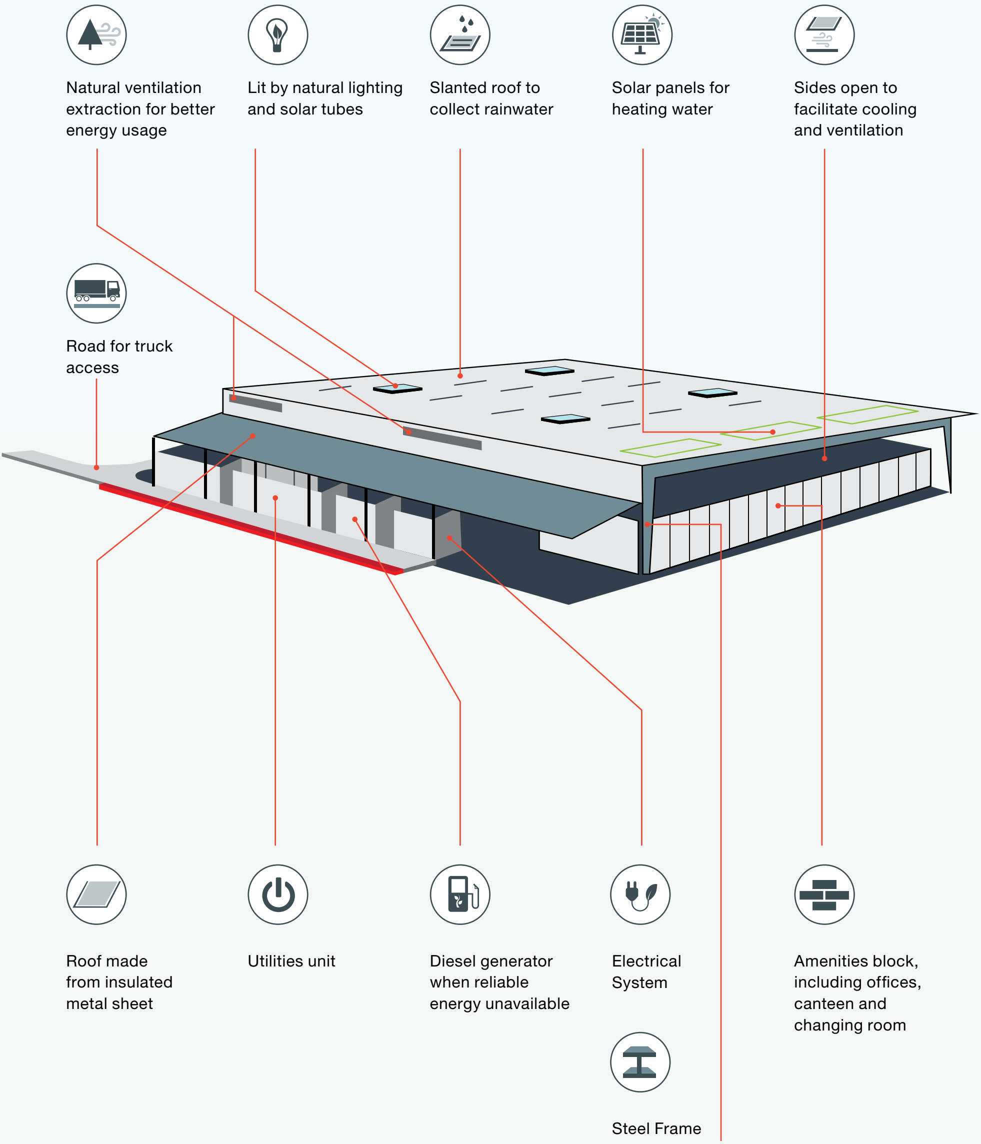
In China, Changan-Ford is using robots from automation technology company ABB on a new vehicle line designed to provide greater flexibility. Using ABB's FlexLean philosophy, the assembly line for the vehicle body is equipped with a number of robotic technologies that allow for rapid switching between car models, in response to shifting market demands. According to ABB, "the ability to produce different car models on the same line reduces the required capital investment of a new line and saves floor space. This flexibility also makes it easier to phase out old models and introduce new models over time, improving the efficiency of the overall line."[55]

The shift to flexible and adaptable factory designs and layouts is in part enabled by the increased use of building information modelling (BIM) in factory design, planning and management. BIM enables production plants to evolve into intelligent digital factories. Digital models of factories enable factory owners and operators to make changes to the physical plants far more quickly and accurately. According to

Digital models of factories enable factory owners and operators to make changes to the physical plants more quickly and accurately

Left: BIM model for Hong Kong Sludge Treatment Facility, the largest sludge treatment works in the world.

The Nestlé Modular Factory Concept



Source: Nestlé in collaboration with Concept Consult Architectes, Lausanne

The Nestlé modular factory will be made of a number of easy-to assemble component parts, designed to offer a flexible, simple and cost-effective solution for creating production sites in the developing world. The average Nestlé factory takes between 18 and 24 months to build and costs between £22m and £36m. The new modular factory could be built and functional in less than 12 months, at a cost of between £11m and £18m.
—Nestlé on its plans to adopt modular factories (2014)

Siemens, when new components are installed in the physical plant in future, they will be able to configure themselves and establish communication with each other, thereby eliminating start-up time and reduce costs. Once in operation, production processes will optimise and even heal themselves.[56]

These digital factories are better able to adapt to disruptions, changes in demand and other influencing factors

Creating a digital factory model for utilisation during both the design phase and operation of the factory is critical in achieving an efficient manufacturing layout. An important benefit is the ability to pre-visualize the factory design and layout in order to fine-tune the relational integration of all components, including the building's structure, building systems, machinery, logistics processes, resource flows and energy production systems. BIM allows designers to perform performance and process-related analysis before the factory is constructed and any equipment installed, optimising machine utilisation and energy consumption, maximising footprint efficiency, and increasing production throughput.

BIM can also identify and create efficiencies in the design of multiple factories across a portfolio of assets. A library of digital factory content and components can be used to quickly assemble a factory design from a toolbox of standard components.

Case Study:

Vitra Circular Factory

In 2013, Vitra, the German furniture manufacturer, unveiled its latest assembly and shipping centre: a 60,000-square-foot circular factory. This design is built for flexibility as logistics and production methods no longer adhere to the strict hierarchical principles of rectangular factories. The circular footprint of the building allows the delivery and loading of goods in different locations, so that the traffic flow inside the hall is reduced, optimised and simplified. The assembly zone in the middle of the building can also be shaped to meet new requirements based on current orders.

© SANAA, Vitra Campus, 2012

Principles for Design for Disassembly[59]

Design for disassembly incorporates a number of core principles. These include:

- Careful initial selection of recycled and recyclable materials. At scale, use of easily recycled materials in new projects can drive industry and governmental development of new recycling technologies.
- Minimise the number of material types used. Fewer material types simplifies sorting and reduces complexity of recycling transport.
- Preferentially use mechanical, rather than chemical, connections. Easy separation and disassembly of components reduces damage to materials and simplifies recycling.
- Embrace modularity. A freely interchangeable building system enables rapid and efficient changes to layout and function.

These digital factories are better able to adapt to disruptions, changes in demand and other influencing factors. The supply chain can be altered by sharing data without interference between manufacturers, supplier and customers, resulting in improved information mobility across the supply chain. This minimises disruption, improving the ability for the supply chain to adapt in sync, independent of location.

Adaptable and modular design

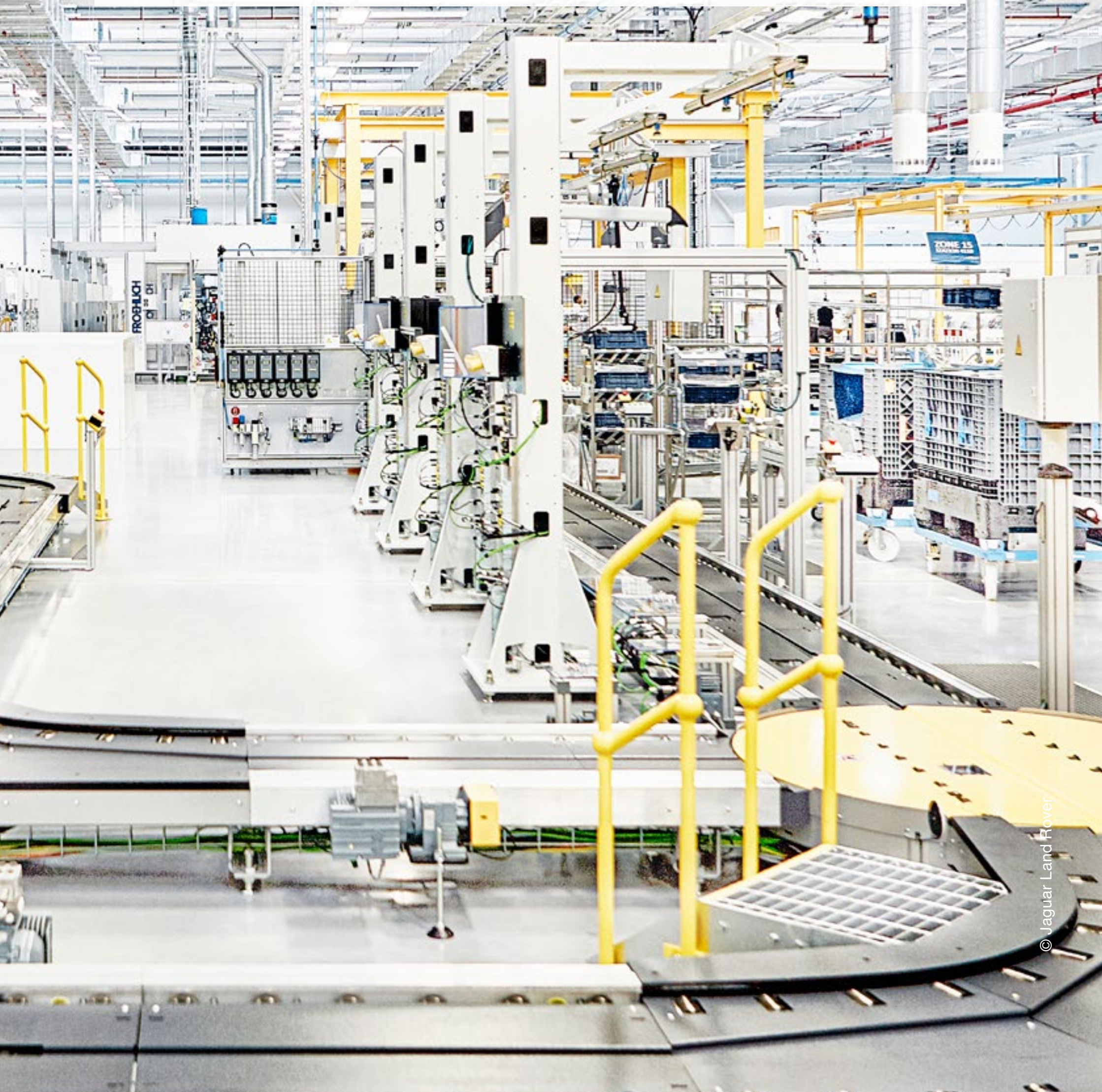
Improved adaptability and flexibility will also mean that factories can be constructed from modular components that are easily disassembled and relocated. Modular structures can be expanded quickly and easily to meet changing spatial requirements. Tented factories, for example, can be used for extra capacity or as stand-alone moveable facilities.

Modularity and disassembly are alternatives to current construction practice, which sees the assembly of buildings as a uni-directional project to create a final structure. However, in the future there will be more focus on design for disassembly. This more cyclical view of the built environment will take into consideration the deconstruction process as well as the construction process.[57]

Case Study:

Jaguar Land Rover Engine Manufacturing Centre

The design of this 95,000sqm factory allows for maximum flexibility and scope for future expansion and the on-going development of the manufacturing process. Through a number of sustainable features, the building is targeting the classification of 'BREEAM Excellent'. These strategies include natural ventilation, solar hot water panels and extensive photovoltaics to partially offset energy costs of the manufacturing process.



© Jaguar Land Rover

Case Study: Advanced Manufacturing Research Centre Factory 2050

The University of Sheffield Advanced Manufacturing Research Centre with Boeing (AMRC), has secured funding for a £43 million state-of-the-art research factory which will be the UK's first fully reconfigurable assembly and component manufacturing facility.

The factory, which will be a focus for collaborative research, will be capable of rapidly switching production between different high-value components and one-off parts. The facility will constructed largely of glass, so that the advanced manufacturing technologies can be displayed, and cover an area of around 4,500sqm.

The factory will "combine technologies including advanced robotics, flexible automation, unmanned workspace, off-line programming in virtual environments linked to plug-and-play robotics, 3D printing from flexible automated systems, man-machine interfaces, and new programming and training tools".[60]

Vertical space and urban possibilities

"Manufacturers can now do more with less space as robots and automation are reducing the space needed for production lines. More vertical space is also being used. This reduction in footprint leads to lower energy costs per square foot."
—Steven Hawkins, Director of Automation Services, Stellar (2012)

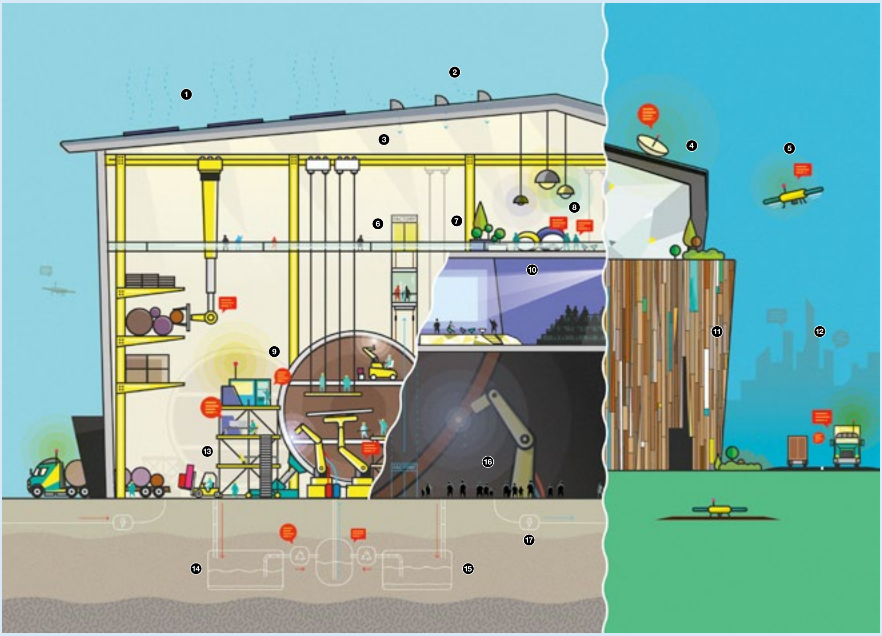
The enduring image of a traditional factory reaches back to the height of the industrial revolution. These highly polluting factories first scarred the urban centre, before moving out to the industrial hinterland. Factories are now beginning to return to the city in a different guise. They are cleaner, greener, quieter and no longer demand large-scale rectilinear spaces. Most of these modern urban factories are assembly plants which need less room, and many are able to occupy vertical spaces.[61]

Cities offer a number of interesting advantages for greener, more sustainable manufacturing models. Urban density allows for a symbiotic relationship where one

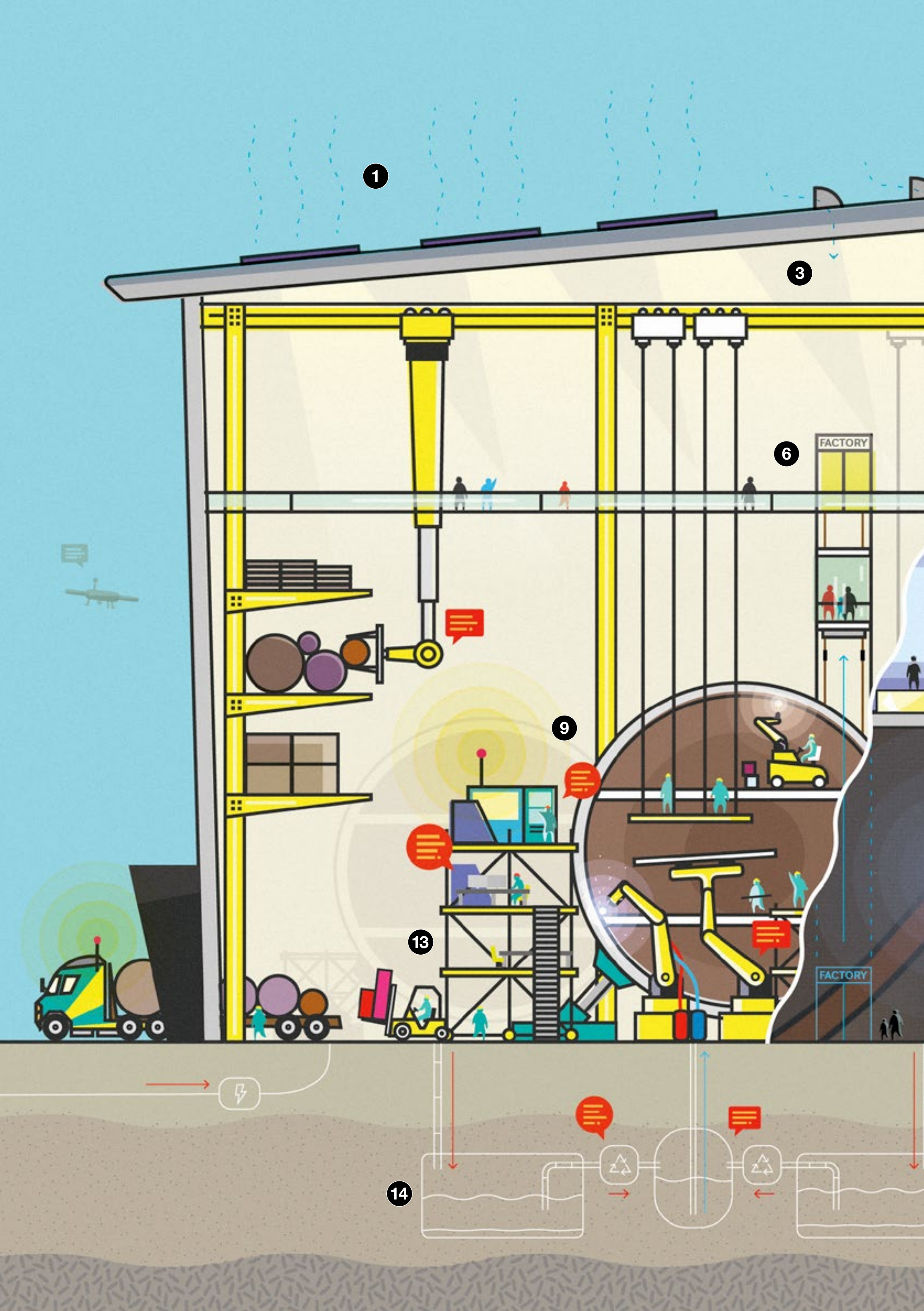
Advancements in ecologically-responsible technology mean that clean manufacturing can exist adjacent to residential spaces, and that work and living can be hybridized in new ways.. Vertical urban factories could produce energy rather than just consume it, and workers could recycle goods, rather than spew them out. This in turn would close the loop of making, consuming and recycling as part of a new urban spatial and economic paradigm.
—Nina Rappaport, architectural historian and critic (2011)

factory can use waste outputs from another as an input, thereby sharing resources. With cleaner, more high-tech processes, factories can fit better into the urban environment. For example, in the production of niche goods such as furniture, garments or high-tech products.[62] Manufacturing also contributes to the vitality of cities, providing job opportunities with a high multiplier effect.[63]

3D printing will allow manufacturing to be more mobile and dispersed. Factory locations are therefore likely to become both more varied and closer to the end consumer.[64] This development, along with the trend of "next-shoring" (developing products closer to where they will be sold) could result in smaller, more central urban factory locations.



1. Sustainable energy (solar)
2. Ventilation and cooling
3. Natural lighting
4. Remote data sharing and analytics / Social data streams
5. Drone logistics network
6. Factory experience
7. Healthy environment
8. Collaborative environments
9. Data analytics
10. Flexible spaces
11. Sustainable construction material
12. Data stream for assessment
13. Modular adaptable spaces
14. Water capture and storage
15. Grey and black water
16. Factory experience
17. Smart Grid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© Chrysler Group

Delivering Change

Manufacturing is entering a new era. Key to this shift is the intersection of the virtual and physical worlds, made possible by the integration of software, sensors and communications within cyber-physical systems. Additive manufacturing is another game-changing trend that has the potential to reduce waste, enable mass customisation and shift manufacturing closer to the end consumer.

These and other trends will influence the design and operation of factories, catalysed by the ability to create digital models of factories, making it more efficient for operators to make changes to the actual physical plant.

Manufacturers will need to be quick to adapt and will have to focus on more sustainable processes and products, including the circular economy. Due to the convergence of the physical and digital, factories of the future will also require a more skilled workforce. Manufacturers will therefore look to locate operations where there is access to a skilled pool of workers.

As manufacturing remains critically important to both the developing world and the economically advanced world, it is important for companies and policy-makers to have a comprehensive understanding of the changing manufacturing landscape, in order to decisively and quickly respond to new challenges and opportunities.

Due to the convergence of the physical and digital, factories of the future will require a more skilled workforce

Left: Workers evaluate paint quality of the 2015 Chrysler 200 at Chrysler Group's Sterling Heights Assembly Plant.

Workers conduct an inspection at BASF's water treatment and paper chemicals plant in Nanjing, China.

Here are eight suggested actions for factory owners and operators to consider:

1. Provide new training opportunities for staff so that they are ready to manage more complex technological processes and utilise cyber-physical assistance systems

2. Provide healthy, comfortable workplace conditions for an increasingly skilled and diverse workforce, including systems and policies to accommodate an ageing workforce

3. Design factories and production facilities that encourage greater openness, integration and collaboration between staff of different backgrounds and skills

4. Explore options for creating modular and adaptive factory designs for rapid expansion or reconfiguration of production capacity in terms of both product and location

Method’s new factory in Chicago is designed to be one of the few LEED Platinum factories in the U.S.

5. Harness the power of sensors, data and advanced analytics to enable rapid and responsive manufacturing processes that can anticipate and respond to changing demand patterns

6. Create sustainable factories that operate at higher material and energy efficiencies by maximising on-site production and the re-use of energy and materials resources. Ultimately, strategies need to be formulated to help transition towards a circular economy in which there is no waste

7. Utilise BIM models to shorten lead times on factory reconfigurations and expansions, and to optimise the relationship between building, machinery and production processes

8. Develop the understanding and implementation of best practice asset management and whole life-cycle costing

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Packaging facility and warehouse for Gerber Foods & Soft Drinks Ltd, Somerset, UK (Arup)

About Arup

Arup is the creative force at the heart of many of the world's most prominent projects in the built environment and across industry. We offer a broad range of professional services that combine to make a real difference to our clients and the communities in which we work.

We are truly global. From 100 offices in 38 countries our 11,000 planners, designers, engineers and consultants deliver innovative projects across the world with creativity and passion.

Founded in 1946 with an enduring set of values, our unique trust ownership fosters a distinctive culture and an intellectual independence that encourages collaborative working. This is reflected in everything we do, allowing us to develop meaningful ideas, help shape agendas and deliver results that frequently surpass the expectations of our clients.

The people at Arup are driven to find a better way and to deliver better solutions for our clients.

We shape a better world.

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Manufacturing has entered a new age of production. This shift in the design and manufacture of goods is not the result of a single trend, but is driven by a broad range of complex and interconnected factors. These influences range from advances in digital technologies and automation to climate change and market demands. The collective consequence is a shift towards design and innovation processes that are increasingly fast, open, collaborative and responsive.

The emerging trends, processes and technologies described in this report will transform the manufacturing landscape. The inevitable shift to leaner, smarter and more flexible forms of production will have a range of impacts on how the factory is designed, how supply chains operate, how people experience changing operational environments and how the future spaces of production will be organised.

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