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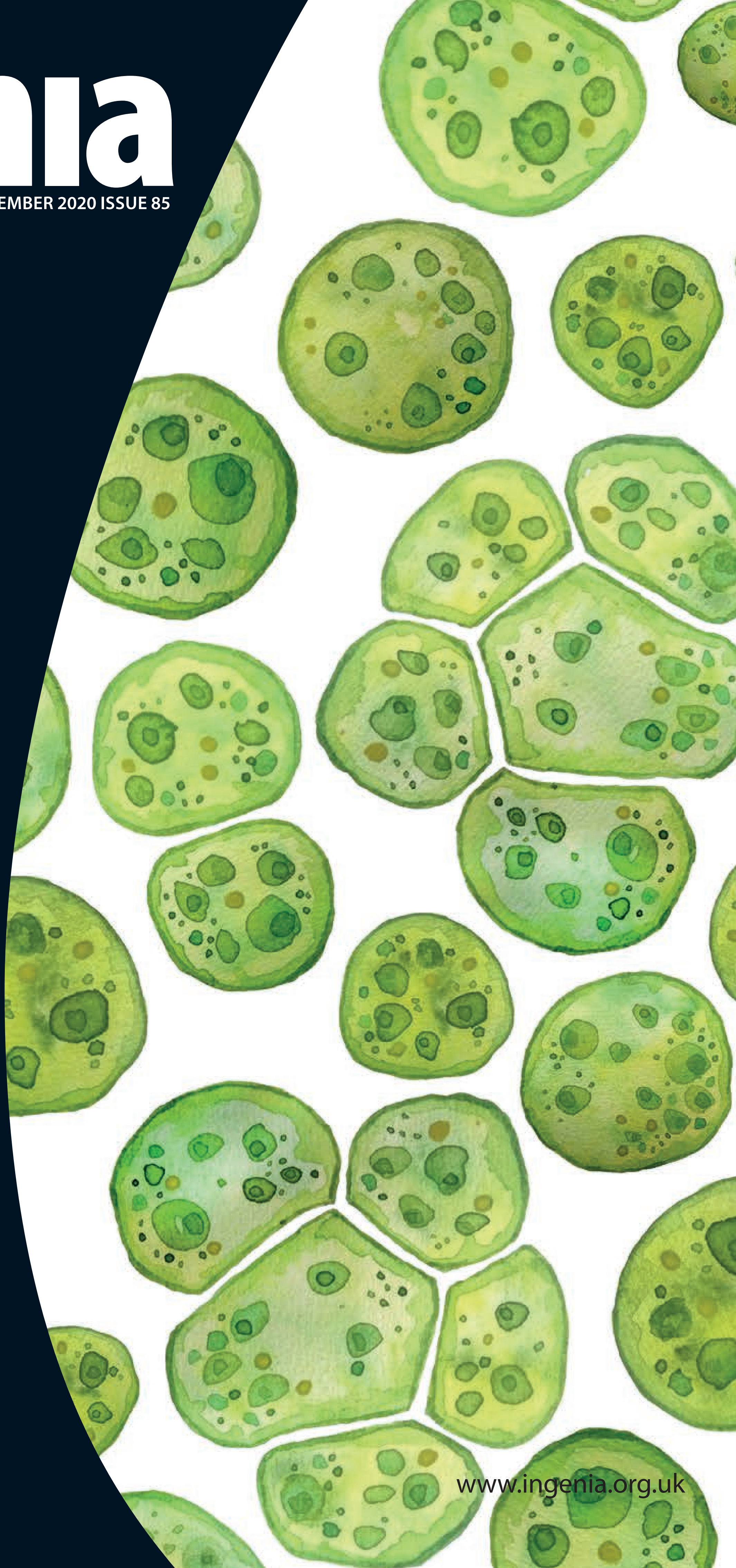

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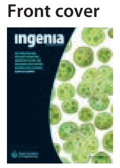

Microalgae, which can be used to clean wastewater
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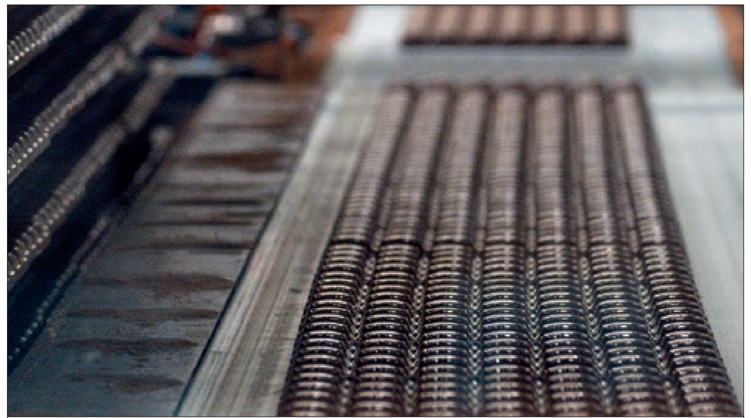
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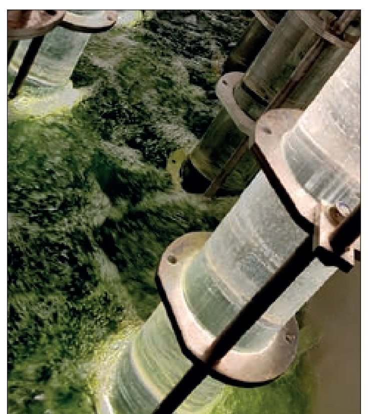
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EDITORIAL

ONE GOAL, TEN POINTS

Scott Steedman CBE FREng

The Prime Minister's November release of the *Ten Point Plan for a Green Industrial Revolution* was a breath of fresh air in the relentless news coverage of the pandemic and the US Presidential election. Signalling multiple initiatives from aerospace to tree planting and green finance, the plan is a call to arms for engineers everywhere. The document is an important expansion of the government's previous plans for the UK to attain net zero emissions of carbon by 2050.

The UN Climate Change Conference COP26, to be hosted by the UK and Italy in Glasgow in November 2021, will have added to the pressure on government to act, even so the *Ten Point Plan* is a step in the right direction. The breadth of the plan signals an understanding in government that industry cannot deliver net zero without immediate action to bring together public and private investment behind a common cause, tackled at national scale.

The UK is already the world leader in the deployment of offshore wind. We have advanced nuclear engineering capability and have talked about the potential for small modular reactors for years. The government has been quietly pushing the development of hydrogen appliances, battery technology, and carbon capture and storage (CCS). Although each area has been successful individually, at national level our approach has been fragmented, hesitant, too small, and lacking the political commitment needed to drive real change.

Does the *Ten Point Plan* go far enough? Industry has given a cautious welcome. But a green industrial revolution will not happen through science alone, it must be forged through new manufacturing output, new construction products, new business models and new forms of investment. Above all, it will require a new mindset, a mindset that embraces the importance of new skills, new jobs and a new, strategic approach to delivering a greener national infrastructure.

Each of the government's ten points is important: offshore wind, hydrogen, nuclear power, electric vehicles, public mobility, aerospace and maritime, buildings, CCS, the natural environment, and innovation and finance, but the key to achieving the goal will be to deliver them together. This plan needs government, industry and environmental interests to keep their eye on the prize and to realise that these are not ten separate ideas but one system.

Silo thinking has handicapped our ability as a nation to deliver innovation at speed and at scale. Stimulating a market for batteries to store electricity in the home needs more than the ability to manufacture batteries. It needs changes to building regulations to stimulate market demand. Some electric vehicles need batteries and others will use fuel cells. Making hydrogen needs electricity or, if using steam reformation, it needs CCS. Using less fossil fuel means generating more electricity from offshore wind and nuclear power. At the same time, we need to improve the energy efficiency of our building stock, reduce pressure on the environment and find more sustainable means of transport, whether by air, sea or land.

Respecting and exploiting our industrial legacy to deliver this plan will be vital. The plan must build on the UK's engineering excellence, both in areas of the country with world-class manufacturing capability and in engineering sectors, such as nuclear energy, where the UK has special expertise, including small modular reactors. (Professor Dieter Helm CBE picks up the theme of the UK's strong science and technology capability in this issue on page 8).

Testing each point in the plan needs engineering insight. Could the plan go further in its ambition for a new hydrogen economy? Could it aim to heat more than just one town by hydrogen by the end of the decade? The plan supports the introduction of CCS to four industrial clusters of traditional industries, but should there be more? How could CCS and nuclear projects be accelerated through design and construction?

We know that the government has its hands full with the pandemic, leaving the EU, the UK internal market, trade negotiations, telecoms security, economic recovery, the list goes on. The Prime Minister's commitment is welcome, but this is a plan that needs to be engineered. No organisation is better suited to lead that work than the Academy. With COP26 coming over the horizon, now is the time for the Academy, through its leadership of the National Engineering Policy Centre, to show us the way forward.

Scott Steedman CBE FREng
Editor-in-Chief

IN BRIEF

CLIMATE-SAVING YOUNG ENGINEERS

Competition winner Maya Mouzouris Marzetti

In September, The Great Exhibition at Home remote learning programme announced its prize winners. Students across the country took part in science experiments at home during lockdown, before submitting a video showing what they had learned.

Maya Mouzouris Marzetti in Year 8, from Park House School in Newbury, was awarded first place for her designs for a flood-resistant house and a high-tech beehive that monitors the hive's health. The judges were impressed by her climate-saving ideas and research as well as her passionate presenting skills.

Second place was awarded to Isaac Pickering and Liliana Moores in Year 6 from Rode Heath Primary School in Cheshire. Their invention, the 'pollution solution', is designed to harvest plastic from the North Atlantic 'garbage patch'.

Megan Waterhouse in Year 5, from Manor House School in Leatherhead, won third place. The judges really enjoyed hearing about Megan's personal connection to engineering, which stemmed from building a greenhouse with her granddad.

In total, seven entries were awarded top prizes, including up to £500 to expand STEM subjects in their school, a meeting with one of the inspirational engineers featured in the competition and 30 special commendation prizes for individual entries.

"The high standard of all final entries was incredibly exciting and the Academy has been delighted to be part of a process that celebrates the innovation and imagination of so many bright young minds and future engineers. We were particularly impressed with the creative way technology was used to showcase engineering solutions in a fun and informative way," said Scott Atkinson, Education Programmes Manager at the Royal Academy of Engineering.

The Great Exhibition at Home's aim is to get British kids thinking about some of the biggest challenges we face today, to encourage the next generation of British scientists and engineers. It is a collaboration between the Royal Academy of Engineering and the Royal Commission for the Exhibition of 1851.

BBC BITESIZE ENGINEERING ACTIVITIES

The Institution of Mechanical Engineers has partnered with BBC Bitesize to offer six STEM at Home activities for its programme, which include activities to encourage children to take an interest in science and technology.

The collection features six of the institution's hands-on STEM at Home activities, which were launched earlier in the year to help parents and teachers during the pandemic. The resources include activity instructions, kit lists and instructional videos, and show students an exciting range of activities, such as building a mechanical hand, hydraulic propagator, catapult, and lunar rover.

BBC Bitesize offers learning resources for children including those who are self-isolating and studying at home, combining online learning with classroom time, or catching up on what they may have missed last term.

Activities can be accessed at **www.bbc.co.uk/bitesize/articles/z64vp4j**

IN BRIEF

UK STUDENTS DESIGN DEVICE TO PREVENT TYRE MICROPLASTICS

Globally, it is estimated that tyre-wear accounts for nearly half of road transport particulate emissions

A group of students from Imperial College London have won this year's national James Dyson Award for their device to curb microplastic emissions from vehicle tyres.

Their device captures microplastic particles from tyres as they are emitted, and aims to reduce the damaging pollution the particles cause. Half a million tonnes of tyre wear is produced annually across Europe and tyre particles are the second-largest microplastic pollutant in our oceans.

Every time a vehicle brakes, accelerates, or turns a corner, the tyres wear down and tiny particles become airborne.

The device is fitted to the wheel of the vehicle and uses electrostatics to collect particles as they are emitted from the tyres, using air flows around a spinning wheel. They claim that their prototype can collect 60% of all airborne particles from tyres, under a controlled environment on their test rig.

Once collected, the fragments can be reused in new tyres or other materials such as ink.

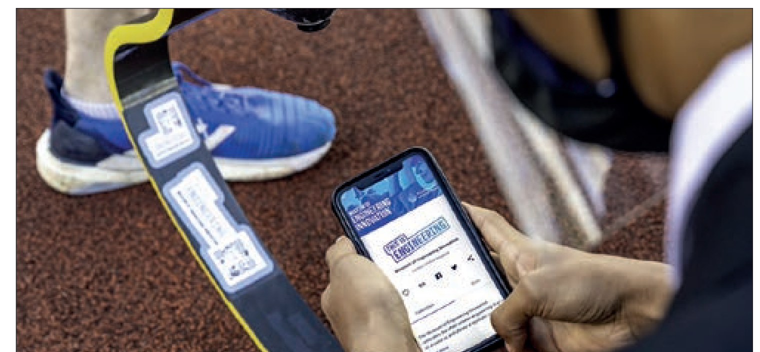
The device was also a runner-up in the international competition, which was won by Blue Box, a biomedical device for pain-free, non-irradiating, non-invasive, low-cost, and in-home breast cancer testing.

VIRTUAL MUSEUM OF ENGINEERING INNOVATION

The Royal Academy of Engineering has announced plans to launch a new virtual museum in 2021 to help tackle the shortage of engineers in the UK.

Instead of being housed in a building, the exhibits in the virtual Museum of Engineering Innovation will be accessible via QR codes or 'QRtefacts'. Placed in accessible locations around the UK, each QRtefact will signpost users to an individual exhibit within the online museum. The museum can also be accessed through Google Arts and Culture. It will celebrate the often-unseen engineering that is all around us, shining a spotlight on the diverse engineers that are making a difference to our everyday lives and futures in a bid to inspire the next generation.

The first collection of exhibits will include the carbon fibre blade of reigning world champion and gold medallist sprinter, Jonnie Peacock MBE. A QR code has been placed on the 'Ferrari of running legs', giving everyone (who can keep up with him) access to the virtual museum. Once scanned, visitors will be able to learn about the incredible engineering that went into making Jonnie's blade, and how far the sporting world has come thanks to engineered high-performance prosthetics.



Jonnie Peacock's running blade being scanned to access the Museum of Engineering Innovation

Jonnie Peacock commented: "Whenever I wear my blade I get such a great response, particularly from children, able bodied and disabled, who think it's really cool. I'd like them to know that I wouldn't be where I am today and have this super cool prosthetic leg if it wasn't for engineers and amazing feats of engineering, which is why I am supporting *This is Engineering* Day, to help demonstrate some of the many different ways engineering makes a difference and to inspire the engineers of the future."

Exhibits featured in the first collection can be accessed at **https://artsandculture.google.com/partner/museum-of-engineering-innovation**

HOW I GOT HERE

HOW I GOT HERE

Q&A

EOIN O'LOUGHLIN & PHILIP TURNER

Eoin O'Loughlin is a fire safety engineer at Arup. Philip Turner is a mechanical building services engineer at Arup. Together they have been working on CareBox, a series of design guidelines for scalable, modular and rapid solutions to provide additional intensive care and ward beds for COVID-19 patients.

WHY DID YOU FIRST BECOME INTERESTED IN SCIENCE/ ENGINEERING?

Eoin: It seemed like the natural progression from a childhood obsessed with Lego! I really enjoy solving problems and am passionate about how good design can have enormous positive and transformative effects on society and our interaction with the environments around us.

Philip: My mum was a secondary school science teacher, so that influenced me growing up. As I got older, I realised that there are so many issues facing our society that require scientific and engineering solutions. I see engineering as the practical implementation of scientific ideas in order to solve problems, so it was the best route to try to make a difference.

HOW DID YOU GET TO WHERE YOU ARE NOW?

Eoin: After focusing on maths and physics in school, I studied civil engineering at the National University of Ireland, Galway. I then enrolled in a master's in structural and fire engineering at the University of Edinburgh. My first job was with a large UK-based multinational, multidisciplinary consultancy. I then joined a small independent fire engineering practice to set up its London office. I joined Arup in 2017, working in the Middle East for three years before returning to London earlier this year.

Philip: I studied further maths, physics and chemistry A levels, and then mechanical engineering at the University of Sheffield, which I chose because it's quite a broad subject and it kept my career options open. After graduation I applied for Arup's graduate scheme as a mechanical building services engineer in London. I identified with Arup's ambitions and philosophy of trying to make the world a better place through good engineering design, and I've now been here for eight years.

Eoin O'Loughlin, fire safety engineer and chartered engineer

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN ENGINEER?

Eoin: Solving problems that make a difference. Being able to apply science, engineering and logic, in collaboration with a broad range of other professionals, to develop solutions for the challenges and opportunities facing communities and the planet today.

Philip: Working with other engineers, architects and clients who want to solve problems collaboratively, and make a positive change to the world around us.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

Eoin: My role involves the application of fire safety science and engineering principles to integrate fire safety considerations and solutions within designs. 'Typical' in 2020 might look quite different to 'typical' pre-pandemic, but fundamentally my work still involves the same core activities – meetings with clients, colleagues, other designers, contractors, and systems suppliers, approvers (such as building control bodies and fire brigades). I also conduct engineering analysis and research to address design challenges, and share ideas through emails, sketches, drawings, and reports.

Philip: My job is to design heating, cooling and ventilation systems in buildings. This can't be done alone, so I spend most of my time collaborating with other people, either in meetings or communicating design solutions to architects, contractors and clients through emails and informal sketches. At the end of a design stage we deliver more formal drawings, reports and specifications that describe the proposed design, so I spend a lot of time producing that documentation and collaborating with my colleagues to pull together a coordinated design. Behind all this documentation there's obviously a whole load of calculations, engineering thinking and learning that goes on.

Philip Turner, mechanical building services engineer and chartered engineer

TELL US A BIT ABOUT CAREBOX

Eoin: CareBox is a series of design guidelines for rapid solutions to provide additional intensive care and ward beds in the event of a surge in COVID-19 patients. It was developed during the 'first wave' of the pandemic, aiming to support governments, healthcare bodies and NGOs around the world to build capacity. The guidelines can be quickly deployed and implemented in a range of settings, from existing healthcare campuses to conversion of existing non-healthcare facilities.

Philip: We looked at three different solutions for expanding healthcare capacity: a 'plug-in' hospital, a containerised ward space that can be installed on open ground adjacent to an existing hospital; re-using spaces, by building the containerised ward in an existing space, such as vacant commercial space or a multi-storey car park; and adapting existing buildings such as conference centres and sports halls, similar to the Nightingale Hospitals that have been developed. The UK's Nightingale Hospitals are great for expanding bed capacity, but they can be difficult to staff and suffer from separation from the infrastructure and facilities that existing hospitals could provide. CareBox tries to increase ward capacity on existing hospital sites to overcome these challenges.

Intensive care unit (ICU) wards within a hospital 'plug-in', one of the extension concepts set out in Arup's CareBox guidelines for expanding COVID-19 healthcare capacity
Learn more at www.arup.com/COVID-19/CareBox

HOW DID YOU GET INVOLVED?

Eoin: In the pandemic's early days, Arup identified a range of ways to help address the unprecedented challenges the world was facing. Through discussions with the team and research, it was clear that fire engineering input would be essential to safely address the complex challenges presented by highly dependent COVID-19 patients, the risks of heightened fire hazards such as oxygen-enriched fires and the novel settings of the extended or converted facilities.

Philip: I work as part of a team that has lots of healthcare experience and has delivered some major hospital projects in recent years. I was asked to lead the second workstream of the CareBox project – re-using spaces. We developed a concept that tried to limit the risk of transmission from patients to staff and the general public. The basic layout of the ward was influenced by our work on laboratories that have 'clean' and 'dirty' airlocks for entry and exit to the wards, and separate gowning and de-gowning areas. The ventilation system moves air from the 'clean' zone to the 'dirty' zone to reduce the airborne spread of the virus. Air is extracted from as close to the patients as possible, behind each bed, so pathogens are extracted as quickly as possible. Any air extracted from the ward is filtered by high-grade pathogen filters before being discharged to atmosphere.

WHAT WOULD BE YOUR ADVICE TO YOUNG PEOPLE LOOKING TO PURSUE A CAREER IN ENGINEERING?

Eoin: Be curious, ask questions, believe in the butterfly effect. Focus on societally impactful work. Find others who share your values.

Philip: Find out what you're passionate about and stick to it. If you care about the work you're doing you'll always be happy, even if there are challenges along the way.

WHAT'S NEXT FOR YOU?

Eoin: The regulations, codes and processes underpinning building fire safety design in the UK are under unprecedented scrutiny. The construction industry needs to implement more robust means of ensuring equitable fire safety is consistently provided for all persons. I have opportunities to contribute to industry advancement in these areas through committees and research, so these will be key focus areas for me.

Philip: The industry is changing very quickly, with a much greater focus on sustainability than there used to be. Many of our clients want to be 'net zero carbon' now and they look to us for advice on how to achieve it. For me, this means I need to keep pushing our designs to be as low carbon as possible, both in operation and in embodied carbon.

OPINION

OPINION

HOW CAN THE UK SOLVE ITS CARBON PROBLEM?

The North Sea is one of the best places in the world to try out CCS. It is also one of the best places for offshore wind

The climate crisis is one of the most pressing challenges that the world faces. As a result of the COVID-19 pandemic, the UK government has the opportunity to 'build back better' and meet its net-zero target by 2050. Dieter Helm CBE, Professor of Economic Policy at the University of Oxford, sets out how Britain can lead the way on climate change action.


Professor Dieter Helm CBE

What can a small island like the UK do to address the global problem of climate change, when it contributes just over 1% of the world's CO_2 emissions – compared to around 29% from China? Even if the UK is no longer a leading economy or a leading world power, the starting point is to stop making climate change worse. This is what net zero by 2050 is supposed to achieve. The Committee on Climate Change (CCC), which advises the UK and devolved governments on emissions targets, claims that "by reducing emissions produced in the UK to zero, we also end our contribution to rising global temperatures".

The ambition to stop causing climate change is a good one, but it is neither quite as straightforward as the CCC claims, nor is it enough. To address global warming, we must address global emissions. The largest share of these comes from China now, and will come from China, India and Africa for the next few decades at least.

The net-zero target is for territorial carbon production. It focuses on emissions in the UK. But a moment's reflection tells us that our carbon footprint goes way beyond emissions from local production. We are a trading nation: China makes lots of that very polluting stuff.

The easy way to help meet the net-zero target is to close down the rest of the UK's carbon-intensive production in petrochemicals, steel and cars, and to import it from China instead. That would make climate change worse but would flatter the UK's net-zero target. Indeed, that is what has been going on in the UK and the EU for the past 30 years. In that period, every year the concentration of carbon in the atmosphere has gone up relentlessly, at around two parts per million (ppm) to now well over 400 ppm. The great economic export-oriented carbon-intensive growth of China has been driven in part by consumption in the UK, the EU and the US.

Once this is recognised, the unilateral aim to make no further contribution to climate change becomes net-zero carbon consumption, not net-zero territorial carbon production. It means we must get serious about carbon imports, and the most efficient answer is to have a carbon tax applied to all sectors of the economy and imports. It should capture the big, so far neglected, emissions from transport, heating and agriculture, not just electricity, and treat imported steel on the same basis as UK steel.

A uniform general carbon tax is a necessary condition if we are to make no further contribution to climate change. But we can do much better both at home and abroad.

A low-carbon economy needs low-carbon infrastructure, as well as R&D and new technologies. We need home infrastructures for decentralised electricity systems, for electric transport, smart charging and smart roads, and for offshore networks for wind generation and for carbon capture and storage (CCS) in the depleted North Sea oil and gas wells – all joined up with smart data and fibre.

The striking thing about the infrastructure requirements is how little we have done so far and how piecemeal and incremental the plans are. The economic regulators have not yet understood the scale of the challenges and how inappropriate the five-year periodic reviews of the network companies are. What the UK needs are joined-up net-zero infrastructure plans, running out to 2030 and to 2050, on a scale that we have not seen since the reconstruction of the electricity networks after the Second World War.

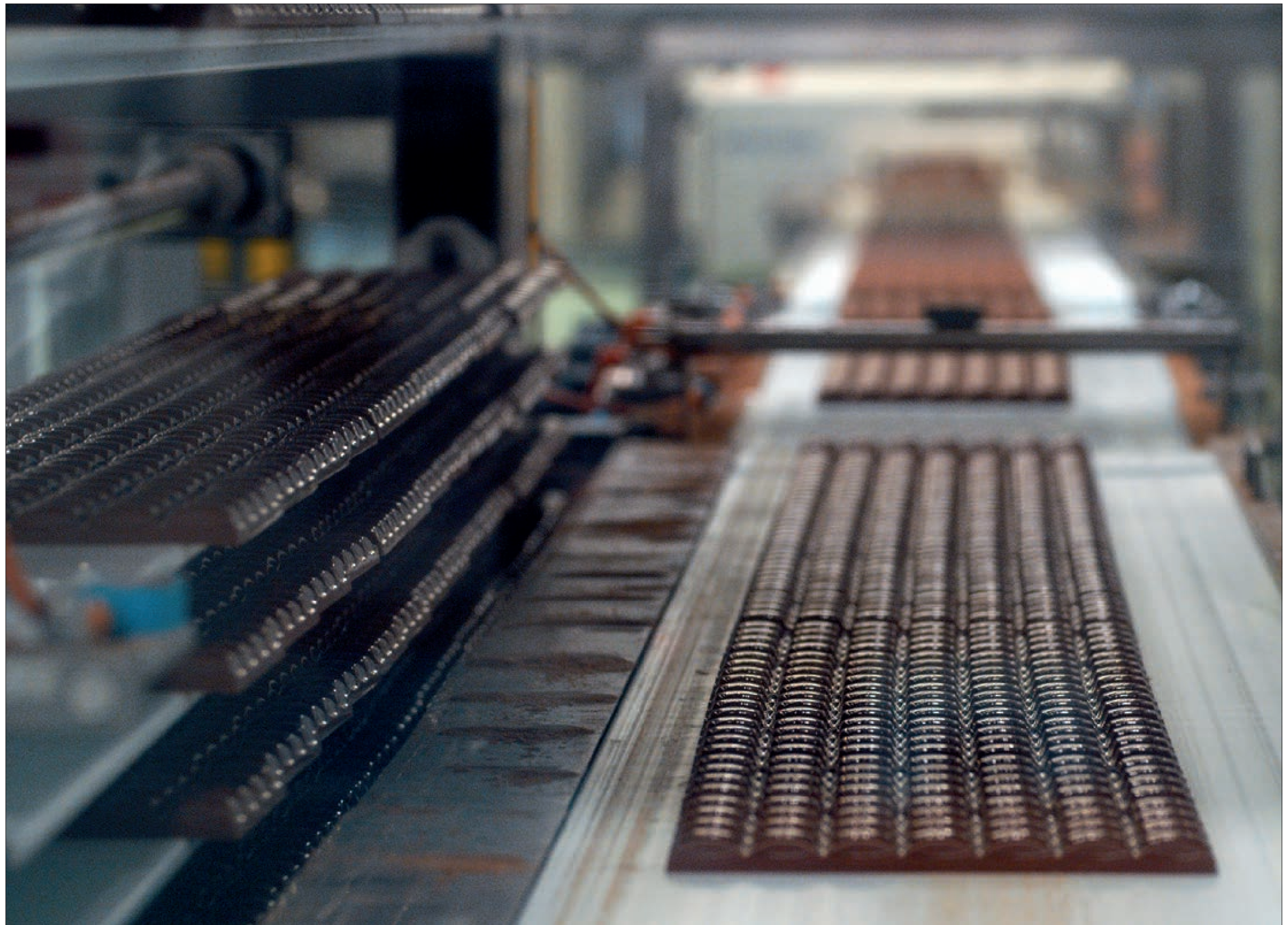
All the above would make a good start, but it would have almost no impact on what others do. A perfect UK in a sea of high-polluting large-world economies would not halt the rise in carbon concentration in the atmosphere. If we want to make a difference, we need to look outwards as well as inwards. The question is: what can the UK do to help others crack their emissions? The answer is a mix of geography, science and technology.

Starting with geography, the UK has two key advantages in the global climate context. It has the shallow North Sea, with its depleted offshore oil and gas wells, its existing oil and gas pipelines, and the fact that it is windy. The North Sea is one of the best places in the world to try out CCS. It is also one of the best places for offshore wind. Irrespective of the impact on UK territorial emissions, any coherent global approach would want to draw on offshore wind and CCS, and the technological advances that come from their deployment at scale. The UK can pass on to the world the lessons that it learns and the technologies it deploys.

The UK has a science and technology base way beyond its economic size. It has R&D capabilities and universities in the top rank in the world. That capability ranges across physical and biological sciences, and is witnessed in meteorology and climate modelling; nuclear and renewables technologies; and in vaccines and other medical advances. This is the area where the UK could make most impact on climate change, developing a host of new technologies and giving them to the world. What it is not good at is deploying them: the UK has been a science powerhouse while its manufacturing capability has eroded to a measly 20% of the UK economy. The UK is a services economy: science is a key service. We need to make more of it.

BIOGRAPHY

Dieter Helm CBE is Professor of Economic Policy at the University of Oxford and Fellow in Economics at New College, Oxford. He has provided extensive advice to UK and European governments and served as a special advisor to the European Commissioner for Energy. His new book *Net Zero: How We Stop Causing Climate Change* was published in September by Harper Collins.



Engineers use complex modelling to achieve identical squares of chocolate that taste the way we expect © Mondelēz International

RAISING THE BAR

There are numerous engineering challenges involved in manufacturing chocolate to consistent standards of taste, texture and appearance. Neil Cumins investigated the engineering behind some of the UK's most popular confectionery.

Chocolate's place in popular culture needs no introduction, yet the engineering behind it is often overlooked. As we snap off a square of our favourite chocolate, we don't think about how the uniformity of each square has been achieved, or stop to consider the complexity involved in developing a new product line.

A team of experts from Mondelēz International, the owners of Cadbury, shed some light on the process. Based in the company's Research, Development and Quality (RDQ) division in Birmingham, they are responsible for maintaining quality and consistency across the Cadbury range of products, as well as developing new manufacturing processes and product lines. In recent years, the team has developed the world's first 3D chocolate printer, calculated the precise tolerances involved in chocolate production, and used crystal morphology to develop a chocolate bar with 30% less sugar.

THE BOURN' IDENTITY

Since the 19th century, the Cadbury brand has been synonymous with Bournville – a model village in Birmingham founded by the Cadbury family that contains a factory and hundreds of homes built for employees. Bournville remains one of the leading global bases for Mondelēz International's RDQ division, and it's here that a group of experts studies topics as diverse as fluid dynamics, structural mechanics, computational chemistry, and data science. Staff have been recruited from fields including food engineering and industrial design; mathematics and statistics; microbiology; and even psychology, reflecting the numerous technical processes involved in manufacturing chocolate.

Dr Beccy Smith is a Principal Scientist in the Modelling and Simulation team. Her department is responsible for developing digital tools that will help to develop better products more quickly, reducing costs: "We solve very diverse problems, from understanding the

Cadbury's cocoa beans come from six key areas: Ghana, Côte d'Ivoire, Indonesia, India, the Dominican Republic, and Brazil © Mondelēz International

A REAL MOUTHFUL

Chocolate manufacturing involves a number of highly technical processes, whose terminology explains their effects on the chocolate's material properties. For instance, tempering describes the process where cocoa butter is subjected to temperature-controlled crystallisation into one of six forms, known as polymorphs. The presence of tiny crystals in the chocolate can significantly affect its texture on the consumer's tongue, and crystal morphology describes the shape of the crystals present in solid chocolate. These can be used to replicate the taste and texture of a particular chocolate recipe with a different ratio of ingredients, such as a bar with a reduced sugar content.

Chocolate has to be viscous to be precisely moulded and shaped. However, as a shear-thinning fluid whose viscosity reduces when the fluid is mixed, keeping it consistently liquified is a particular challenge. The process of returning it to a solid state is known as crystallisation and is done in a carefully controlled manner once the chocolate has been poured into a mould that will determine its finished appearance.

impact of altering ingredients to improving consumer appreciation of our products." The department looks at problems such as predicting how moving to recyclable packaging could alter shelf life, and how process parameters can be optimised to improve quality.

Dr Smith cites a range of advanced scientific processes used at Bournville to develop a range of products from chocolates and biscuits to powdered beverages and meal components. "We use computational fluid dynamics (CFD) to predict the flow of liquids and gases and the transfer of heat. We conduct finite element analysis (FEA) to predict the movement and deformation of materials and transfer of heat. We undertake discrete event simulation to predict movement of material down a factory line or in a supply chain, alongside advanced process modelling to predict chemical and physical transformations within our factory unit operations."

Alongside data science techniques like artificial intelligence and machine learning, this scientific analysis directly influences the products we buy in shops, as Dr Smith explains: "The chocolate team often designs new shapes of filled chocolate units, such as caramels or cremes. These are made by filling a mould with liquid chocolate, then turning it over and vibrating it to shake out all but a shell of chocolate, before cooling to a solid and adding the filling and a chocolate base. Historically, we had to do many pilot plant experiments to find out what vibration settings create different thicknesses of shell, and many laboratory experiments to find out how strong the different shells are as we can't risk our products breaking in the supply chain." Now, by using computational modelling, the company can validate ideas on a computer instead, accelerating new product development.

CHOCS AWAY

The RDQ team was also responsible for launching a 3D chocolate printer in 2019. This project started in 2015, with Senior Group Leader Nim Mistry heading the team from 2018, shortly after the decision was made to give the prototype machine its consumer debut in Australia. Nothing like this had been done before, and Nim's team recognised the need to demonstrate what could be achieved, while determining consumer demand for customised products and the public's enthusiasm for watching live chocolate printing.

"We had a year to launch, which was a tight timeframe," Nim recalls. "We had to run conceptual consumer tests on 3D printing, set up collaborations with partners to develop the concept, and then build the machine itself." This latter stage was handled by 3P Innovation, assembling a machine powered by standard 3D printing software: "The machine understands CNC G-code, which is similar to what you'd find in any other 3D printer software, and it also runs on the Rhino JavaScript engine. The main difference from a normal 3D printer is that we've got people working on the design with an understanding of how chocolate operates, to adapt the design to meet that criteria."

"One question we got asked a lot was whether we'd done anything to the chocolate to be able to print on the machine. The answer was no. We used standard chocolate, and consumers were surprised that it tasted like standard Cadbury Dairy Milk, even though it was a bit flakier in terms of texture because of the layer by layer detail that you get from a 3D printer."

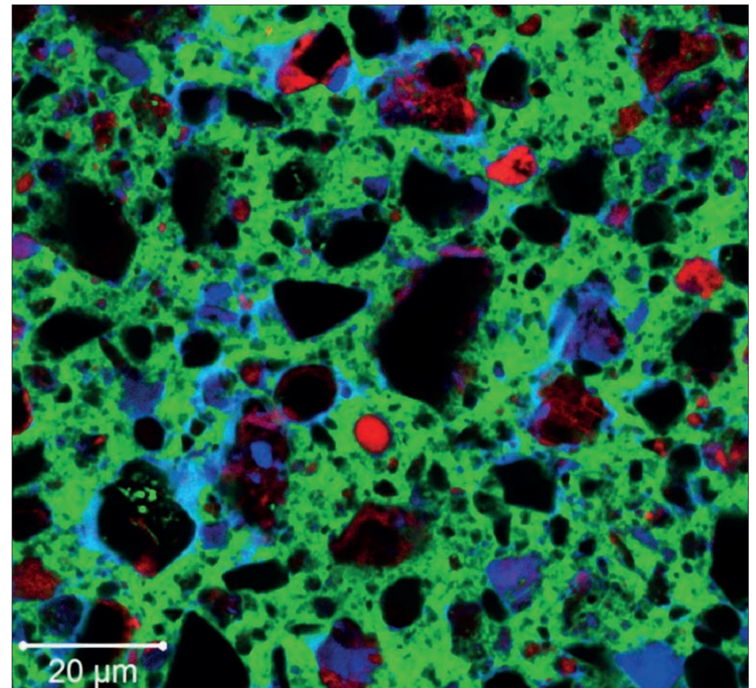
Standing two metres tall and 600 millimetres square, the printer was ready in time for World Chocolate Day 2019, and had a high-profile debut at Australian department store Myer. It produced eight identical chocolates at a time. Customers could select any one of 34 patterns, ranging from seasonal snowflakes and stars to Antipodean animals like turtles and kangaroos. The full alphabet was also programmed into the machine, which was Cadbury branded and equipped with a viewing window so people could watch the machine printing. "One thing that was important for a machine in a pop-up environment was that people could see it printing live," Nim points out.

The most vital attribute of the 3D printer was its ability to dispense chocolate without any deviation in taste, texture or consistency. Pending patents limit the RDQ team's ability to disclose how this was achieved, but Nim acknowledges the results have surprised many consumers: "One question we got asked a lot was whether we'd done anything to the chocolate to be able to print on the machine. The answer was no. We used standard chocolate, and consumers were surprised that it tasted like standard Cadbury Dairy Milk, even though it was a bit flakier in terms of texture because of the layer by layer detail that you get from a 3D printer."

AN ACQUIRED TASTE

It might come as a shock to British consumers, but chocolate recipes are often modified for different markets. Cadbury Dairy Milk in Australia tastes slightly different to its British sibling, in response to consumer preferences. However, it's critically important for every chocolate or bar produced in a specific country to deliver the consumer expectation of taste, texture and flavour. This is one of the areas Research Fellow Emma McLeod focuses on, and she acknowledges that customer expectations of quality standards impose stringent restrictions on product specifications.

The RDQ team uses cutting-edge technology to standardise the production process and the quality of its output, as Emma explains: "I currently lead a platform investigating how to bring more of these measurements online, so that we have real-time measurement of quality, rather than relying on infrequent sampling and after-the-event measurement. Once we have the online measurements, we can then enable better control of our processes using advanced control techniques. These quality standards are important as they ensure that we deliver our consumer promise on every bar, right first time." Ensuring that the systems work in real time requires a lot of design creativity.



Confocal microscopy image (an optical imaging technique for increasing optical resolution and contrast of a micrograph) showing the breakdown of ingredients in chocolate: fat (green), sugar (black), protein (red), and cocoa solids (blue) © Mondelēz International

SMOOTH OPERATOR

Taste and texture are critical to how consumers perceive chocolate. Ensuring that the notoriously tricky material remains completely smooth is a key quality parameter. "Consumers talk about chocolate being sandy or gritty if there are particles bigger than 30 to 40 µm," admits Emma. "However, if we go too fine, the chocolate can be seen as slimy. As a result, we refine our chocolate and measure the particle size distribution." This is a challenge, as the liquid chocolate is a suspension of particles in a fat continuous system. It has a high viscosity and engineers can't use the light-based methods that are used in other industries, as you can't see through the liquid chocolate. Handling liquid chocolate is a challenge in itself: "It is generally seen as a shear-thinning fluid, but the solids can sediment and the fat can start to crystallise." Keeping the molten chocolate moving and suitably warm is therefore essential while measuring its constituent elements, as well as helping to preserve its smoothness.

Smoothness was also a critical factor in developing a version of Cadbury Dairy Milk chocolate with 30% less sugar. Dr Ian Noble is a Senior RDQ Director and he explains how this ambitious target imposed several formulation and process engineering challenges. "During the product design phase, we had to produce the correct microstructure in the final product to deliver the correct sensory experience while also delivering the correct material transformations through each unit operation, from Cadbury's milk chocolate crumb through to the final packed bar. Removing such a large proportion of the solid phase of a product required extensive work to find appropriate replacement materials that don't impact the oral processing of the product. We had to replicate the texture, melt rate, aroma release, and ingredient dissolution to

Removing 30% of the sugar from a bar of chocolate meant extensive work to find appropriate replacement ingredients that didn't impact the taste or texture of the product © Mondelēz International deliver the Cadbury Dairy Milk chocolate product experience, using crystal morphology and final crystallisation process to deliver the required product microstructure."

Described by Mondelēz International as "the most significant innovation in the brand's history", the reduced-sugar milk chocolate reflects the challenges of calculating how raw ingredients can combine to achieve certain outcomes. According to RDQ Director Richard Bardsley, insights into how ingredients are structured or blended together help to build a greater understanding of how those ingredients deliver different taste and texture attributes: "When we can characterise the ingredient functionality more precisely within the actual product, it enables us to consider which is the most appropriate recipe combination, and which will deliver the best overall consumer experience. Increasing the manufacturing precision and complexity does give more formulation options, but there is always then a trade-off to consider in terms of the ingredient cost versus fixed asset cost."

This cost effectiveness is being achieved partly through greater automation, which has been an evolving process ever since the Bournville factory opened. Indeed, it has mirrored several industrial revolutions common to other manufacturing sectors. "Initially it used very basic mechanical

Greater automation has transformed the manufacturing process © Mondelēz International

power", says Richard, "before following the assembly line philosophy with automated machines." More recently, new high output manufacturing lines have been introduced. In the last five years, a significant transformation has occurred and now the majority of the Mondelēz International brands are produced on these new lines. This has improved productivity across the whole business, not just in chocolate processing. "The speed of these lines now requires a much higher use of automation for both the control and quality monitoring purposes. Products are moving so fast along conveyors that it's almost invisible to the human eye."

FOILED AGAIN

The production lines are a blur of activity nowadays thanks to greater automation, which has always gone hand-in-hand with new product development. "Cadbury's originally made drinking chocolate," Dr Noble points out, "then moved into making chocolate and the iconic Cadbury Dairy Milk. The journey has continued to this day as a fundamental part of our DNA. The wonderful diversity of food cultures around the world requires us to work closely with consumers to ensure that our products meet their expectations and taste buds, while also exploring heritage ingredients from around the world, including cacao pulp in our new CaPao products."

Next time you unwrap the foil from a newly-launched bar of chocolate, it's worth taking a moment to consider the years of research and development involved in bringing it to market.

BIOGRAPHIES

The following Mondelēz International staff had input into the article:

Dr Ian Noble is a Senior RDQ Director at Mondelēz International.

Dr Beccy Smith is a Principal Scientist in the Modelling and Simulation team.

Nim Mistry is a Senior Group Leader.

Emma McLeod is a Research Fellow.

Richard Bardsley is an RDQ Director.

DELIVERING FAST-TRACK COVID-19 VACCINES

Typically, it can take up to a decade to develop a vaccine. The COVID-19 pandemic has compressed timelines as groups around the world race to come up with a vaccine. Rachel Jones talked to Dr Donal Cronin FREng, formerly Head of Global Engineering at AstraZeneca, Martin Smith, Head of Manufacturing Sciences and Technology, and Chris Lucas, Chief Operating Officer, both from the Vaccines Manufacturing and Innovation Centre, about the engineering challenges of manufacturing and supplying a COVID-19 vaccine.

The COVID-19 pandemic has significantly impacted countries and people across the world. The race to find a vaccine is ongoing, with some projects publishing promising results from Phase III trials © Shutterstock

A CGI rendering of the eventual Vaccines Manufacturing and Innovation Centre (VMIC) site in Harwell, Oxfordshire. An important aspect of VMIC's work will be training new generations of engineers and technicians. Undergraduate and postgraduate industrial placements, continuing professional development and support for those mid-career will create opportunities not just in the UK but also in the international vaccines community © VMIC

The COVID-19 pandemic has already caused an estimated 1.3 million deaths and more than 200 groups around the world are working to develop vaccines to stop the virus's spread. With the molecular blueprint of the virus published in January, phases of development that normally take years have been overlapped in the push to deliver a vaccine as soon as possible. Leading candidates include a project backed by the University of Oxford and AstraZeneca, which takes a 'viral vector' approach that uses a virus to carry the vaccine into the body. Two vaccines currently leading the race, developed by Pfizer/BioNTech and US biotech firm Moderna, are reported respectively to show 90% and 95% protection. Both use an mRNA approach, with 'messenger' ribonucleic acid (RNA) – sets of instructions for cells to make proteins – preparing the immune system. Imperial College London is taking an alternative approach, using self-amplifying RNA to produce copies of itself that can instruct cells to make the coronavirus protein.

ADDRESSING THE TASK

Establishing vaccine manufacture and supply is a complex task, with governments, industry and other stakeholders working together to share risks and costs. In the UK, pandemic-related shortages and delays are presenting new challenges alongside a backdrop of a gradual decline in UK vaccines expertise and manufacturing capacity. Developing vaccines has low profit margins and, as vaccines are given to healthy people, the regulation process is especially stringent.

The Vaccines Manufacturing and Innovation Centre (VMIC) has set up a temporary rapid deployment site to provide extra capacity to develop and manufacture vaccines. VMIC is a not-for-profit vaccine manufacturing organisation established by the University of Oxford, Imperial College London and the London School of Hygiene and Tropical Medicine, and largely funded by UK government. Its main site at the Harwell Science and Innovation Campus in Oxfordshire will open in mid-2021. It will develop and manufacture vaccines that need differing approaches, including production to take candidate vaccines up to large-scale manufacture.

VMIC has established a temporary site in Oxford, in collaboration with gene therapy firm Oxford Biomedica, to become one of the producers of the Oxford/AstraZeneca vaccine. A 'virtual VMIC' comprises two manufacturing suites approved by the necessary regulatory bodies.

A RISK-BASED APPROACH

Investing in manufacturing processes during clinical trials means that vaccine developers are ready to ship sufficient quantities as soon as a vaccine receives regulatory approval. Clinical trials begin with a small study of healthy people to evaluate safety and immune responses at varying doses (Phase I). The trials then progress through larger safety and efficacy studies (Phase II). The vaccine is studied in thousands of people (Phase III). A regulatory review of the results by the Medicines and Healthcare products Regulatory Agency (MHRA) in the UK follows. However, this step can take place after manufacturing begins but there is no guarantee of efficacy or approval. "I would expect the regulators to know about trial progress and outcomes as they occur so they can carry out a rolling review," says Dr Donal Cronin FREng, an engineering and safety consultant and formerly head of AstraZeneca's global engineering and technology organisation. "When final data from the trial are available, the regulators can then complete approval processes quickly."

If approval is delayed, a vaccine made in bulk may go to waste; conversely a vaccine could be approved before there is time to make enough product. Ideally, a candidate vaccine is manufactured in bulk during trials, wins approval, and is then distributed widely. Groups putting vaccine candidates into production will take a risk-based approach. The bigger the risk level – or, in this case, global need – the sooner production begins. In some cases, the need is so high that large-scale manufacture begins in parallel with Phase I trials. Depending on manufacturing approach, technology and scale, the time taken to produce batches can vary considerably, as can the quantities of vaccine produced. Supply chains will be primed as soon as approval comes, with tens of millions of doses – made 'at risk' prior to approval – ready to be released.

DIFFERING PLATFORMS

The first vaccines to be approved may be the most welcome, but they may not remain the most effective. "The COVID-19 virus is slow to mutate but any group would be remiss if it wasn't looking at this issue of mutation," says Dr Cronin. AstraZeneca's viral-vector platform may be the focus for the UK's virtual VMIC but no-one knows which winners will emerge in the long term. To cater for different vaccine platforms, VMIC's main Harwell site is "technology agnostic" and can use different technologies to solve different problems.

VMIC anticipates being able to work at laboratory and intermediate scale on any major vaccine platform. Martin Smith, Head of Manufacturing Sciences and Technology at VMIC, explains that the facility is preparing to work on as many platforms as possible. "Engineers are trained in lateral thinking, how to best appropriate one technology for another purpose… The challenge lies in choosing and installing the most appropriate and flexible equipment that will allow us to do rapid process development, and robust and flexible manufacturing across the scale."

VMIC is receiving support in kind from pharmaceutical companies including Janssen Pharmaceuticals, MSD Ltd, and Cytiva Ltd, and will work closely with industry, to leverage understanding of currently available production technologies. Transfer of processes is another challenge, as companies may possess equipment with differing characteristics. The key to responding rapidly to outbreaks of disease, such as the current pandemic, lies in understanding these differences and assessing risks when scaling processes 'up' (in volume) or 'out' (into multiple bioreactor units, which carry out a biological reaction or process on an industrial scale). Some risks can be addressed through small-scale experimentation such as mixing studies – analysis of flow patterns resulting from mixing within a bioreactor to ensure sufficient mass-transfer is available without harming delicate cells. These may be needed for different types of bioreactors.

Cutting complexity will help to reduce risk, says Smith – and this is made easier by having all operations on a single site. "We not only have process development for the design of the manufacturing process, but we can transfer that technology and remove bottlenecks. All functions are under one roof with a mapped out end-to-end process." VMIC can add value, he says, in its "complete understanding of the value chain, from raw material to the filled vial". The Harwell site will make vaccines in bulk and fill vials in one facility, using the same personnel, quality management system and warehousing, removing risk by reducing interfaces and interactions that take time and add complexity.

Bioreactors are an example of the specialist manufacturing equipment the VMIC has purchased for its virtual VMIC facility, such as these Allegro™ STR bioreactors 50 L and 200 L © Pall Corporation

PRODUCTION

Production processes are an important factor in the development and manufacture of any vaccine. They are also subject to regulatory control. Any alteration to the manufacturing process has implications for product quality. There are numerous variables in any production process, including time, temperature and agitation conditions. To manage these, the production process must be recorded and understood thoroughly. Developers must implement production controls, and all equipment and services must be well defined and validated.

Registered production processes must then be replicated exactly in full-scale production. "When a manufacturer establishes production at larger scales to meet demand, it cannot modify a purification technique or substitute a raw ingredient without retesting or re-approval," says Dr Cronin. "From a medical point of view, any deviation could introduce the risk of producing a slightly different product. Manufacturers must be true to the original process or face going through the approval process again. This ties your hands in some respects but calls for greater ingenuity to meet increasing demand."

To make fast-track vaccines, manufacturers will overlap normally sequential activities. Production begins with generating an antigen to create an immune response. Viruses can be grown in primary cells such as chicken eggs or on continuous lines of host cells recognised for their ability to grow and develop various biomedical species. Recombinant protein (where genetic material comes from multiple sources in a lab), deriving from viruses or bacteria, can be generated in yeast, bacteria, or cell cultures.

A production-scale single-use bioreactor is essentially a multi-layer, disposable plastic bag, produced in sizes up to 5,000 litres. This sits in a frame that rocks to produce a gentle wave, with the surface resting on a heated plate to control temperature. In viral production processes, the ability to create a fast turnover of product batches means single-use products can maximise output and reduce investment. The removal of certain utilities means a smaller area for production is required and a simpler process.

For COVID-19 vaccines, single-use technologies will create flexible, agile, accessible manufacturing. Dr Cronin predicts that most companies will use this approach for cell growth and harvesting. With preparation for production of vaccines on a mass scale, there could be a shortage of disposable technology. "Everyone will be looking for single-use tubing, bioreactor bags, and all the paraphernalia to regulate and control temperature and other manufacturing parameters."

Vaccine manufacture will consist of automatic packaging machines such as this for packaging ampoules with vaccine, injection and medical drugs
© Shutterstock

Once generated, the antigen is isolated from the cells used to generate it, and then purified. The desirable component is usually extracted through centrifuging, sometimes followed by other separation techniques. Chromatography may then be used as a separation process to remove impurities. The purified antigen is then combined with adjuvants, stabilisers and preservatives (and perhaps emulsified) to form the final preparation.

Typically filled in single-dose or multi-dose vials, a vaccine preparation is freeze-dried and sealed, removing water to leave a powder that can be dissolved into liquid again. Freeze-driers are complex items with a finite number of suppliers, so obtaining these could represent another challenge, says Dr Cronin. "You might be looking at a lead time of 16 months for them." In some instances, bulk vaccine is supplied in liquid form to dispensaries, with small volumes taken off for daily clinics. This needs a less complex manufacturing process, but the vaccine may have a shorter shelf life and may involve a more demanding supply chain.

SUPPLY CHAIN PRESSURES

Pressures on supply chains for equipment and components have increased during the pandemic. Strategic decisions on supply chain, such as locations and personnel for manufacturing, formulation, filling, and final packing, and for transportation and distribution, need to be made well in advance before a vaccine candidate reaches formulation and packaging. One option is to locate manufacturing formulation and packing in one place and set up global supply chains to deliver vaccines. A single centre of expertise may help control quality and compliance but a centralised model carries risks, says Dr Cronin. "It's likely to be highly complex, lack agility, and create variable delivery times to get the vaccine to end points." For example, if an entire global supply comes from one source, delivery to adjacent countries is likely to be much faster than to countries on the opposite side of the world (taking into account travel time, multiple customs clearances, and so on), which will affect shelf life and stability.

VMIC's permanent facility at Harwell will establish processes to manufacture up to 70 million doses of a pandemic vaccine within four to six months, with specified and procured filling and packaging lines. "Our filling lines are technology agnostic," says Chris Lucas, Chief Operating Officer at VMIC. "We will formulate a drug substance to the right presentation and send it to the filling suite to be put into vials and passed to a packaging line. From there it can be sent on for distribution."

Dr Cronin believes producers will create in-region or in-country distribution hubs, with vaccine products sent from factories to logistics partners offering temperature control warehousing and guaranteed security. From there, once local drug administration authorities give final approval, the vaccines will flow to governments and private entities, such as charities and private healthcare.

QUALITY CONTROL AND SECURITY

Distribution is the next step. Quality control and assurance tend to be well-established and well-resourced processes in major pharma companies. For every five people involved in production, one will be in quality management. "Together with analytical specialists, this tends to be the most intensively staffed part of the production chain," says Dr Cronin. Quality assurance culminates in batch release, with doses dispatched into the distribution chain. Warehouses, lorries and transfer procedures then need to retain products within a carefully controlled temperature range.

Irrespective of how the vaccine is supplied, development consortia must ensure supply chain integrity, not just security of supply but security of the chain itself. COVID-19 vaccines will need protection to prevent theft from the supply chain and to stop copying, substitution or adulteration that not only threaten patient health but also threaten the manufacturers' finances and reputations. Covert security features and overt features on packaging, such as 2D barcodes and holographics, can help ensure integrity. A vial's barcode could enable it to be traced to a particular batch made on a particular day, with records and release data to verify this. Aggregated packs of vaccines, transported by lorry, will be fitted with radio-frequency identification devices to convey not just consignment data such as temperature and vertical orientation, but also where the vehicle is. This enables checks on deviation and disturbance.

A MARATHON, NOT A SPRINT

Despite the effort going into developing and producing effective vaccines, it's possible their safe shelf life could prove too short. Many biological preparations become unstable during storage, so typical vaccine development will involve taking product from the first production and putting it on stability trials for two years. With compressed timelines, these trials are taking place in parallel with other activities. Early samples are being monitored for degradation, while accelerated stability trials involve storing the product in variable formats with variations in temperature and humidity. Another critical engineering challenge for manufacturers is to generate and maintain these atmospheric conditions but, as Dr Cronin notes, "it's only from this sort of work that we will get shelf-life data".

As the global community reacts at an unprecedented pace to this challenge, Dr Cronin commends companies and academic institutions for the way they are working at speed and forming creative collaborations to pursue the discovery, development and manufacture of vaccines – despite having no guarantee of success. "It is testament to the leadership of these organisations and the professionalism and ingenuity of their scientists and engineers."

HOW DO VACCINES WORK?

Vaccines work by training our bodies to recognise and respond to proteins that are produced by disease-causing (pathogenic) organisms, such as viruses or bacteria. When weak germs are injected into the body, the portion of the pathogen known as the antigen trains the immune system to respond to infection by creating antibodies. Of 236 vaccine candidates being developed for COVID-19, some take traditional approaches to vaccine development, using inactivated virus or attenuated pathogens. Another popular approach uses part of a virus rather than the whole virus. Some projects employ a virus-like non-infectious particle that cannot replicate and contains no viral genetic material, offering a safer alternative to attenuated virus.

Typically, a vaccine contains an antigen or adjuvant that provides immunity against a disease. Antigens are obtained from the structure of disease-causing organisms: the immune system recognises these as 'foreign', triggering a protective immune response to the vaccine. Adjuvants are added to vaccines to stimulate the production of antibodies against the vaccine to make it more effective. A vaccine will also contain: preservatives and stabilisers to keep the vaccine safe and stable; production materials such as cell-culture material; antibiotics like neomycin to help stop outside germs and bacteria growing in the vaccine; and inactivating material such as formaldehyde, which can weaken or kill viruses, bacteria or toxins in the vaccine.

In manufacture, creation of a validated and reproducible production process – a basic requirement for any regulated medicine – is the overriding challenge. Essentially, this means that all ingredients must be characterised, registered, available, and procured at a reproducible and defined standard.

BIOGRAPHIES

Dr Donal Cronin FREng is an engineering and safety consultant to several leading pharmaceutical, bio-pharmaceutical, and chemical companies in Europe, Asia and North America. He has held a wide range of leadership roles in process development, operations and engineering. Most recently he was Head of Global Engineering and Technology in AstraZeneca.

Martin Smith is Head of Manufacturing Sciences and Technology at the Vaccines Manufacturing and Innovation Centre.

Chris Lucas is Chief Operating Officer at the Vaccines Manufacturing and Innovation Centre.

The editors would like to thank Dr Rosie Dobbs for her help in putting together the abstract for this article.

INTELLIGENT WEED CONTROL


A Garford Robocrop in-row automatic hoe system operating with two-metre wide sections – these are matched to the width of the drill or transplanter

Weeds are plants out of place. When they grow within crops they compete for light, nutrients, moisture, and space, and can often reduce crop yield and quality of the plants that are being farmed. Dr Paul Miller FREng spoke to Dr Nick Tillett, Director of Tillett and Hague Technology, about the advances that are allowing farmers to control weeds using less chemicals.

Some weeds are also now resistant to previously effective herbicides and there is limited new chemistry to rectify this, partly because of the high development costs and constraints relating to environmental and human safety

For farmers, weeds may be plants that we widely recognise as weeds, such as thistle or dock plants. Or they might be otherwise useful plants that are self-sown from previous seasons and considered weeds, known as volunteer crop plants. Weeds growing within field and horticultural crops compete for light, nutrients, moisture, and space, and can often reduce crop yield. The presence of weeds can also make harvesting difficult and they can contaminate the harvest, for example with seeds or leaves.

Traditionally, farmers have controlled weeds by hoeing, cutting the growing unwanted plant just below the soil level. This operation used to be conducted manually, and still is by gardeners and a few very small-scale specialist growers, using a range of bladed implements for the task. However, manual hoeing is slow, physically demanding and requires concentration to distinguish between crop and weed and to ensure that the required number of crop plants remains in each area. When hoeing, it is important that the largest area possible is covered while the conditions are favourable – dry conditions are best, as there is much less opportunity for weeds to regrow. It is also important to kill the weeds early, before they compete with crop plants, which is easiest when they are small and at an early stage of growth.

In the era of modern farming, most weed control has used selective herbicides applied to crops as water-based sprays or to the soil as granules. This has been sufficient, timely, cost effective, and can be achieved with relatively low levels of labour. It has generally controlled weeds well, with only small effects on crop plants. However, the potential unintended effects of herbicides on the environment (on plants, animals and birds), human health, and water supplies has caused concerns.

Farmers and growers are increasingly finding it harder to buy appropriate herbicides, as obtaining approval for developing and using them is difficult, which also increases the cost of development. For some high-value vegetable crops, the choice of selective herbicides is now severely limited by regulations. Some weeds are also now resistant to previously effective herbicides and there is limited new chemistry to rectify this, partly because of the high development costs and constraints relating to environmental and human safety. There is therefore real pressure to find alternative sustainable and cost-effective ways of controlling weeds.

AUTOMATED HOEING

The first approaches to replacing manual hoeing involved mounting fixed hoe blades on a tool bar, a frame that is supported on a vehicle, which then moves through the crop with blades on the bar removing weeds from between rows. Steering the hoe blades in this situation is critical: the blades need to be within 25 millimetres of the crop plants. Weeds closer than that are likely to be out-competed by the crop and die away. It can be hard to achieve this level of accuracy while operating a vehicle, so farmers often hoed further away from the crop than was ideal, leaving a wider untreated area with a greater risk of weed competition close to the crop. One way to improve accuracy was to use a second operator who steered the tool bar separately from the vehicle. However, this increased costs, could only be done at relatively slow speeds and was difficult to carry out, particularly over extended periods as operators got tired and made mistakes.

There were several challenges that needed to be solved to make automated hoeing a viable option including: identifying small crop plants in the presence of a weed canopy; operating in variable light conditions, such as shadows of the vehicle and tool frame; being robust enough to operate reliably in relatively harsh environments and with staff skilled in operating farm equipment; and matching hoeing systems to the spacing arrangements used to plant the crop.

Recent technological advances have enabled automated hoeing to become a reality. Steering has been improved by using high-resolution satellite navigation systems mounted on the toolbar, alongside a hydraulically actuated side-shift to position hoe blades similarly to the seed drill when they were planted. However, using the crops themselves as a reference for steering the blades has proved to be a more robust approach. In 2001, British company Garford Farm Machinery Ltd launched its Robocrop precision-guided hoe using a vision-guidance system developed by Tillett and Hague Technology Ltd, another

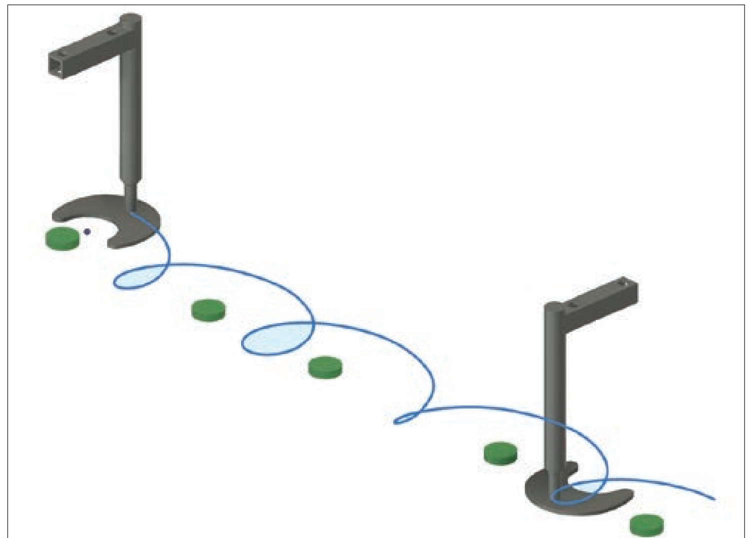
Three tractor-mounted 6-metre wide sections of vision-guided hoe and (inset) the control and monitoring system for the machine

British company. This system can operate speeds of up to 12 kilometres an hour and while remaining within 10 millimetres of the crop row. One of the advantages it has over a human operator is that it can maintain this performance consistently throughout the working day.

Vision-guided systems use forward-facing cameras to collect sequences of images. An onboard computer system then analyses the images to identify crop rows and their position on the ground, and steers the hoe blades in response. The operator can see performance information on a console mounted in the vehicle cab, which shows the images collected, row positions and the actions being taken to steer the hoe blades. This on-screen information directs them to drive the machine down the crop rows, control the forward speed, and monitor the system's performance.

REMOVING WEEDS FROM CROP ROWS

Some crop plants are competitive enough to suppress weed growth when spacing between plants in the row is relatively small. However, when plants are more widely spaced, for example for growing lettuce, cabbage, cauliflower, and sprout crops, weed growth needs to be controlled. Once the position of the crop row has been established, the onboard computer can analyse the images to determine the positions of plants within the row based on the expected spacing and likely characteristics (size, shape and colour) of the plants. The machine can then hoe the region between plants: the Tillett and Hague in-row weeding system uses a hoe blade that is rotated in a cycloidal pattern (see image on right) that is matched to the detected spacing by varying the speed. This enables the system to remove weeds within the row and adjust the path so that the blade goes around the crop plants. Hydraulic or low voltage electric motors control the rotation, which can treat up to six plants per second in each row.



A diagram of the cycloid hoe path

SPOT SPRAYING

In some crops, the presence of large individual weeds, for example volunteer potatoes in crops of onions or carrots, can cause substantial problems that are difficult to address with either hoeing or selective herbicide sprays. Large weeds can sometimes establish much more quickly than the crop, making them hard to treat with hoeing without damaging the crop. The same image-analysis approaches, used to find rows and control the mechanical hoe, can be used for spot herbicide sprayer systems. These identify the position and size of 'large' weeds using the position within the crop row, colour, shape, and size within the captured images. The system can then target the spray at the detected weed only.

Field trials with commercial prototypes have shown that this system removes more than 90% of weeds with less crop damage than any alternative options, including manual treatments.

Spot sprayer weed control is a good example of the strategies that can be implemented with vision-guided systems. Spraying a total herbicide (one that kills all plants) risks damage to neighbouring crop plants through drift and splash, which can be adjusted within a vision-guided system's control algorithm. The perimeter of a detected weed is defined by a polygon within the algorithm. Specialised nozzles mounted in a linear array across the machine then identify the area and spray it.

Some herbicides do not require the full area inside the polygon to be treated to achieve weed kill. In those cases, the risk of drift and splash on to neighbouring crop plants can be reduced by only switching on the minimum of nozzles required to achieve the required percentage cover. For example, it might only be necessary to turn on nozzle two to achieve adequate treatment. Alternative strategies could apply selective herbicides to the full area that the machine detects, since drift or splash on to neighbouring crop plants would not result in high levels of damage. Herbicide usage would still be reduced by typically more than 95% when compared to traditional overall application.

A spot sprayer working in a crop of onions to treat volunteer potatoes – a difficult weed in this crop. The tractor is steered with GPS but the vision system positions the spray nozzles relative to the crop

COMMERCIAL USE

Over the past 25 years, research and development has explored ways of controlling weeds that are less reliant on herbicides. These approaches have included methods based on improved targeting of herbicides, for example by using directed laser beams and high voltage discharges. However, few have been commercially successful or competitive in terms of cost, safety, efficacy, and work rate. Systems using vision-guided hoeing are now well established commercially: for example, Tillett and Hague Technology Ltd sells more than 500 control systems a year to 15 equipment manufacturers worldwide – with most of the automated hoeing units being used outside the UK. The technology is making a substantial contribution to establishing sustainable and environmentally friendly approaches to food production.

An example of a spot-treated volunteer potato in a crop of carrots: top – before treatment; bottom – after treatment. There is relatively low damage to the crop – the area where the weed was growing has been influenced by the competitive effect of the plant rather than the treatment

BIOGRAPHY

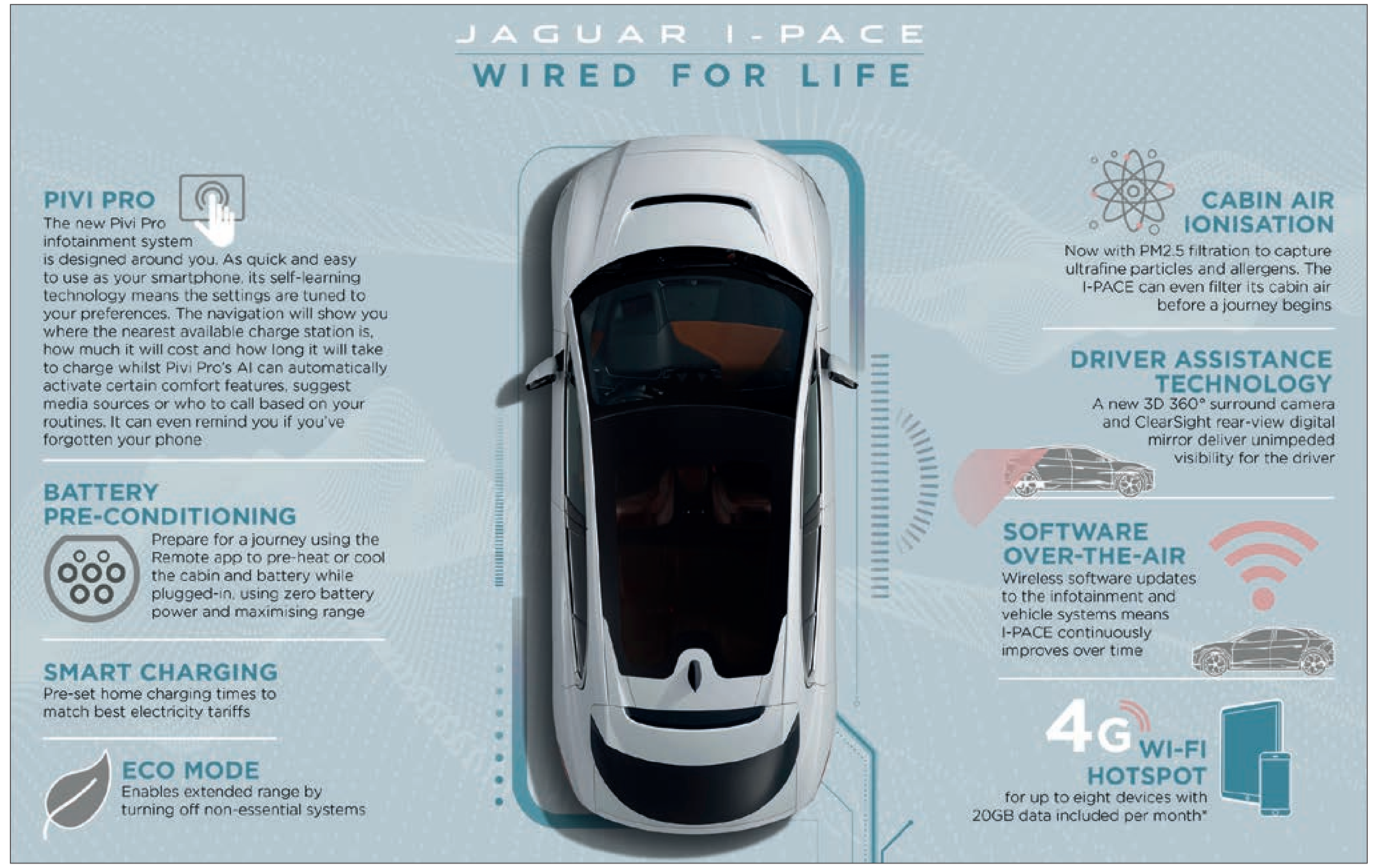
Dr Paul Miller FREng was Technical Director at Silsoe Research Institute in Bedfordshire until its closure in 2006. After a period of working as a Specialist Advisor for the National Institute of Agricultural Botany (NIAB) and as secretary to the Douglas Bomford Trust, in 2016 he was involved in setting up Silsoe Spray Applications Ltd where he is now the Technical Director.

Dr Nick Tillett spent five years in manufacturing industry before joining Silsoe Research Institute to work on projects ranging from robotic milking to mechanical weeding. In 2005, he formed Tillett and Hague Technology with Dr Tony Hague.

The I-PACE is Jaguar's first all-electric vehicle © Jaguar Land Rover

CHARGING INTO THE FUTURE

The all-electric Jaguar I-PACE has collected many awards since it first left car showrooms in 2018, including its engineering team being recognised as MacRobert Award finalists. Michael Kenward CBE spoke to Jaguar Land Rover's Stephen Boulter, Vehicle Engineering Manager for I-PACE, and Nick Rogers FREng, Executive Director Product Engineering, about the challenges of developing the company's first electric vehicle.



As one of the engineers leading the team creating Jaguar's first all-electric car, Stephen Boulter likes to demonstrate the vehicle's impressive acceleration. Driving the I-PACE into the Jaguar Land Rover (JLR) engineering centre at Gaydon, Warwickshire, Boulter warns to "hold tight" as he demonstrates the car's performance. Started as a research programme in 2013, the company's engineers set out to learn about battery electric vehicles (BEVs) and pave the way for engineering future electric models. In addition to the conventional combustion engine and a fully battery electric vehicle (BEV), most of JLR's models are available in 'mild' and plug-in hybrid versions, combining batteries and internal combustion engines. JLR started the electrification of its range with the Range Rover, which was the first hybrid, followed by several other Jaguar and Land Rover vehicles including, most recently, the Jaguar E-PACE plug-in hybrid.

From 2020, all new Jaguar and Land Rover vehicles are electrified, including the new Jaguar E-PACE and F-PACE.

EVOLUTION OF ELECTRIC

As vehicle engineering manager for the I-PACE, Boulter led a team that included around 400 engineers at its peak, who were drawn from many disciplines, including some not previously involved in car design. The engineers set out to create a BEV that would live up to customers' expectations of the famous marque. Nick Rogers, Executive Director – Product Engineering at JLR, describes the task as "quite a challenge". When designing an electric vehicle, it is not as simple as taking batteries and electric motors as

JLR describes it as a 'multi-physics' approach: bringing together different types of expertise to create a working solution. The engineers had to develop their own simulation tools and models

alternatives to a fuel tank and an internal combustion engine and installing them in a chassis. "It is not individual pieces of technology, it is actually the integration of a series of systems," says Rogers.

The move into electrification followed another revolution in JLR's approach to sourcing propulsion units. Instead of buying internal combustion engines, in 2011 the company announced that it would build a new generation of diesel and petrol engines for the clean combustion era. This resulted in the Ingenium range of engines, a MacRobert Award finalist in 2016 ('MacRobert Award 2016', *Ingenia* 67). JLR invested more than £1 billion in a new Engine Manufacturing Centre near Wolverhampton, only to see the whole idea of diesel engines thrown up in the air. After encouraging motorists with tax incentives to buy fuel efficient diesel engines, the UK government quickly changed course. Diesels went from hero-to-zero almost overnight, forcing the car industry to rethink its approach.

JLR decided to accelerate its electrification plans. In future, all new models will be electrified with some combination of mild hybrid, plug-in hybrid and BEV variants, including both petrol and diesel hybrids. JLR had anticipated the need for 'electrified engines' when it built the new engine plant: the Engine Manufacturing Centre also houses the assembly of electric drive units.

LEARNING CURVE

The engineers creating the I-PACE also had to devise a fresh approach to creating new models. At first, they didn't have the usual five-year gestation period for a new model. Rogers described the I-PACE as not just a product but "an ongoing R&D project". The engineers didn't know exactly what they were putting together when they started work: the team couldn't draw on its new diesel factory for an engine; and the engineers didn't know what the batteries would look like when they began work on a chassis to hold them.

The change of gear also meant calling on different branches of engineering, including some that were relatively new to the car maker. As the MacRobert Award judges noted, battery technology, heat-pump technology, electric drive units, and the hardware and software control systems are different disciplines from those required for vehicles built around an internal combustion engine.

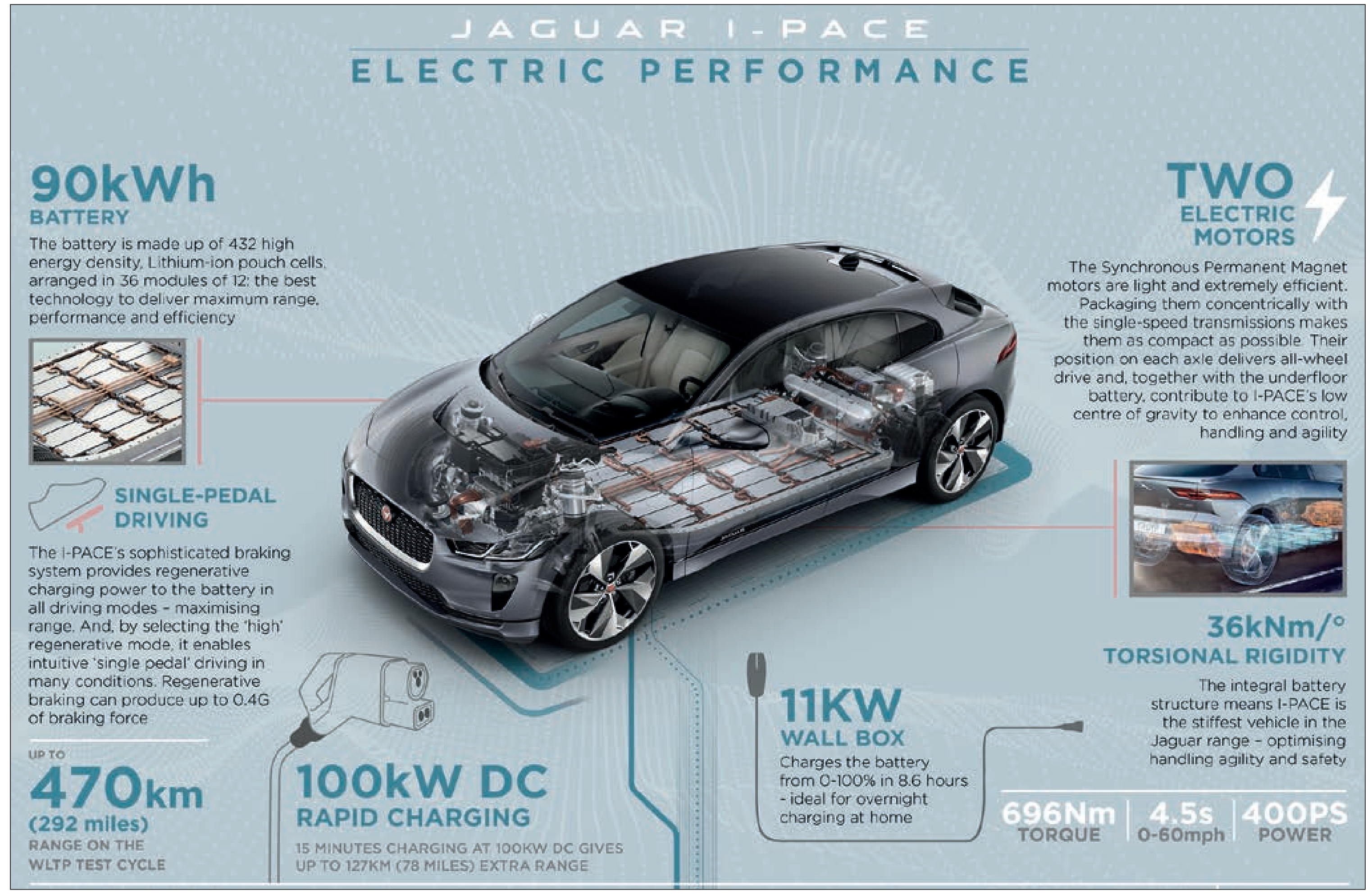
Battery technology was one of the key innovations in the I-PACE. Of all the systems involved, the battery sets the pattern for the rest of the vehicle. The car's power comes from 432 lithium-ion nickel cobalt manganese 'pouch cells'. Arranged in 36 modules, the cells can store 90 kWh of energy, enough to propel the I-PACE up to 470 kilometres (Worldwide Harmonized Light Vehicles Test Procedure).

JLR could draw on LG Chem for pouch cells, but it needed to decide how to bring them together and control their output for optimum performance and safety. JLR describes it as a 'multi-physics' approach: bringing together different types of expertise to create a working solution. The engineers had to develop their own simulation tools and models. Here, too, the systems approach was important. The engineers worked closely with their suppliers and internal teams to create a system that monitored and controlled each pouch cell. This is the key to delivering an optimised thermal strategy and developing the heat, ventilation and air conditioning (HVAC) system among other things.

THERMAL MANAGEMENT

The thermal strategy set the pattern for the development of customised heat-pump technology. Whereas internal combustion engines can provide heat to keep passengers comfortable, batteries are responsible for powering the vehicle's heating mechanisms. It took a significant R&D effort on the part of JLR's engineers to develop and verify the complex thermodynamic models needed to address these challenges. The work involved modelling scenarios of the vehicle operating in a range of different external temperatures. For example, batteries are famous for losing power as the temperature falls and JLR's engineers wanted to create a car that could deliver as near as possible its rated range in very cold weather.

The answer to thermal management of the I-PACE was to develop a heat-pump system with a coolant that collects ambient and waste heat, from the vehicle's electronics as well as the batteries and motors. This coolant is then compressed to raise its temperature and to control the temperatures of the battery and the car's cabin. Waste heat extracted from the battery can also then be used to heat the cabin. This reduces the battery power needed for the HVAC system by a factor of three, improving the vehicle's range. JLR's thermal management engineers also



developed controls that adapt to the number of passengers in the vehicle.

SHARING KNOWLEDGE

When it came to finding electric motors for the I-PACE, JLR did not have to start from scratch. It drew on its experience as a part of EVOKE, a major Innovate UK programme that ran between 2014 and 2016 to develop a plug-in hybrid vehicle. EVOKE brought together suppliers and researchers with expertise in electrical motor design to investigate concepts based on permanent magnet motors. The R&D programme did not develop a usable electric motor, but it did put JLR's engineers on the right path and gave them the confidence to develop their own motors for the company's first series-production BEV.

The engineers took a novel approach to the winding geometry for the magnets in the pair of electric motors that power the I-PACE. Other companies were working along similar lines, but JLR was the first to put a particular type of 'hairpin winding' into production, allowing a higher 'copper fill', which gives careful control of the magnetic flux in use. As a result, the motors have a better power density and more consistent characteristics than traditional permanent magnets. The result is a light synchronous permanent magnet motor that can be up to 97% efficient, resulting in a total system efficiency that is more than double that of the best combustion engines.

The positioning of the electric motors also adds to the car's performance. Packaging the motors concentrically with single-speed transmissions makes them as compact as possible. The position of the motors on each axle delivers all-wheel drive. Together with the underfloor battery, the positioning of the motors contributes to the I-PACE's low centre of gravity. This enhances the car's control, handling and agility, essential characteristics that Jaguar drivers expect.

The fourth key innovation the MacRobert Award judges considered were the all-important software and control systems in the I-PACE. Much of this work, with 250,000 lines of code, is covered by 17 patents. JLR's in-house software development for the powertrain supervisory control software and systems, now a team of 120 people, dates back to 2006. JLR's decision to develop a BEV created new challenges for the software engineers, not least in squeezing every kilometre possible out of a battery charge. One development that sits firmly in BEV territory is the motor's torque control systems for acceleration and deceleration. This can avoid the need for conventional brakes or the need to use a brake pedal, although the I-PACE does have a foundation braking system.

Torque control is commonly used in cars to control the operation of four-wheel-drive on slippery surfaces and for control when driving uphill or downhill. In an electric vehicle, torque control also plays a large part in the braking system. As the car slows down, the motors recharge the battery to such an extent that the I-PACE rarely needs to use friction braking. Regenerative braking, which can decelerate at up to 0.4 g, accounts for almost all braking events. This doesn't just save energy; more than 90% of braking events in daily use can be achieved through regenerative braking alone, improving driver comfort and reducing particulate emissions from the braking system.

CHARGE AND CONTROL

Battery use is at the heart of any electric vehicle, with efficient and economic use of electricity as important in charging as it is in consumption. The system can schedule overnight charging when connected to an 11 kW wall box, it can achieve up to 53 kilometres (33 miles) of range per hour, while a full charge from empty takes only 8.6 hours. A quicker 15-minute top up at 100 kW DC can give an extra driving range of up to 127 kilometres (78 miles).

The I-PACE has a suite of smart range-optimising technologies. For example, when plugged in before a journey, the I-PACE can use mains electricity to raise (or lower) the temperature of the car's battery, as well as the cabin, to maximise range. The software can even pick a route that also maximises the car's range.

The critical nature of the control systems, and the need to ensure safety, means that all software undergoes extensive and rigorous testing to cover all anticipated faults. This complies with the highest level of current industry standards. The vehicle also incorporates a parallel software watchdog system, which independently monitors vehicle operation.

RECOGNITION

As the MacRobert Award judges saw it, JLR faced particular business challenges when setting out to build electric vehicles. Unlike startups created to design and make electric vehicles from scratch, established car makers cannot tear up existing financial models. Alternatively, they can draw on proven technologies, with no need to reinvent the wheels, but they also must resist the temptation to draw too heavily on them. The judges were impressed by the engineering team's integration of a significant portfolio of state-of-the-art technologies into the I-PACE, with much of that technology developed in-house. Even more impressive is the overall integration of these to produce, in the UK, the world's first premium battery electric SUV.

The engineers who judged the MacRobert Award were not alone in appreciating the combination of innovations that went into the I-PACE. The car also appealed to the judges at several motor industry events. It was the first vehicle to win three categories in the same year at the World Car Awards in 2019: World Car of the Year, World Car Design of the Year, and World Green Car.

The technologies that drive the Jaguar I-PACE © Jaguar Land Rover

BIOGRAPHIES

Stephen Boulter is Vehicle Engineering Manager at Jaguar Land Rover. He built his first electric motorcycle at the age of 13, using a starter motor from a Land Rover and a battery from a mobility scooter. Stephen studied engineering at university, and then led the engineering of the Jaguar I-PACE.

Nick Rogers FREng is Executive Director Product Engineering at Jaguar Land Rover. He has 37 years' experience in the automotive industry. Starting as a technician apprentice, Nick now leads Jaguar Land Rover's global engineering operations. He encourages technical curiosity and disruptive innovation throughout his whole team.

HOW TO KEEP A SOCIAL DISTANCE

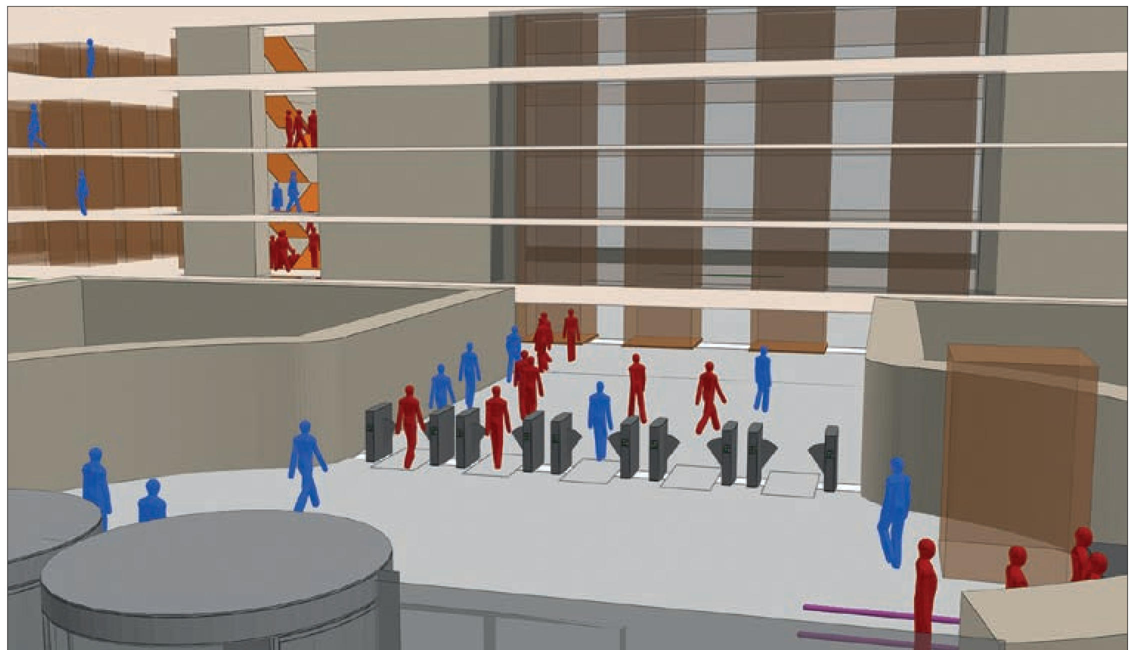
No-one knows exactly how long the coronavirus pandemic will be with us. How can we implement social distance policies into the operations of buildings and facilities now? © Arup

As COVID-19 continues to have impacts across the world, Arup has adapted its established MassMotion software to help clients reconfigure their buildings for a cautious return to work, including appropriate social distancing. Writer Hugh Ferguson talked to Arup engineers Lachlan Miles, Product Director for MassMotion; Alan Dunlop, associate leading the NHS project; Paul Lynch, Arup Advanced Digital Engineering; and architect James Ward, Arup Space Explorer, about the technology and its applications.

As the world plans for a new form of post-pandemic normality, operators of buildings – whether airports or rail stations, offices or malls, hospitals or schools, sports stadiums or art galleries – are reassessing how they can operate safely and efficiently with COVID-19 still in circulation.

There are many factors they must assess, including the wearing (or not) of face masks, more rigorous cleansing regimes, touch-free devices, ventilation systems, home working, and staggered working hours. However, the single issue that emerges as the most urgent in all countries is the maintenance of appropriate social distancing, whether 1 metre, 1.5 metres or 2 metres depending on location and the level of restrictions in place at any time.

Many businesses and organisations worldwide have returned to work in limited numbers and plan to ramp this up when conditions allow. But there are many questions to answer first: how do they expand occupancy safely? How many people is a safe number? How close together can they work? Decisions can be made by rule of thumb, but it would be more efficient to have a simple tool that could test alternative strategies and layouts based on data and an understanding of human behaviour.

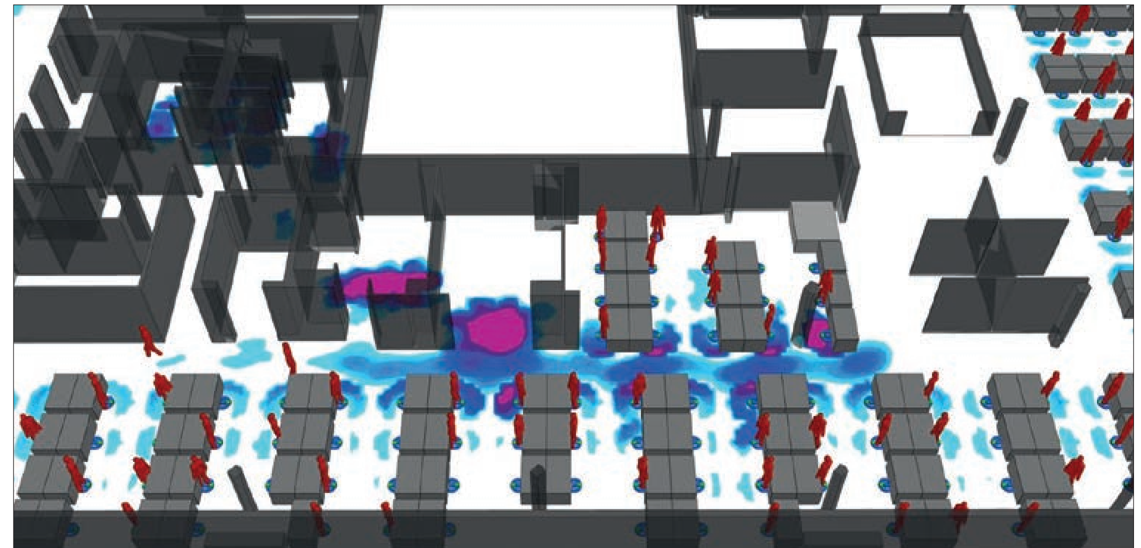


A still image from a MassMotion model of people moving through the lobby and lifts of an office building, with blue figures turning red when social distancing is compromised. From the model, a heat map can then be produced to identify places where minimum distancing standards are most often infringed © Arup

This is where MassMotion software comes in: its technology creates simulations of pedestrian movement based on modelling physical space combined with research on pedestrian behaviour and data from real-world projects. The software was originally developed for large infrastructure projects, modelling the aggregate of many individual movements and mimicking the variety of human behaviour (see 'Modelling technology'). It was then simple to factor in additional data on people's behaviour under COVID-19 restrictions, which varies from those who strive to maintain social distancing in all circumstances to those who take little notice of the rules.

Working in conjunction with Arup's workspace planning app, SpaceExplorer, businesses can model an office floorplan and furniture and define the number of proposed occupants and roles. Space Explorer can then interface directly with MassMotion and set up the simulation parameters for the movements during the day, including trips to the toilet or the kitchen. Output data can then be supplemented by video with real-time simulations of people's movements, identifying where and how often 'clashes' are likely to occur. Rapid iteration with changes of layout and numbers of people can help identify optimum risk-based solutions.

Often, the most critical point in the building is not the office floor but the building's entrance, reception area and lifts, with tall buildings and their lifts presenting a particular challenge. Here, the options tested are likely to include staggered working hours, which



A 3D image of an office floorplate at full occupancy, showing social distancing 'hot spots'. Iterations with different levels of occupancy and office layouts can help to identify optimum conditions. Learn more at www.arup.com/space-explorer © Arup

MODELLING TECHNOLOGY

With MassMotion, Arup developed a new set of tools based on individual, virtual 'agents' to represent and understand people's movement in any environment. These agents can be programmed to mimic human behaviour and the 'social forces' that drive their decisions, for example in a train station or airport they might avoid proximity to neighbours; pause at a café for a cup of coffee; or stop at a travel information board, pass through a turnstile or go up an escalator, based on their destination preferences. They make their own choices about appropriate actions based on the dynamics of their environment. The agents were assigned attributes based on field surveys: for example, the ratio of men to women – who, on average, walk at a slightly shorter step and slower pace than men – and whether they are commuters (who know where they are going) or tourists (who are not so sure).

Borrowing from existing 3D software, information from the design is used to develop a virtual environment based on a set of polygon mesh objects that represent the walkable areas and obstructions within them. The walkable areas are then broken down into circulation spaces, such as rooms, pavements or platforms, and connection elements, including doors, stairs and passageways. The agents themselves then decide their most appropriate routes across the environment between the various origins and destinations, their decisions based not just on distance, congestion and vertical movement but also on each agent's individual personality profile. Some agents will walk slowly and always wait to queue for the escalators; others will take the stairs at the first sign of congestion – and everything in between.

Agent profiles are based on existing data on pedestrian behaviour, combined with surveys of passengers at similar existing spaces. Where the model is being used to predict the effect of making changes to an existing environment, it can be calibrated by first applying it to the existing layout and tweaking the weighting factors to get a better fit with survey results.

Early applications were for major transport infrastructure such as Toronto's Union Station and Beijing's Daxing Airport, and more specialised tasks such as the mass evacuation of buildings, managing major venues, and designing large buildings and retail spaces. More recently MassMotion has been refined for smaller buildings and spaces – and now, for application with social distancing.

In all applications, the results are data-driven based on understanding of human behaviour, so decisions can be more robust and – in applications relevant to COVID-19 – provide more comfort to staff in returning to offices. Find out more about MassMotion at **www.arup.com/massmotion**

WHITTINGTON HOSPITAL

Every winter, UK hospitals face a seasonal surge of patients that puts huge pressure on crowded accident and emergency departments. This year, with the pandemic still active, they will need to have in place additional safety measures – particularly social distancing in their waiting areas, which could lead to severe overcrowding at times for non-COVID patients seeking treatment.

Consequently Arup, in collaboration with Whittington Health NHS Trust, organised a pilot study to help resolve capacity concerns within the A&E department of the Trust's North London hospital, using MassMotion. Attendances at the emergency department, and patient journeys through it, were simulated in order to predict how the department might cope during the winter months, under socially distanced conditions with reduced waiting room capacity.

Starting with a 2D AutoCAD plan of the hospital, and a set of granular, anonymised patient data from the emergency department's attendance records for 2019, an accurate 3D digital model was created to simulate the movement of patients, and people accompanying them, as they moved through the emergency department for assessment and treatment during the busiest period of winter. For example, a patient might wait to be registered, be sent for an X-ray, return to the waiting room, be examined by a doctor, and then return to the waiting room before discharge.

Arup was then able to explore the registration, movement and discharge of patients, along with the available space and seating areas, and demonstrate the scale of anticipated overcrowding during peak periods, with social distancing measures in place. This enabled the hospital team to analyse pressure points and review alternative actions, while maintaining high clinical standards and adhering to stringent COVID-19 requirements.

No simple standard equation exists to tell hospitals what capacity they need, and the pandemic has increased the importance and urgency of ensuring that space constraints do not impact on patient safety. Most social distancing measures up to now have been introduced through simple physical spatial planning, often based on several unproven assumptions about how the public will move and use the space.

Working with the hospital's data team, Arup identified the 'busiest' winter day and each patient's and companion's journey was accurately modelled from the 2019 data, incorporating MassMotion's data-based understanding of variations in people's behaviour. The output was presented as video simulations showing individuals' movement through the hospital, which helped senior NHS managers understand the scale of the overcrowding.

The modelling demonstrated that the potential issue was serious. If no action was taken, then the temporary socially distanced waiting room already in place could reach 250% capacity – with more than twice the current amount of space needed for the adult waiting area. In a secondary paediatric waiting area, with a much higher proportion of child patients being accompanied, the hospital could reach 500% of its capacity.

Working closely with the Trust, a range of proposals were developed, including: additional reception desk staff during peak periods to limit queueing; limiting the number of people accompanying adult patients at peak periods; reconfiguring existing waiting room arrangements to create more space; repurposing adjacent rooms as waiting areas; and spatial planning of additional, separate waiting area 'pods' for adults and children just outside the emergency department.

The data-driven evidence-based approach enabled the hospital's leadership to gain confidence in their decisions and helped build the successful case for additional funding to implement changes before the winter season.

A MassMotion model of the emergency waiting room at the Whittington Hospital, showing the 'do nothing' case (left) with the situation with all the proposed measures in place (right). The colour coding of the figures relate to the triage category of the patients, from (in this case) yellow (urgent) through green (standard) to blue (non-urgent). Accompanying persons are in white, and staff in pink © Arup

In the longer run, applying automatic touchless technologies to commonly touched surfaces such as light switches, toilets, lift buttons, doors, and gates can help reduce risk

can relieve pressure on the reception and lifts.

Social distancing may be the first and most urgent issue that building owners need to address, but it is far from the only one. The virus can also spread by touch or by circulating in the office's ventilation system (see 'Transmission in confined spaces').

Applying an anti-viral coating to frequently contacted surfaces such as door handles and instituting a rigorous cleansing routine can serve as a quick fix. In the longer run, applying automatic touchless technologies to commonly touched surfaces such as light switches, toilets, lift buttons, doors, and gates can help reduce risk.

Buildings' heating, ventilation and air conditioning systems also need scrutiny. A study of one of Arup's own UK regional offices showed that a change from the current temporary 2 metre spacing regime to 1 metre could increase office capacity by 60%, but would also increase people's exposure to others' exhaled breath via air circulation by 80% – despite the office having an above-average ventilation system. Sensors can be installed to track what is in the air. While they can't detect a virus, sensors that monitor other products of exhalation, like CO_2, can be used to identify spaces with poor ventilation. Solutions can include high-performance air filters and upgrading ventilation systems.

For the longer term, wider issues need to be addressed. If and when most people have had a COVID-19 vaccine, 2020 measures will no longer be needed – unless and until another pandemic arrives: building owners are likely to want their offices to be pandemic resilient. It is likely that post-pandemic offices will bear little resemblance to those at the start of 2020, with people spending more time working at home on tasks formerly done at an office workstation, and more office space devoted to meetings and social contact with colleagues and clients.

Some COVID-19 measures, notably increased ventilation, will impact negatively on efforts to reduce carbon emissions. This suggests that flexibility needs to be built in so, for example, offices can run in low-energy mode or pandemic mode, depending on circumstances. While COVID-19 may have temporarily distracted us from the climate emergency, the importance of keeping sustainability at the heart of building solutions should remain at the forefront of decisions.

TRANSMISSION IN CONFINED SPACES

Although our understanding of COVID-19 and its transmission is still developing, we know that the virus is carried in the respiratory droplets of infected people. People emit these when coughing and sneezing, but also when talking, shouting, or singing, and even to an extent when breathing.

The size of the droplets varies depending on the type of respiratory activity. Size is important because volume scales with the diameter cubed, and the greater the volume, the more virus copies it can hold. Most of the droplets produced by talking tend to be around 1 micron, and generally less than 10 microns in diameter. Coughing and sneezing produce more and larger droplets, while simply breathing produces fewer, and typically smaller droplets.

The size is also important because droplets less than 10 microns in diameter can be carried on air currents that are typical of air speeds in indoor environments, in particular in the thermal plume generated from the body heat of people, rather than dropping to the floor as large 'ballistic' droplets would.

So, a lot of the droplets produced by people talking and breathing will circulate in the air until they are removed by ventilation, deposited on surfaces, or filtered out by filtration units. These are small droplets, and in many circumstances, they may be unlikely to carry enough of the virus to cause a significant infection response. However, where ventilation is poor, or the infected person generates a particularly large amount of virus in their exhalations, or there are multiple infected people within a space, these droplets can accumulate in higher concentrations, raising the risk of infection and illness. The concentration of respiratory droplets, even in these riskier spaces will still be higher closer to the infected person, so social distancing should still be effective at reducing risk indoors, but does not eliminate all risk.

The effectiveness of masks varies by construction and the size of the droplets. However, even simple cotton masks, when well-fitted, are effective in reducing droplets from breathing and talking, as well as coughing and sneezing.

BIOGRAPHIES

Lachlan Miles is Product Director for MassMotion at Arup.

Alan Dunlop is a Project Manager who led the Whittington Hospital project for Arup.

Paul Lynch is a Senior Engineer who specialises in fluid dynamics at Arup.

James Ward is a chartered Architect with extensive commercial office experience at Arup.

CLEANING WASTEWATER WITH ALGAE

Algae is used in wastewater tanks to purify the water © I-Phyc

When a toilet is flushed, bath emptied or washing machine finishes, that wastewater needs to be treated and discharged safely into the environment. Additional cleaning is becoming more important as regulations call for lower levels of phosphorous in returned water. Geoff Watts spoke to Andrew Best, Business Development Manager at Industrial Phycology, about a technique that is using algae for purification.

Through a clever combination of biology and engineering, I-Phyc has created a practicable and economic way of using algae to give this wastewater a further clean up before discharging into the environment

The idea of using algae to purify polluted water has been discussed for decades. However, aside from a few niche applications or in circumstances where resources are so limited that nothing else is readily available, algae have yet to make it into the mainstream. That could soon change.

A demonstration plant installed at a Wessex Water sewage works on the outskirts of Weston-super-Mare in Somerset is showing the way. Before the wastewater generated by the works is released into the environment, a portion of it is passing through a further set of tanks installed by a company called Industrial Phycology (I-Phyc). Through a clever combination of biology and engineering, I-Phyc has created a practicable and economic way of using algae to give this wastewater a further clean up before discharging into the environment.

CLEAN WATER

The need for additional cleaning of wastewater grows increasingly pressing. In response to the EU's Water Framework Directive, regulators have become more vigilant. In particular, the Directive reduces the maximum permissible level of phosphorus in the water discharged by some sewage plants from 2 mg/l to 0.2 mg/l. Although no longer an EU member, the UK remains committed to a phased introduction of the new and lower level for at least the next five years.

Where wastewater is already getting an additional clean up, the methods currently used are mostly chemical. The standard technology for removing phosphate is by precipitation using salts of calcium, aluminium or iron followed by sedimentation and filtration to produce a sludge, which then requires disposal. I-Phyc claims that algae can do the same job more completely and more cheaply – and without generating a chemical sludge.

CHEMICAL REACTIONS

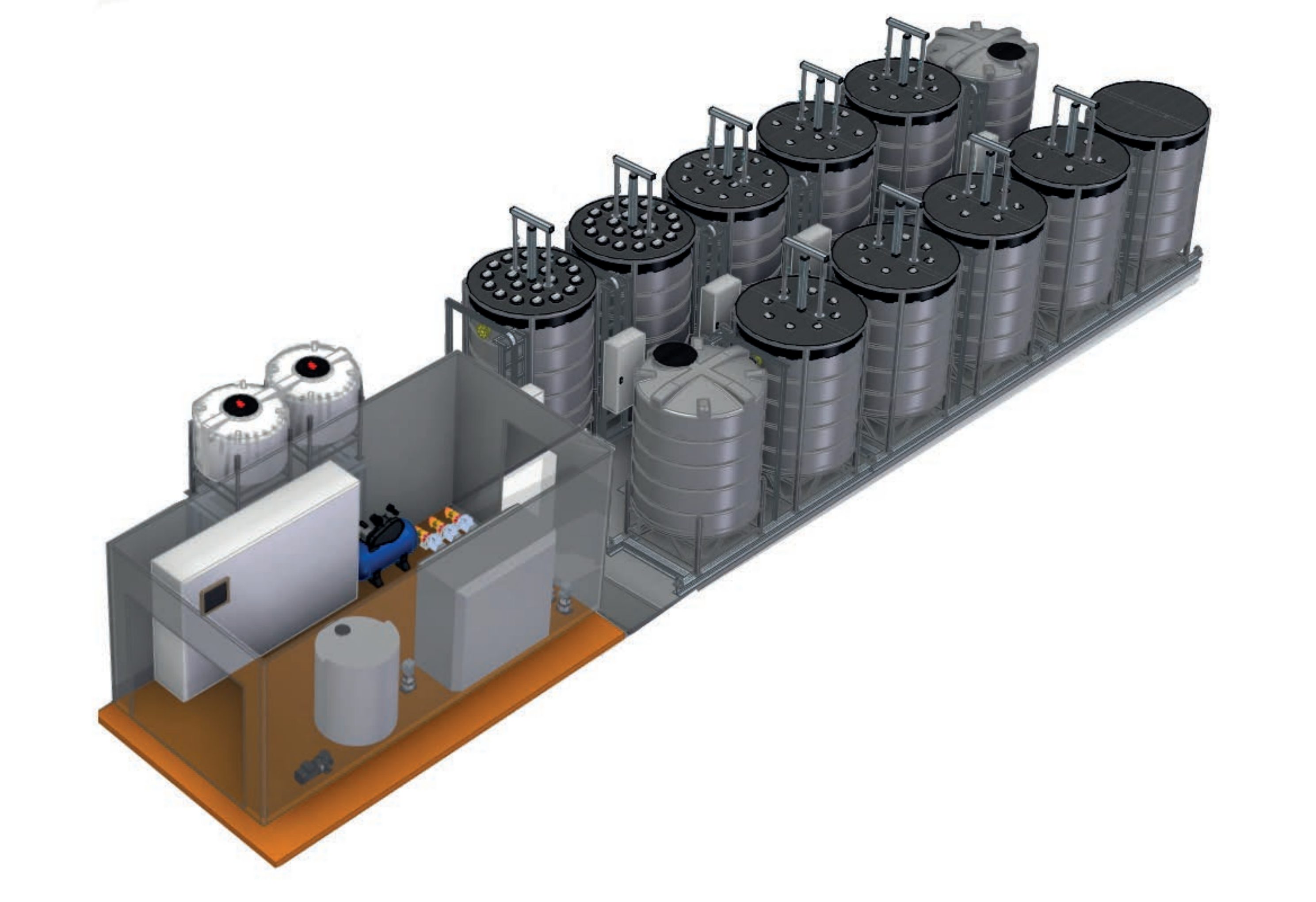
Algal metabolism relies on photosynthesis – a process needing carbon dioxide, water and light used by plants and other organisms to produce a chemical reaction to fuel their activities. Algae therefore need light to grow and reproduce. The simplest way of treating wastewater is to channel it into open tanks, add the algae, leave the tanks exposed to sunlight, and let biology perform its magic. The drawback is that a flourishing population of growing algae soon limits the penetration of light into the depths of the water in which it is growing. Only those organisms at or near the surface can get the light required to function at full capacity.

Tanks or pools that are shallow, and cover a much greater surface area, overcome this hurdle – but football-pitch-sized chunks of land are not universally available. The space required for such a set up may well render the installation impracticable, uneconomic or simply impossible: practicality, and the weather, simply rule them out for much of the UK. "They are a non-starter as they do not treat and reuse algae as we are able to do in a controlled environment,

WHAT ARE ALGAE?

Algae is the collective term for a diverse group of photosynthetic aquatic organisms that range in form and appearance from pond scum to seaweed. The algae used in I-Phyc's plant are free-floating and mostly unicellular microalgae, which range in size up to tens of microns (a single human hair is normally between 20 and 100 microns wide).

Their value as water purifiers is a consequence of their ability to absorb nutrients and other materials from their surroundings. Particularly important is their capacity to remove the phosphates and nitrogen found in sewage wastewater – and do so to an extent difficult to match using conventional chemical methods. The speed at which this removal occurs is affected by the ambient temperature, and by the availability of nutrients and light. The scientific study of algae is known as phycology.



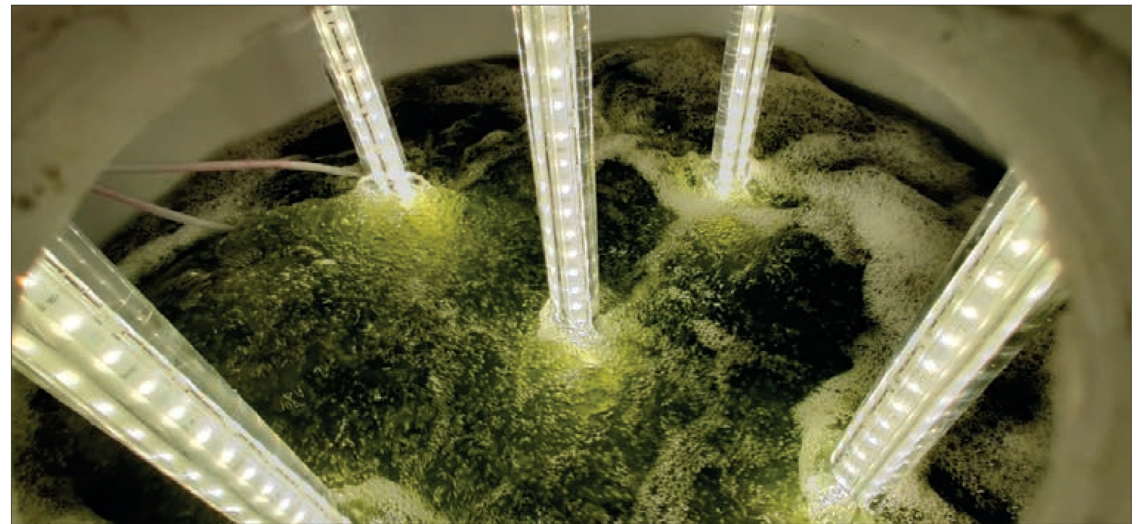
A computer-generated image of an I-Phyc treatment plant © I-Phyc

providing the correct amount of light 24 hours a day," says water engineer Andrew Best, I-Phyc's Business Development Manager. "We outperform removal rates; where algal ponds take days to remove 1 or 2 mg/l [of phosphorous], we can remove 8 mg/l (or more) in six hours. The current technology uses chemicals to precipitate solids, the chemical and disposal of these solids carry a far larger energy (and CO_2) footprint than the energy we use to provide lighting for the algae." Although operated on a commercial scale in a few countries with more abundant land and sunlight than the UK, the shallow tank solution to the light penetration problem has not been widely adopted. Another alternative would be to pump the wastewater and algae into long glass tubes exposed to surrounding light. This has been tried and is successful at a small scale. However, so far it has not proved practicable on an industrial level, partly on account of the photosynthetic activity of the algae, leading to a build up of toxic levels of oxygen in the tubes.

I-Phyc's approach to the problem lies not in bringing algae to the light but bringing light to the algae. The company was set up in 2012 by algal scientist Daniel Murray, then working at the University of Bath, but now I-Phyc's Chief Technology Officer. His decision to form a company was fostered by signs of encouragement from the water industry, and by the self-evident need for new thinking on the issue of removing contaminants from wastewater.

I-Phyc devised its system, tested it at laboratory scale, built a pilot plant and then, with the cooperation of Wessex Water, the demonstration plant that is now installed and operating at Weston-super-Mare. The algae and wastewater in the system are housed in large 25 cubic metre tanks. Light is brought to their interior via arrays of vertical glass tubes, descending into the depth of the tanks. The light itself comes from LEDs within the tubes. The density of the tube array is such that all microalgae in the tank will receive sufficient white light to actively photosynthesise.

Bubbles released from the bottom of the tank and rising up through it ensure that the water and algae are kept moving. Although the tubes are fitted with a wiper mechanism, Andrew insists that "happy and well-fed algae" tend not to stick to surfaces.



Tubes filled with LED lights reach the bottom of the wastewater tanks, allowing the algae to photosynthesise © I-Phyc

CONDITIONED ALGAE

Besides supplying the light needed by the algae, I-Phyc uses another trick: a means of gearing up the organisms to perform the work they are about to undertake and so boost their productivity. It calls this phase of the process 'conditioning'. The company, for commercial reasons, is reluctant to go into the precise details of the conditioning process, but its effects on the activity of the algae are marked.

When the conditioned algae are subsequently mixed with wastewater, they rapidly absorb the phosphate within it, typically in six to eight hours. Once the process is complete, the now phosphate-rich algae are separated from the water by centrifugal action using equipment not unlike that routinely employed in the food and brewing industries. In appearance the recovered organisms resemble a thick and dark green pesto sauce.

Most of these algae are returned to the conditioning tanks to begin the cycle over again. But a small proportion – whatever is more than the needs of the process itself – can be harvested as a potentially saleable byproduct, for example as an agricultural fertiliser, as they are rich in phosphorous and nitrogen. Indeed, they have an advantage over conventional liquid fertilisers, some fraction of which run off the fields before they can be usefully taken up by crops. Minerals bound into algal tissue are released more slowly into the surrounding soil and are consequently less likely to run off. A small rural sewage works serving a population of 500 might produce up to two cubic metres of algae annually. The value of this may be only marginal in reducing the cost of the operation but chemical processing, by contrast, produces a sludge that is not only valueless, but also imposes a disposal cost. And the operators of a sewage works using algae would, of course, be spared the need to buy the agents required for chemical processing.

The performance of the conditioned algae is impressive: more than a threefold increase in phosphate removal compared with unconditioned organisms. Chemical removal methods operating at the limit of their performance might be able to bring the phosphorus level in wastewater down to 0.25 mg/l, but algal treatment reaches this level with ease. I-Phyc's process can take the phosphorus down to as low as 0.05 mg/l.

SMALL-SCALE SEWAGE WORKS

The company's Weston plant takes and treats only 5 to 10 cubic metres per hour of the full output of Western Water's sewage works. This is because I-Phyc's current process has been designed for smaller sewage works dealing with populations of below 2,000. Hundreds of such plants, dotted around the country, are currently faced with the problem of deciding how best to meet the new wastewater standards, so that is where the company is concentrating it's efforts. Although Andrew says that "In the future larger works may well be on our radar".

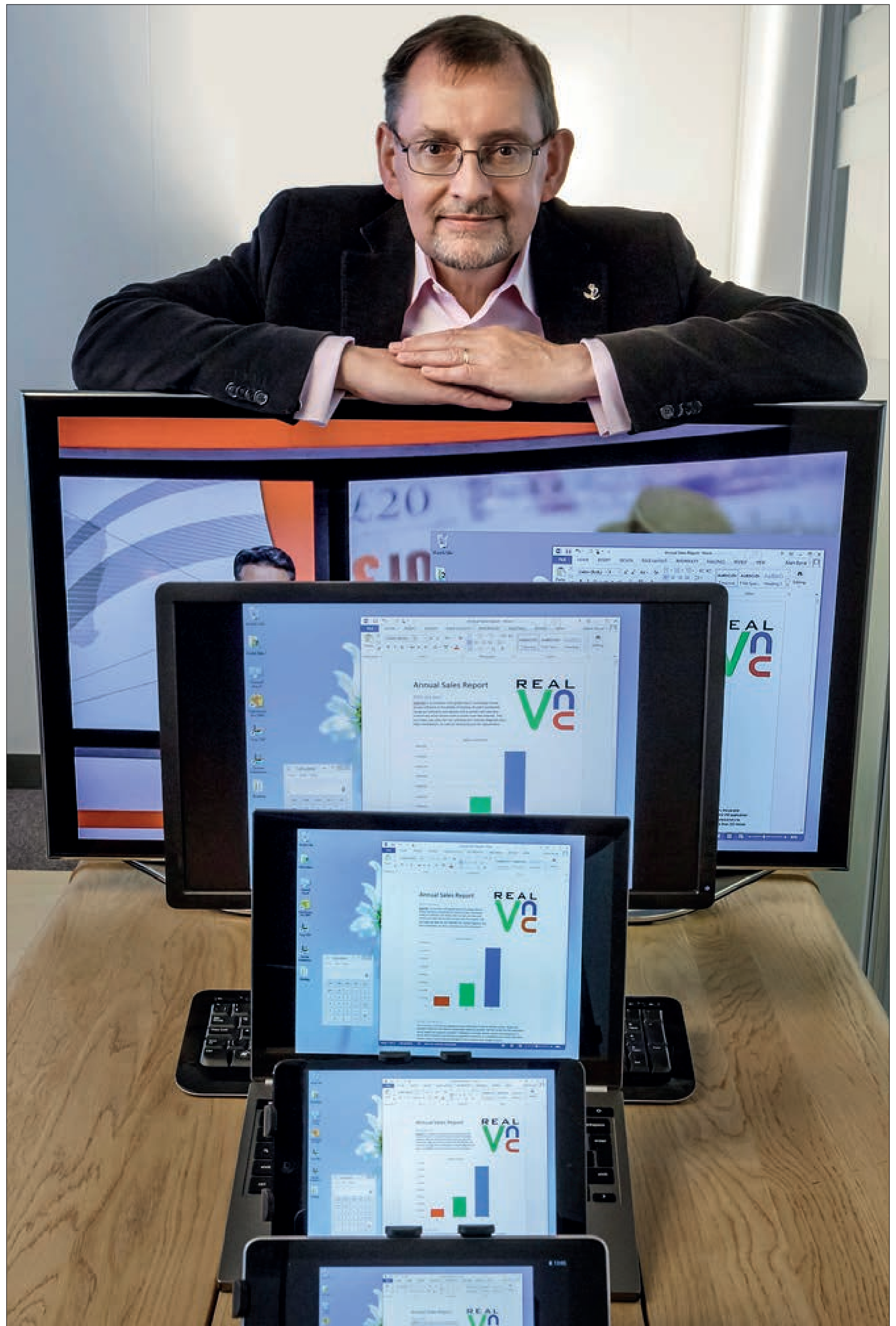
A study by the company has compared the capital and running costs of algal as opposed to chemical processing. It concluded that these costs could be as much as 20% and 50% respectively lower using algae, which also have a lower carbon footprint and, more importantly, remove ammonia from wastewater as well as phosphorus: two pollutants extracted for the price of one. I-Phyc is in discussion with three other water companies and anticipates announcing the construction of new plants soon. Integration into existing treatment plants presents, in principle, no problem. The additional process is simply 'bolted on' as one last step in the overall sewage treatment process before the water is finally discharged from the plant.

Even without regulation, public awareness of environmental pollution puts a pressure on officialdom to set higher standards of control. Wastewater is unlikely to prove an exception. If at some time in the future there is a demand to remove, for example, pharmaceutical residues, any sewage works using algal treatment would be well prepared. The versatility of these organisms is such that they can take up not only drugs but many other contaminants such as insecticides and plasticisers.

If all goes as I-Phyc hopes, the future of wastewater treatment will soon be acquiring a markedly greener tint.

BIOGRAPHY

Andrew Best is Business Development Manager at I-Phyc. He has spent 25 years working in water technology sales, including many years installing phosphorous removal systems.


Dr Andrew Harter CBE DL FREng

A PASSION FOR NETWORKS

It wasn't just the development of a new approach to connecting computers that singled out Dr Andrew Harter CBE DL FREng, he also invented new ways of bringing technology to the world. He talked to Michael Kenward OBE about the origins of the smartphone and his time as High Sheriff of Cambridgeshire.

He may be a leading light in the innovation hub of Cambridge, but Dr Andrew Harter CBE DL FREng's influence does not stretch far enough to get him a decent internet connection to his home. Fortunately, as an innovator in networking technology, he can overcome the challenges of living in one of the city's infamous 'not spots', where broadband speeds are stuck in the 20th century. Dr Harter is a director of RealVNC, a company he founded with his colleagues to commercialise their research into computer networking at the AT&T Cambridge Laboratory. Thanks to RealVNC software, which won the Royal Academy of Engineering's MacRobert Award in 2013, Dr Harter and many millions across the world can work from home during lockdown, accessing computers remotely and sharing screens during video conferencing.

YOUNG ENGINEER

Like many, Dr Harter was bitten by the engineering bug when messing around with things when younger. "I loved tinkering with things as a boy," he says. Dr Harter was inspired by his grandfather – a cabinet maker turned engineer, who made Spitfire propellors during the Second World War. "We spent hours making things together: in wood, metal or whatever." Dr Harter attributes this activity to his fascination with taking things apart, putting them back together and then trying to make them work again.

At school Dr Harter became interested in electronics. "Electronics wasn't in the curriculum, but I taught myself." He used his hobby to good effect, building a stage lighting system for the school. He lauds his school, a boys' grammar school in Wakefield, for nurturing creative, enquiring minds that solve problems. "Hobbies spill over into academic learning. They feed off each other."

Dr Harter's interest in electronics led him to computers. These were the early days of home computing, the era of the Sinclair Spectrum and BBC Micro. You could buy a kit of parts and build your own computer, but he went further. "I designed and built my own computer out of components from the electronics catalogue," he explains, buying a microprocessor chip and designing a circuit to make it work. As it sprang into life, his grandad's contribution was to make a splendid wooden case for the 'Harter Mark I' with its flashing lights and switches.

When it came to turning his interest in technology into a career, Dr Harter opted to first study maths at the University of Cambridge. Why not study for a degree in a more obvious engineering subject? He believes that mathematics provides a good grounding in many areas of engineering. There is logic, precision and rigour to it, he adds, "that is really good training for an engineer, for a computer scientist."

KEEN ON COMPUTERS

The transition into computer engineering began during the degree course, when Dr Harter took holiday jobs at Acorn Computers working for Professor Andy Hopper CBE FREng FRS and Dr Hermann Hauser KBE FREng FRS. Acorn pioneered personal computing in the UK, making its own devices and the groundbreaking BBC Micro. Dr Harter's holiday jobs involved computer-aided design for some of Acorn's electronic chips and led to the research for his PhD. "Notwithstanding the fact that I enjoyed the discipline of maths," he says, "I have always enjoyed applying things." His PhD involved research into three-dimensional integrated-circuit layouts and resulted in a novel computer-aided design system. "That was all software," Harter explains, "coming up with new algorithms and new ways of laying out chips, circuit design in three dimensions." The PhD not only collected an accolade as the year's best PhD dissertation on computer science in the UK, it ended up as a book, which is still in print.

THE WORLD'S FIRST SMARTPHONE?


The AT&T broadband phone

Towards the end of the 20th century, Dr Harter and his team at AT&T Laboratories Cambridge showed off what they called a 'broadband phone'.

The desktop version was designed and built from scratch. It had an ARM processor; a full-colour touchscreen; a wired ethernet connection; cloud architecture; a set of apps from a curated app store; and an intuitive graphical user interface. Around 500 were produced and were such a hit that the team quickly turned their minds to a portable version.

Using a state-of-the-art PDA, Dr Harter led the team to reimplement the exact same software architecture on the mobile device, which had broadband connectivity through a Wi-Fi card. Nearly a decade later, Dr Harter and his colleagues were amused when Apple's first iPhone reached the market. It was similar to the AT&T device. In what may have been another pioneering development, the team's broadband phones ran on a version of Linux, later used in Google's Android devices.

Dr Harter reflects that his fully functional broadband phone family could have been manufactured at a similar cost to today's products. He adds that society wasn't quite ready. When he later reflected on the fate of the idea, he said: "There is a saying in the investment community that being too early is a good as being wrong. But the concepts we mapped out have undoubtedly lived on."

One part of the innovation behind the broadband phone also lives on in the VNC system.

When the UK entered its first lockdown, staff at RealVNC knew some of their solutions were already being used to keep critical infrastructure running. After all, the business provides virtual network computing (VNC) technology that allows secure remote access to computers. NHS trusts are among the company's clients and many diagnostic imaging machines rely on the technology

In 1990, with the PhD completed, Professor Hopper recruited Dr Harter to join what was then the Olivetti Research Laboratory. The lab started life in 1985 as Olivetti's research operation when the Italian company acquired Acorn Computers. Dr Harter became one of three deputy directors and then the lab's director of research and engineering. In 1999, following another takeover, the research centre became the AT&T Cambridge Laboratory.

He describes the lab as "a very interesting model, which sadly doesn't seem to exist anymore". Impact was not measured just by academic papers, but also by technology transfer, licensing deals and spin-outs. "The lab paid for itself several times over, in the return to our parent companies." Independent and industrially funded, he adds, "we operated on the edge of the university. We placed grants in the engineering and computer science departments to establish collaborative projects. We funded PhD students and welcomed interns. Some of us had university roles to a greater or lesser extent. There was a great synergy."

The lab's research focused on high-speed networking, wireless communications and a forward-looking view on their applications. Groups also worked on projects that would later be recognised as part of the Internet of Things, an 'active badge', for example, that would track where people and objects were and control and configure devices accordingly.

The lab's engineers designed advanced prototypes, building and assembling some of the most sophisticated systems around. "We built, what were at the time, the world's most advanced, high-resolution, full-colour digitally networked multimedia systems." The lab even came up with what Dr Harter likes to describe as the world's first smartphone: a device that predates Apple's iPhone.

This type of work came to an end in 2002, when the 'dot com' bubble and big companies everywhere cut back on R&D. Overnight AT&T went from having seven labs, including Cambridge, to having just one in the US.

This 'extinction event', as Dr Harter describes it, was by no means the end of the road for the work carried out by the AT&T Cambridge Laboratory. "It was an awful time, making about 60 really talented engineers and computer scientists redundant," he says. "But what was fascinating was that rather than 60 people going their separate ways, they formed some 10 or so startup companies." This migration grew out of how the lab was run: small groups of engineers intensely focused on a particular topic and its commercial application. After the lab closed, "people essentially continued their line of research in a startup". Some tapped into the local network of 'angels' and venture capital to raise funds, some set up consultancies and some grew organically. "I think they are all still around in some shape or form," says Dr Harter. "They have all done very well."

REMOTE WORKING

One of those successful spin-outs was RealVNC, the business that Dr Harter set up, with Professor Hopper and three other colleagues that had worked together on virtual network computing (VNC), the challenge of remote networking of computers. If you have ever sat in front of a computer watching someone control it from afar, you may well have come under the spell of VNC. "It is a way of remotely accessing one computer screen from another," Dr Harter explains, "so you can see and use one computer screen from anywhere else on the planet." The key to RealVNC's technology is in the underlying algorithms that reduce how much data must pass between devices. The data traffic uses patented encoding to efficiently send only those parts of a screen that are changing.

Dr Harter had already convinced the lab to make a version of VNC freely available in an early example of open-source software, and by 2002 there were many millions of users already. "The point was to create the market that we could subsequently tap into and monetise," says Dr Harter. RealVNC became the vehicle for the commercial transition. Dr Harter led the company up an organic growth path, resisting external investment. Instead RealVNC started selling 'I love VNC' branded mouse mats, T-shirts and baseball caps to users of the free software, which made them hundreds of thousands of pounds. It helped that RealVNC was giving away decent software, which also worked on different kinds of computer. The software architecture behind the systems means that it can easily be made to work on any device with a screen, including those that do not yet exist.

Then, some users told the company that they didn't need any more T-shirts but would like to support the business by giving money, without strings. As Dr Harter recalls: "We thought 'this can't be right', but we indulged them." So RealVNC put a 'Donate' button on the front page of its website and made another few hundred thousand pounds. Dr Harter believes this is the earliest example in technology of what is now called crowdfunding, a term that wasn't even coined until much later in 2006.

The company's business model then came up with another move that has also become a part of the software business landscape. "We pioneered what is now known as the freemium model," Dr Harter says. "You provide a free version and then charge for a license key that unlocks a better experience. It could perform better, have stronger security, or work in slightly different ways with more features."

RealVNC didn't just create a commercial success, it has picked up several awards over the years, including three Queen's Awards for Enterprise and the Academy's MacRobert Award (see 'Remote access software', *Ingenia* 57). As John Robinson CBE FREng, Chair of the MacRobert Award judging panel at the time, said: "RealVNC was selected for the MacRobert Award because of the engineering excellence and tenacious entrepreneurship required for them to have opened the door to countless new markets for new product and services. For a relatively small UK company with no external investors to have grown to work with the world's biggest technology companies is truly inspiring."

NETWORKS AND ECOSYSTEMS

Dr Harter believes that the success of companies like RealVNC owes much to the fact that there is something about Cambridge that encourages the birth of new businesses. It helps that the city has the essential ingredients, including a top university, to be an innovation powerhouse. Cambridge may be a small place, but there is a lot going on, with plenty of companies in life sciences and technology. "We are all really quite close together physically and through our networks. There is a concentration that means people do know each other. Then there is money," he adds. "There are private investors, there are angel investors and there is venture capital here on tap." Throw in business incubators and hubs in some of the research and business parks and Cambridge has plenty of spaces in which to innovate and grow. There are many lawyers and accountants with extensive early-stage and mergers and acquisitions experience.

The final ingredient, says Dr Harter, is networking organisations. He should know, having chaired Cambridge Network since 2014. Cambridge Network was created 20 years ago as a partnership between the university and local business to foster the exchange of ideas and practices. You don't even have to be a Cambridge academic to tap into the local network, Dr Harter insists. "Not all of the technology and startups have come out of the university by any stretch of imagination."

In his time as High Sheriff of Cambridgeshire, Dr Harter and his family took part in many fundraising activities, including the Cambridge Half Marathon

COMMUNITY SPIRIT

Dr Harter believes strongly in the importance of business supporting the wider community. "I think it is an obligation to put something back into society," says Dr Harter, pointing to hundreds of thousands of pounds of financial support that RealVNC has provided over the years. "Time and expertise are sometimes just as valuable, and we encourage staff to participate in voluntary and charitable work."

He has taken this a step further. Between 2018 and 2019, Dr Harter was appointed the High Sheriff of Cambridgeshire, an ancient office that is over 1,000 years old. Originally the monarch's representative in the county with substantive powers such as maintaining law and order, these days the role is essentially ceremonial.

During his year as High Sheriff, Dr Harter and his family threw themselves into fundraising for charity. "Some people describe our year as being quite hyperactive," he says with a laugh. "We decided to cross over the county in lots of weird and wonderful ways." There was a cycle ride from Peterborough in the north to Cambridge in the south. This was on two tandem cycles, with Dr Harter and his wife Lily Bacon on the front as captains and their two young sons on the back as stokers. Then there was a mad dash with an early morning start to visit every railway station in the county by train in a day. They rounded off the year with a 42-mile walk from Ely Cathedral to Peterborough Cathedral following the Hereward Way through the Fens, fittingly during storm Gareth. His year as Sheriff raised over £100,000 to support smaller charities in the county.

Dr Harter and his wife's fundraising continues – both are Deputy Lieutenants of Cambridgeshire – again, with an imaginative approach. The latest session was sparked off by their own experience during the first lockdown. "We struggled with trying to school our boys at home," he explains, "and we are very fortunate." There are families in and around Cambridge and Cambridgeshire that are far less fortunate, he adds. "Cambridge is a very unequal city. You have prosperity in the centre and just a mile or two away you have schools where half the kids receive free school meals." Dr Harter's response was yet another challenge. When the London Marathon fell victim to the global pandemic, he looked for something to do instead. "We worked out, by chance, that the distance between all of the 31 colleges of the university, in alphabetical order, starting at Christ's and finishing at Wolfson, is almost exactly a full marathon distance." So, they completed their virtual London Marathon by criss-crossing the streets of Cambridge. "We raised £50,000, which we put into recovery projects in some of the maintained schools in Cambridgeshire."

While in the past, Dr Harter would also have been responsible for collecting the king's taxes as the High Sheriff of Cambridgeshire, in that role and as Deputy Lieutenants, he and his wife have done the reverse: encouraging those who are able to enhance the opportunities of others.

BIOGRAPHY

Michael Kenward OBE has been a freelance writer since 1990 and is a member of the *Ingenia* Editorial Board. He is Editor-at-Large of *Science|Business*.

CAREER TIMELINE AND DISTINCTIONS

Studied mathematics and computer science at the University of Cambridge **1980–1983**. PhD in computer science, **1990**. Research Engineer, Principal Research Engineer, Director of Research and Engineering, AT&T Laboratories Cambridge, **1990–2002**. Founded RealVNC, **2002**. Awarded Royal Academy of Engineering Silver Medal, **2010**. Fellow of the Royal Academy of Engineering, **2011**. Received the MacRobert Award, **2013**. Trustee of the Royal Academy of Engineering, **2013–2016.** Appointed Chair of the Cambridge Network, **2014**. Honorary Doctor of Science, Anglia Ruskin University, **2015**. Awarded the Institution of Engineering and Technology's Faraday Medal, **2016**. CBE for services to engineering, **2017**. Director, RealVNC, **2002 to present day**.

TRAFFIC LIGHTS FOR THE TIDE

The Holy Island Causeway Indicator is a small gadget that lights up to show visitors whether the causeway is safe at a glance, helping prevent people getting stranded due to flooding.

Twice a day, the Holy Island of Lindisfarne is cut off from the mainland by fast-moving tides. Almost monthly, the Royal National Lifeboat Institution (RNLI) is called out to rescue the occupants of cars stranded after the causeway floods. Northumberland County Council publishes a monthly table of safe and unsafe crossing times on its website, but Professor Andy Stanford-Clark, Chief Technology Officer for IBM in UK and Ireland, had an innovative idea to use the Internet of Things (IoT) to create an easy-to-read traffic light system.

The resulting Holy Island Causeway Indicator (HICI) is a small device that allows visitors and residents to quickly see the current state of the causeway. The 40-millimetre cube is 3D printed in translucent plastic. During safe times it glows green, while during unsafe times it turns red.

Professor Stanford-Clark wanted to clearly convey the information about whether the causeway was open or closed. The original design brief was to control traffic lights at the ends of the causeway, but after meetings with the Highways department, and vendors of traffic light and road signage equipment, it quickly became apparent that some product changes would be required for remote operation.

Instead, Professor Stanford-Clark decided to use the IoT to publish the important information. He analysed the requirements of the system and quickly eliminated physical sensors because of reliability, power and connectivity constraints. Instead, he used data from published tide tables from oceanographic models to indicate when it was safe to cross the causeway.

The Holy Island Crossing Indicator glows green when it's safe to cross the causeway to Lindisfarne

He had already developed a Wi-Fi-connected IoT device called GlowOrb, which contains a microcontroller and a red/green/blue LED bulb, the colour of which can be controlled via an MQTT connection to the IBM Watson IoT Platform (a server that appropriately routes the messages it receives). This could readily be adapted to be the output device.

The council webpage is cleanly formatted with a row per day, and up to two safe (green) and two unsafe (red) time intervals per day. Analysing the HTML of such a table is quite easy and reliable, as long as the design of the website is not changed in a way that invalidates the code. The project initially used this page as a data source for the safe and unsafe tide times, but has since been granted access to the application programming interface (API) behind the web page, which is immune to website redesigns and is more easily accessed.

An application running in the Cloud, written in the Node-RED 'low-code' programming environment, is triggered to run each day just after midnight. The tide times for the next 24 hours are retrieved through the API, and the content is analysed to determine times of the safe/unsafe transitions. These times are pushed into an event queue and tagged with whether it is a transition to green (safe) or red (unsafe).

Another flow in Node-RED runs every minute. This looks at the transition time at the head of the event queue and whether it's time to change colour. It then publishes the appropriate colour to the MQTT broker to which all the indicators are connected. They all receive the new colour command and change colour to reflect the new state of the causeway.

Initial buyers of the HICI device gave feedback that a countdown to when the causeway was next open or closed would be valuable, as was knowing the actual time of the transition. This led to two further prototypes being developed: a countdown clock and a tide time display device.

The small device is powered by USB and can be placed in a prominent position, so visitors and residents can see at a glance when it's safe to cross – and each purchase includes a donation to the RNLI.

For more information: **travelnorthumberland.co.uk/product/hici/**

HOW DOES THAT WORK?

ELECTRIC HAIRDRYER

Invented in the 1920s, the electric hairdryer is an everyday household object that has changed significantly over the past century – and is likely to continue developing as technology evolves. Its production consists of various engineering elements.

Most households probably have an electric hairdryer – a handheld device that we use to dry and style our hair. The small device uses various engineering elements to heat and blow air. Engineers must consider: electrical power consumption; materials for heating and cooling; the design, consumer appeal, structure, durability and weight; and the electronics for safe operation.

When a hairdryer is connected to a power socket and switched on, the electricity powers a heating element and an electric motor, which operates a fan in the dryer. The heating element converts the electrical energy into heat of up to 2,000 Watts. This process is known as resistive heating and is used in other household appliances, like the electric kettle and toaster.

Hairdryers often have a ceramic or polymer frame and casing. Polymers are lightweight plastic materials with a limitless range of colours and significant degrees of strength. They are also good thermal and electrical insulators. They protect the internal components of the hairdryer and users from burns and electric shock. Polymer casing also allows for injection moulding; a fast manufacturing process used to produce large numbers of identical items of plastic with compartments that interlock with snap-fasteners for easy assembly.

The electrical motor and fan are at the back of the casing in an area called the air inlet, which is covered with a fine mesh screen to prevent objects accidentally getting caught in the fan blades. At the opposite end is the air outlet, with a heat resistant and protective front grill, where the nozzle is attached. The heating element, which sits in between the air inlet and outlet, is a conductor usually made of coiled nichrome wire, typically 30 centimetres in length. The wire looks like a coiled spring and is wrapped around an insulating board

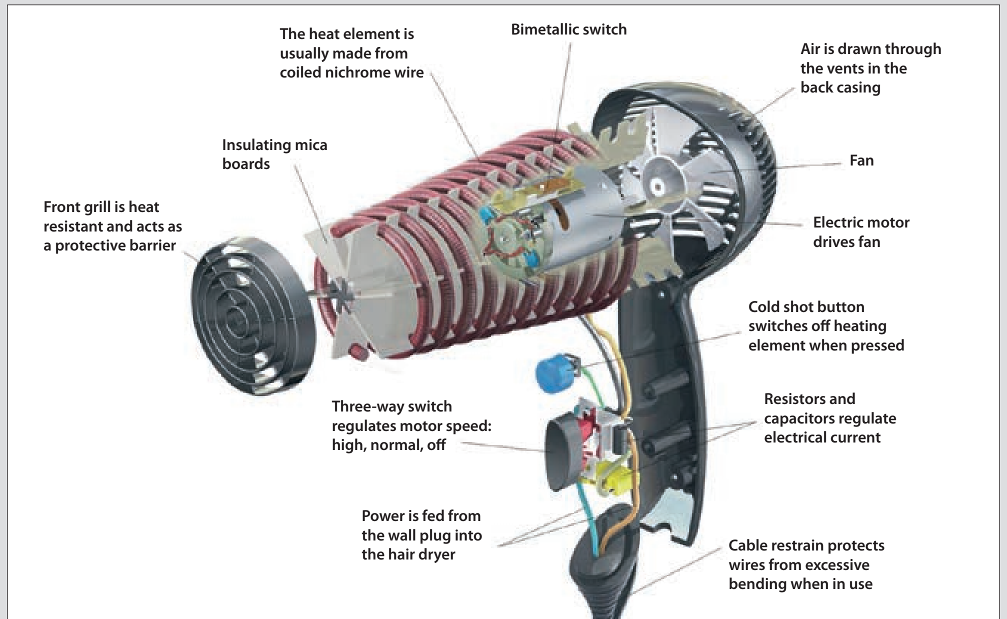


Diagram of a traditional hairdryer © Anthony Samboer

so that the entire heating element is only a few centimetres long. This insulating board is usually made of mica, a mineral found in India, Belgium, Brazil, and China, which can withstand extreme temperatures. Two flat pieces of mica form a three-dimensional X that has notches cut in the edges to keep the wrapped coiled nichrome wires in place, allowing air to flow through the long barrel casing.

An electrical circuit connects the ends of the heating element's coiled wires to the power. The three-way switch in the handle controls the power to the motor and heating element, allowing control of the airflow and temperature. Sensors keep the hairdryer at a comfortable temperature and detect overheating. A cut-off switch made from a bimetallic strip shuts the unit down when necessary, preventing the hairdryer from exceeding 60°C. A thermal fuse built into the circuit provides another layer of safety, instantly breaking the circuit when the temperature exceeds the limit. The ground-fault circuit interrupter is built into the hairdryer to prevent electrocution. It senses how much current is flowing through the circuit and can shut it off if it detects a leak or a short circuit.

The electric fan rotates and blows air across the heating element. As the air passes through the heating element, the air is warmed and heated up. The hot air exits the dryer through a nozzle, to concentrate the air flow. When it reaches wet hair, it absorbs the moisture and dries the hair.

BIOGRAPHY

Dr Ozak Esu is an ambassador for the Queen Elizabeth Prize for Engineering (QEPrize). She is a chartered electronic and electrical engineer and a member of the Institution of Engineering and Technology. Follow her on Twitter: @esu_o