ingenia

JUNE 2021 ISSUE 87

DIGITAL TWINS
FROM 1G TO 6G
CONCRETE BOX TUNNEL
CLEARING TRAIN TRACKS
HRH THE DUKE OF EDINBURGH
SMALL NUCLEAR REACTORS

Royal Academy of Engineering

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Front cover

A small modular reactor at sunrise
© UKSMR Consortium

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WELCOME

"Read on to explore how engineering makes a difference and shapes the future

In April, we heard the very sad news that His Royal Highness The Duke of Edinburgh had passed away. His passion for the role of engineering in society has been an inspiration to countless people in their careers. As Senior Fellow of the Royal Academy of Engineering, he was so engaged and enthusiastic about our work and in this issue we have reprinted an article he wrote in 2009 for *Ingenia*, 'Promoting engineering' – his words resonate now just as they did back then.

Elsewhere in this issue, we learn about how engineers are using digital twins to monitor bridges' performance and help grow underground crops; engineering techniques to keep our railways running – from solutions to the troublesome problem of leaves on the lines to jacking a curved concrete box tunnel; edible packaging made from seaweed; the global collaboration behind evolving mobile technologies; and how small modular reactors will contribute to achieving net zero.

In our 'Opinion' section, Dr Mark Fletcher FREng, Global Water Business Leader at Arup, calls for design to embrace regeneration of our natural systems. We have a rich insight into the career of maritime engineer Dr RV Ahilan FREng whose interest in fluid mechanics led him into offshore work and renewable energy. Josh Oldham, an Aston Martin apprentice, shares how his early interests in Lego and maths led to a career in engineering.

Do read on to explore how engineering makes a difference and shapes the future. As His Royal Highness said in 2006: "There is no doubt in my mind that our future prosperity and comfort depends on the talents and ingenuity of engineers."

Faith Wainwright

Faith Wainwright MBE FREng
Editor-in-Chief

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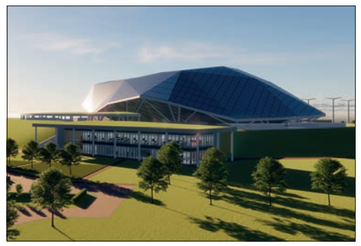
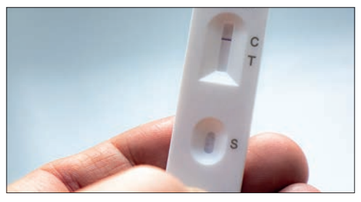




IN BRIEF

HEALTHCARE AND LIFESTYLE INNOVATIONS VIE FOR MACROBERT AWARD

Creo Medical, DnaNudge and PragmatIC Semiconductor have been announced as finalists for the 2021 MacRobert Award for world-leading UK engineering innovations that could help us all live healthier, more sustainable lives.

As the most prestigious prize for UK engineering innovation, the MacRobert Award shortlist recognises engineering innovations that show how engineers and technologists are crucial to the UK's recovery and future economic development. From more accurate cancer treatment and personalised medicine to new smart labels in pharmaceuticals and nutrition, each of these groundbreaking developments reflect the UK's global leadership in engineering innovation and promise to unlock widespread societal and environmental benefits.

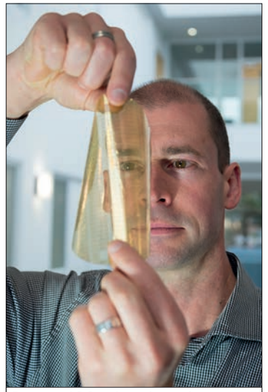
Creo Medical has developed advanced miniaturised surgical tools that uniquely integrate radio frequency and high-frequency microwave energy for highly targeted, minimally invasive endoscopic surgery. These tools dramatically improve patient outcomes for cancer care, while minimising the need for traditional surgical interventions, moving treatment out of the operating room. The tools promise to transform clinical outcomes for patients, reducing recovery times and avoiding the risks of open

Creo Medical's miniaturised surgical tools that assist highly targeted, minimally invasive endoscopic surgery © Creo Medical

surgery. The new technology enables cost savings of up to £10,000 per procedure in NHS hospitals – a 50% saving on traditional surgery.

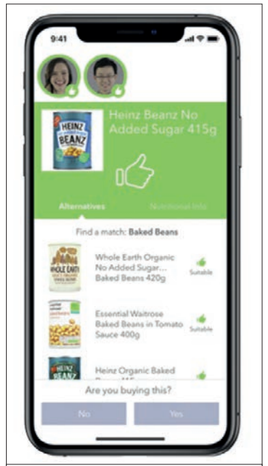
DnaNudge's pioneering genetic testing technology enables consumers to shop more healthily – taking into account their DNA and lifestyle. Following a simple cheek swab, DnaNudge's NudgeBox analyser maps the user's genetic profile to key nutrition-related health traits such as obesity, diabetes, hypertension, and cholesterol. Customers can then use their wearable DnaBand and mobile app to scan products while they shop and be guided by their DNA towards healthier choices. The technology has been rapidly adapted into a gold-standard, 90-minute lab-free RT-PCR test for COVID-19 and is now being used in NHS hospitals, care homes and supporting the return of the arts sector.

PragmatIC Semiconductor's electronic engineering innovation takes the silicon



PragmatIC Semiconductor's ultra-low-cost thin and flexible integrated circuits can be embedded in everyday objects from food and drink packaging to medical consumables © PragmatIC Semiconductor

out of silicon chips, resulting in ultra-low-cost thin and flexible integrated circuits. These can be inexpensively embedded in everyday objects from food and drink packaging to medical consumables, a crucial step in achieving the Internet of Things and addressing a range of application sectors including the circular economy and digital healthcare. The technology reduces manufacturing cycle time from months to less than a day, allowing agile 'just in time' production of microchips and avoiding the risks and waste of global supply chains. In addition, traditional silicon chip fabrication methods have enormous carbon and water



DneNudge's DnaBand and mobile app allows consumers to scan products while they shop, with their DNA guiding them towards healthier choices © DnaNudge

footprints, while the PragmatIC approach reduces this by more than 100-fold.

The winner of this year's MacRobert Award will be announced in July. The winning team will receive the signature MacRobert Award gold medal and a £50,000 cash prize.

The MacRobert Award is run by the Royal Academy of Engineering with support from the Worshipful Company of Engineers. Since 1969, it has recognised engineering achievements that demonstrate outstanding innovation, tangible societal benefit and proven commercial success.

MATHEMATICIAN FIRST WOMAN TO WIN PRINCE PHILIP MEDAL

Dr Gladys West, whose mathematical modelling paved the way for the engineering innovation of GPS, has become the first woman to win the Royal Academy of Engineering's Prince Philip Medal.

As a pioneer in the use of complex mathematics and efficient programming to process early satellite data to generate accurate, repeatable and global models of the Earth's geoid, her work underpinned the mapping functions of GPS and the study of global mean sea level.

Dr Gladys West in 2018 at her induction to the US Air Force Hall of Fame

HRH The Princess Royal, Royal Fellow of the Academy, presented the gold medal via a virtual audience with Dr West at her home in the US.

Speaking from her home at Gatcombe Park, Dr West said: "It is hard for me to believe that I was a little Black girl on the farm who had a dream to get off the farm, get educated, and make enough money to take care of myself. And now, I have realised my dreams and reached a height beyond what I anticipated. I encourage young women to believe in yourself, find your passion, work hard and apply yourself, stay committed, find a mentor, participate in activities that relate to your passion, never give up, always keep setting new goals and continue to strive to reach them, and most of all – follow your dreams."

Dr West is the first woman to win the Prince Philip Medal in the 30 years since it was presented for the first time in 1991 to Air Commodore Sir Frank Whittle, wartime pioneer and inventor of the jet engine.

WORK BEGINS ON TUNNELS UNDER LONDON

In May, work started on a 32.5 kilometre tunnelling project underneath London, which will see the rewiring of South London with a network of tunnels from Wimbledon to Crayford – works that are vital for the future of the city's electricity supply.

London Power Tunnels is National Grid's £1 billion flagship project and follows the original London Power Tunnels project, north of the Thames. Work began with the arrival of 'Edith', a tunnel boring machine (TBM) weighing around 140 tonnes, whose name was chosen to honour Edith Clarke, the first female electrical engineer and pioneer who used maths to improve our understanding of power transmission.

Alice Delahunty, President of Electricity Transmission at National Grid, said: "Our London Power Tunnels project is making sure electricity reaches homes and businesses in London safely, reliably and efficiently … A huge amount of work has gone into making this possible … Despite its challenges our engineers have been able to deliver this vital project and reach this milestone."

London Power Tunnels' New Cross site © National Grid

ENGAGING FUTURE ENGINEERS

In April, the Royal Academy of Engineering announced 26 new Ingenious public engagement awards for projects that will engage the public with an exciting variety of engineering themes.

The 26 awards focus on projects that will raise awareness of the impact of engineering among people of all ages and backgrounds and provide a focus on working with groups underrepresented in engineering. The projects are currently underway across the UK, from Edinburgh to Bristol, Bangor to Birmingham.

One of the projects is New Scots Connect, which will link engineers with new Scots, such as refugees and asylum seekers and those with diverse migration backgrounds in Scotland. Engineers will support the development of transferable skills and technical English language through creative engineering-themed activities.

In Bedtime Stories for Very Young Engineers, engineers, parents and carers will learn about the skills, information and raw materials they need to create fun and engaging bedtime stories to introduce two- to five-year-olds to the world of making, improving and maintaining the human-made world around us.

Many projects focus on environmental issues such as reducing plastic waste and the role of engineering in tackling climate change. In Engineering Sustainable Photographic Processes, an artist-photographer and engineers from the University of Birmingham will show participants how to create photographic prints, using materials engineering skills to build cameras and to create their own developers and emulsions.

The scheme reopens for applications on 30 June, offering funding from £3,000 to £30,000 for public engagement projects that will excite and inform the public of the wonders of engineering, while providing engineers with skills and experience in public engagement.

The deadline for applications closes on 8 September 2021. To read a full list of current projects, find out more about Ingenious and to apply, please visit **www.raeng.org.uk/ingenious**

Dr Anna Ploszajski from Bedtime Stories for Very Young Engineers

WORLD'S FIRST 3D-PRINTED HOUSE


The house has printed concrete floors and a printed roof © Project Milestone

Residents have moved into Europe's first 3D-printed concrete home: a two-bedroom bungalow in the Netherlands.

The house consists of 24 printed concrete elements, which were printed layer by layer at the printing plant in Eindhoven. The elements were transported by truck to the building site and placed on a foundation. The house was then given a roof and frames, and the finishing touches applied.

Concrete has been the most used building material in the world for decades. 3D-printed concrete has advantages, including the ability to lay concrete only where it is needed – traditionally poured concrete is solid and contains much more concrete than is needed, creating extra CO_2 emissions. 3D printing also allows for printing different types, qualities and colours of concrete, all in one integrated product.

This house is the first of five and the engineers plan to print the fifth on site.

GET INVOLVED IN ENGINEERING


© London Transport Museum

LONDON TRANSPORT MUSEUM GOES VIRTUAL

Visitors can now experience the Museum's popular Hidden London Euston station tour virtually, with a live tour guide to answer questions. Virtual guests will step back in time as specialist guides talk them through the history of Euston station, journeying through the passageways, emergency stairs and a lift shaft once part of the Hampstead Tube railway.

For more information, visit **www.ltmuseum.co.uk/hidden-london**

CLIMATE CHANGE CATASTROPHE!

This free six-part video series started in May and shares inspiring perspectives on one of the biggest challenges of our time – climate change. It's all about what children think about climate change – their hopes, fears and ideas for the future. The team has worked with students from across the North of England as well as scientists and engineers at Newcastle University.

For more information, visit **www.cap-a-pie.co.uk/climate-change-catastrophe**

INTERNATIONAL WOMEN IN ENGINEERING DAY

23 June

This year's International Women in Engineering Day has the theme of 'Engineering Heroes'. It will celebrate the amazing work that women engineers around the world are doing not just to respond to the pandemic but also to support lives and livelihoods every day.

BIG BANG DIGITAL

23 June to 25 June

Aimed at 11- to 14-year-olds, this three-day event offers a range of interactive sessions covering climate change, food production, medicine, energy, and more, from organisations including the NHS, Rolls-Royce, Specsavers, the Institution of Engineering and Technology, and the Environment Agency.

To register your school, please visit **www.thebigbang.org.uk/big-bang-digital/registration**

EDINBURGH SCIENCE FESTIVAL

26 June to 11 July

This year's festival has over 160 online events and experiences for all ages, covering exhibitions, presenter-led workshops, science shows, discussions, and downloadable family activities. It also has several outdoor experiences such as walks, tours, trails, exhibitions, and installations, which are on display around the city this summer.

To find out what's on, visit **www.sciencefestival.co.uk**

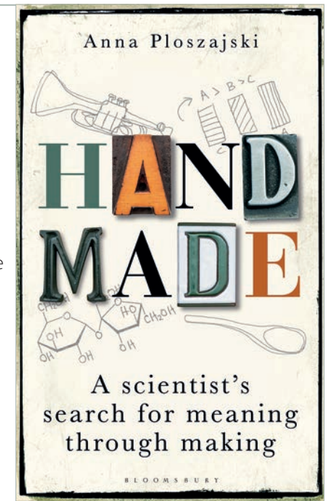
THE ROYAL SOCIETY SUMMER SCIENCE 2021

8 to 11 July

Has there ever been life on Mars? Would you trust a robot surgeon? What's a bee's favourite flower? Summer Science returns for 2021 with a digital showcase of cutting-edge UK science. With a packed programme of inspiring talks, fascinating interactive workshops, fun science from home activities and exciting digital content, there is something for all ages, including workshops for schools.

For more information, visit **www.royalsociety.org/science-events-and-lectures/2021/summer-science-exhibition**

HANDMADE PODCAST AND BOOK



Materials scientist Dr Anna Ploszajski's new book, *Handmade: a scientist's search for meaning through making*, sees her travels the length and breadth of the country to meet makers, artists and craftspeople to try her hand at their craft. Scientific progress has given us a good understanding of the properties of many different materials, but Anna visits the makers, artists and craftspeople to learn from their hands-on knowledge. The book accompanies her weekly *Handmade* podcast, which has over 80 interviews that explore the personal connections we all have with the materials around us.

To find out more, visit **www.annaploszajski.com**

HOW I GOT HERE

Q&A

JOSH OLDHAM
DEGREE APPRENTICE

Josh Oldham is a manufacturing degree apprentice working at Aston Martin and studying applied engineering at WMG, University of Warwick.

WHY DID YOU FIRST BECOME INTERESTED IN SCIENCE/ ENGINEERING?

Two key things inspired me. The first was Lego; as a child I loved to build Lego Technic models and progressed to the more challenging models. I enjoyed seeing what went into making a moveable, functioning model; learning how the mechanisms would perform; and adapting them based on certain inputs and what was needed to make something work.

Second, I had a maths teacher in secondary school who was passionate about the subject. Her passion and the support that she gave me in class truly gave me a love for maths and developed my enjoyment and ability to problem solve. I began to question how I could use this in a career and so I decided that I wanted to pursue engineering.

HOW DID YOU GET TO WHERE YOU ARE NOW?

When I progressed to sixth form, I wanted to choose subjects that would be closely linked to a career in engineering and so studied maths, product design, physics, and engineering.

At my sixth form, WMG Academy, I had the opportunity to do a one-week work experience placement at Jaguar Land Rover. This helped me gain an appreciation as to what goes into an automotive business, supporting me as I started my apprenticeship with Aston Martin.

After my studies had finished, I received a call from my career advisor at WMG Academy, telling me that Aston Martin was looking to employ more apprentices and would I be interested in applying. I had already decided that I wanted to go down the degree apprenticeship route as it would allow me to study the theory involved with engineering while applying it at the same time. I accepted the offer and am now in my third year.

WHAT HAS BEEN YOUR BIGGEST ACHIEVEMENT TO DATE?

At WMG Academy we had regular visits from outside companies to teach us about certain subjects. Employees from Aston Martin presented on subjects such as material selection, manufacturing processes and CAD/CAM. As I went into my first year at Aston Martin, I was given the opportunity to go to WMG Academy and present to the students studying the course that I had completed only a couple of years before. Not only did this mean a great deal to me but it led to another recent great opportunity. In normal years, Aston Martin supports WMG Academy in its open day events. However, because of COVID-19, WMG asked us to send through a short promotional video instead. Another apprentice and I then filmed a video to send to the academy, which was later shared during National Apprenticeship Week by both Aston Martin's COO and a Minister from the Department for Education, which has been a very encouraging experience.

As an apprentice, Josh rotates around the business, finding out how different departments work

WHAT IS YOUR FAVOURITE THING ABOUT BEING AN APPRENTICE ENGINEER?

One of my favourite things is that while studying engineering, I get to apply the theory to the workplace and vice-versa. The degree course that I am studying at WMG, University of Warwick, is applied engineering and is specifically for part-time, work-based learners, so the content that is taught can be applied to our places of work. In my first year, I did the module of applied engineering design, where we were tasked to go into our workplaces, identify a problem or challenge faced by the business, and see, using the design principles that we had been taught, how we could amend the issue. Almost every day a new, unknown challenge will arise and it allows me to assess the situation and think about the best option going forward.

WHAT DOES A TYPICAL DAY AT WORK INVOLVE FOR YOU?

Well one notable thing about engineering is that no two days are the same and that is especially the case when on a rotational period as an apprentice.

In my current role I am working on the Vantage F1 Edition (recently made public) where my time will be split between working in the office and on the manufacturing line. When a new vehicle is introduced, an issue may arise and it is the role of New Model Launch (NML) to make sure that a concern is raised, it is contained/controlled and we, as a business, work towards a solution. Being in NML means you find yourself constantly working with different departments towards the same goal. I will typically speak to colleagues in different areas, building up relationships and helping one another with challenges we may be facing. On top of this, a typical working day will also involve being given time to work on my university studies.

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

Work experience! I always want to promote work experience as it teaches you how to behave and react to situations that you may face. This can be a part-time or full-time job, an apprenticeship or simply a week's placement at an engineering company. You constantly learn, which in turn allows you to increase in the skills that you have, and all these things gained can then be transferred to different job roles and day-to-day life. Work experience is only beneficial if you are willing to learn; about different areas, different processes and so on. If you don't ask questions then you don't learn, so my advice would be: ask questions to help you grow as an engineer.

WHAT'S NEXT FOR YOU?

Thinking short term, I am determined to complete both my degree at WMG and my apprenticeship programme, which are both due to finish September 2022. With these qualifications I would then like to continue with Aston Martin as a senior engineer and progress from there. I haven't specified a department as I'm still rotating around the business and it may be that in the future I find a department that I would prefer to pursue a career in. If all goes according to plan, the next goal after that would be to continue taking on more responsibility as time goes on, with the aspiration to one day work at a manager or senior manager level.

QUICK-FIRE FACTS

Age: **22**

Qualifications: **Working towards a BEng (Hons) in Applied Engineering at WMG, University of Warwick.**

Biggest engineering inspiration: **Both my grandad (who was a mechanical engineer) and Robert Bamford (co-founder of Aston Martin) have been real inspirations to me and are driving forces in staying focused and committed to my role in engineering.**

Most-used technology: **iPhone 11.**

Three words that describe you: **Inquisitive, enthusiastic, meticulous.**

OPINION

OPINION

RETHINKING THE FUTURE THROUGH DESIGN

The coincidence of climate crisis, biodiversity crisis and a global pandemic highlight the fragility of our existence and the complex interdependencies between natural systems, engineered systems, and public health and wellbeing. Dr Mark Fletcher FREng, Global Water Business Leader at Arup, argues that a change in thinking in the way we work is needed, and that engineers need to rethink design and embrace systems thinking.

Dr Mark Fletcher FREng

It is half a century since a series of economic and energy crises led to a realisation that current development trajectories could not be sustained; resources were finite and there may be limits to growth. It became evident then that global challenges in the future may not be solvable through technology or the established pathways of planning and infrastructure delivery. There emerged an awareness of the interdependencies between ecosystems and human systems. The need to rediscover how we might design with nature became apparent. Over time, the concept of 'sustainable development' became established, slowly infiltrating mainstream practice, leading to more holistic approaches and, in recent years, the widespread adoption of the United Nations' Sustainable Development Goals – global aims to achieve a better and more sustainable future for all. But the shift in the way we work has not been fast or deep enough to address the issues foreseen decades ago. There has been lots of rhetoric but insufficient action, as the need was not perceived as acute.

It has become increasingly clear that our natural systems have become depleted, degraded and out of balance due to human development. In many areas, our human and social systems are also struggling to provide a resilient and equitable social foundation. The pandemic has highlighted again how poverty and inequality increases vulnerability to shocks and stresses. It is no longer sufficient merely to 'sustain' current systems: in many areas we need to restore and enhance them to leave them in a better place for future generations. For example in Hull, we have been assessing the water resilience of the city and how regenerative interventions across natural, engineered and human systems can play an active role going forward.

It is no longer sufficient merely to 'sustain' current systems: in many areas we need to restore and enhance them to leave them in a better place for future generations

Arup was founded on the principles of integrated design: crossing silos, balancing science, engineering, and creativity with arts and culture to create better outcomes. As we rethink what that means in the face of current challenges, the role of design in its broadest sense feels more important than ever. Design needs to embrace a greater understanding of our natural systems, natural processes, and their interdependencies with other systems such as transport, energy, food, people, and place. Ian McHarg's *Design with Nature*, published in 1971, is a seminal work in the history of ecological design and urbanism. In advance of geographic information systems, it pioneered novel approaches to design and decision-making informed by data and insight across natural and human systems. It seems more relevant than ever as we rethink and recalibrate our relationship with the natural world and the way we design within it. Within the water sector, for example, we must consider how restoring, protecting and enhancing the integrated water cycle can become a catalyst for increasing the resilience, health and wellbeing of our human and natural systems. This could mean restoring a river to sustain greater biodiversity, increase the value of place, encourage greater social interaction with the river, and stimulate economic regeneration. Similar approaches can be taken across all the work of engineers and designers. The most important aspect is not the starting point, but the subsequent process and the outcomes. The concept of regenerative design is a powerful way to capture this approach, which goes beyond the status quo to create net gain across the entire system, minimising loss of biodiversity and helping to restore ecological networks. This can be qualitatively and quantitatively assessed through the social, natural and economic capital derived from the eco-system services provided by the intervention.

What we design is shifting. We are as likely to be curating nature-based solutions, working with a wide range of other disciplines, as engineering more traditionally derived infrastructure. We will work more frequently with the complexity of retrofitting existing buildings, infrastructure and landscapes within our evolving developed world. How we design is changing too. Designing for resilience and regeneration means a renewed focus on collaborative process, openness, diversity, adaptability, and consideration of place-based insight and lived experience.

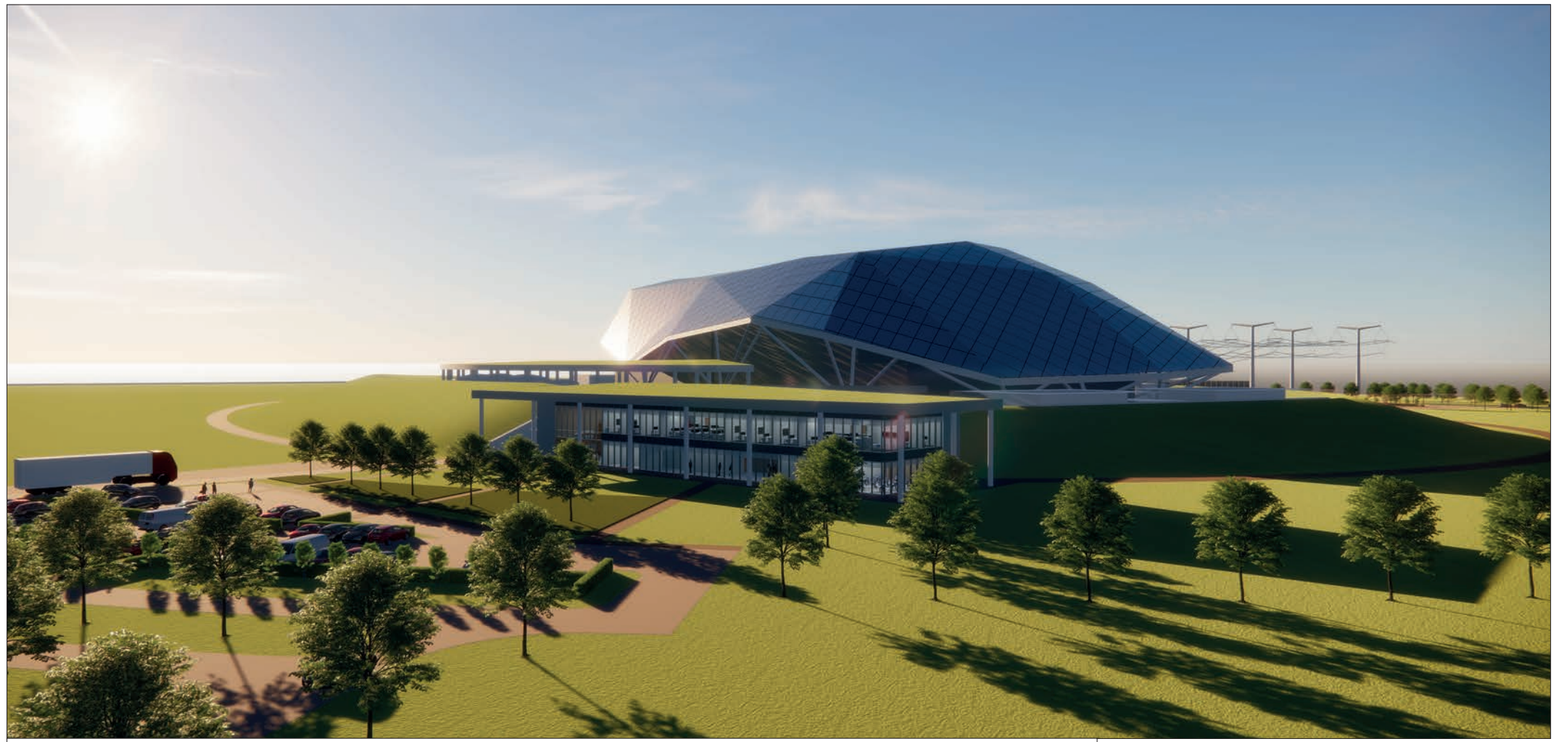
As we evolve our thinking and reflect on publications such as *Design with Nature*, the most important word within that title is 'with'. To design with [water, nature, people, community, place, contingency, time, and so on] means looking beyond, continuing to push boundaries, and absorbing more into our current practice as engineers with a primary focus on outcome. This means extending our own skills and broadening our collaboration with others while increasing our understanding of the natural processes and system we are working within. Our work is becoming more complex, challenging, meaningful, and exciting as a result. For example in Shanghai, we are working at city scale to develop a drainage masterplan, which embraces nature-based blue-green infrastructure as part of a restorative and regenerative approach.

We need to embrace sustainability, practice regenerative design, design for resilience, and respect planetary boundaries. We need to take an integrated approach, embrace the context of working within a natural system, harness the best of technology and balance this with stronger, fundamentally embedded social and cultural considerations. All these principles are critical and inter-related. They have been useful in broadening out the scope and focus of engineering practice and building a wider shared narrative about our future.

Terminology is bound to shift. New concepts and framings will emerge, but the underlying principles are established now and the imperative to act is clear. As engineers we need to do all we can to accelerate holistic, regenerative outcomes for people, places, and the planet. We should tune ourselves into nature. Learn from it and work with it. We cannot wait another 50 years.

BIOGRAPHY

Dr Mark Fletcher FREng currently leads Arup's Global Water Business. He became an Arup Fellow in 2017, an Honorary Fellow of the Society for the Environment in 2018 and a Fellow of the Royal Academy of Engineering in 2019. He is also Chair of the Water Industry Forum, Leadership Council Member of UK Water Partnership and Board Member for British Water.



An earth embankment around the power station integrates with the surrounding landscape. An SMR would be small enough to sit alongside an integrated 'energy park' or in remote locations connected to the electricity transmission network © UKSMR Consortium

Did you know?

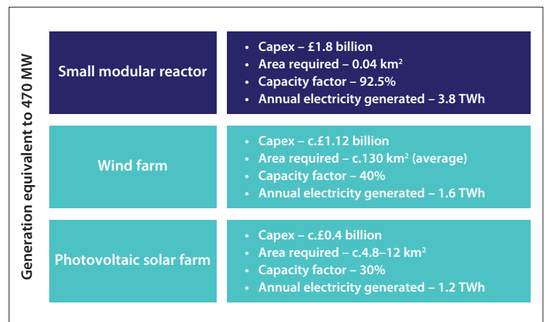
- SMRs produce up to 500 MW of electricity
- Around 90% of an SMR will be factory fabricated and moved to sites for assembly
- An SMR has a footprint of about one and a half football pitches
- Modular design and a construction canopy reduce the risk of delays

We must abandon fossil fuels as an energy source if we are to achieve the UK's target of net zero by 2050. Low-carbon energy sources, such as hydroelectricity, wind, solar, and nuclear energy, now provide less than 15% of the world's energy. Paul Stein FREng, Chief Technology Officer of Rolls-Royce, and Sophie Macfarlane-Smith, the company's Head of Customer Business for civil nuclear and small modular reactors, explain how SMRs could help to achieve net zero.

NUCLEAR DESIGNS ON A LOW-CARBON FUTURE

The future energy market will be fundamentally different as the world eliminates carbon emissions in a move to an age of 'net zero'. Cost-competitive, scalable and reliable sources of clean electricity will be a key element, both for direct use, as today, to charge electric vehicles, and potentially to power the production of synthetic fuels generated from hydrogen and captured carbon, to create fossil-free hydrocarbons as substitutes for oil and gas.

While new technologies can and must continue to be developed, we need to deploy existing low-carbon technologies more reliably and affordably to achieve net zero by 2050. We cannot rely on existing renewable technologies to fulfil those energy requirements alone because of their intermittency and the scale of the energy storage needed to accommodate their variability. For these reasons, wind and solar have significant limits. Nuclear power is increasingly seen as an integral solution for many countries and industrial users.



A small nuclear reactor would fit on an area smaller than two football pitches, less than land required for other fossil-free electricity generators

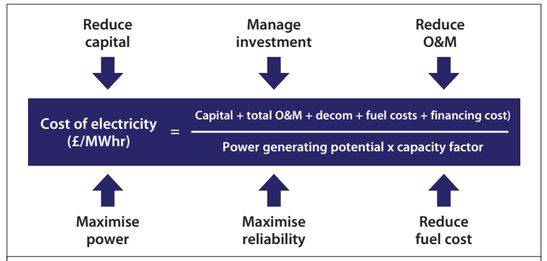
SMALL-SCALE NUCLEAR ENERGY

Nuclear power currently produces around 10% of the world's electricity. This power source can deliver safe, reliable low-carbon power consistently from relatively compact power stations to feed the electricity grid. Nuclear power stations can also provide heat and electricity to installations that can deliver other forms of decarbonised energy along with district heating. However, nuclear power has yet to be widely adopted. This is in part because of the high cost of the large individual power stations now on offer, and because the price of nuclear electricity from those facilities cannot compete with power from other sources.

Small modular reactors (SMRs) are a potential solution to this problem. The term SMR covers a range of differing nuclear technologies but it

essentially refers to a newer generation of reactors designed to generate typically less than 500 MWe megawatts of electrical power, The idea is that factories will manufacture SMR components and systems for transport as modules for installation and commissioning at site. It is essentially a factory fabricated, road transportable and site assembled, fully integrated nuclear power station. The International Atomic Energy Agency (IAEA) currently lists over 70 different SMR designs under development using various technologies, including conventional water-cooled reactors, high temperature gas-cooled reactors, molten salt reactors, and micro-reactors, smaller devices with outputs of up to 10 MWe. There are also different approaches to manufacturing, installation and operation of these designs.

A consortium led by Rolls-Royce has devised an SMR where each plant is around the size of one and a half football pitches. Its design is projected to cost £1.8 billion for a power station with an output of 470 MWe with a four-year build time. The key principle behind the design is to enable the safe delivery of low-carbon power at the lowest Levelised Cost of Electricity (LCoE) to the consumer. The LCoE is a commonly used way of comparing the costs of different ways of generating electricity. The LCoE incorporates energy projects' complete costs and, for this UK-SMR programme, the LCoE also includes the cost of waste management and decommissioning. Each SMR aims to operate for 60 years at a LCoE (real delivered cost) between £35 and £50/MWh, roughly the current wholesale market price.



The Rolls-Royce-led consortium uses this equation to ensure that decisions across the SMR programme result in the lowest cost of electricity

PLANT DESIGN

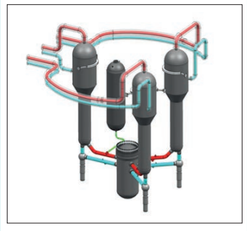
The consortium's focus has been on aspects of plant design that impact LCoE. These include construction, capital costs, financing risk, build time, and operation and maintenance costs. This analysis has resulted in various decisions. These include the design not just of the nuclear island but of the complete power station. It also influenced the decision to base the design on a pressurised water reactor (PWR) and accompanying off-the-shelf fuel technology, using standard nuclear energy technology used in 400 reactors around the world. In this way it could ensure compatibility with existing regulatory processes and existing nuclear infrastructure around fuel and waste routes. The focus on LCoE also resulted in a decision to adopt factory fabrication and modularisation followed by plant assembly on an aseismic bearing – a giant shock absorber that neutralises local seismic conditions.

PWRs have been the predominant nuclear technology since the development of the first commercial plant in the 1960s. Various designs of PWR constitute the majority of the world's nuclear power fleet, including the UK's latest generation of reactors. The consortium saw this proven technology as the best option in combination with advanced digital, manufacturing and construction techniques. Operators and nuclear regulators globally understand the fundamental design of PWRs, reducing regulatory risk and the need for a prototype, further reducing cost and time to deployment.

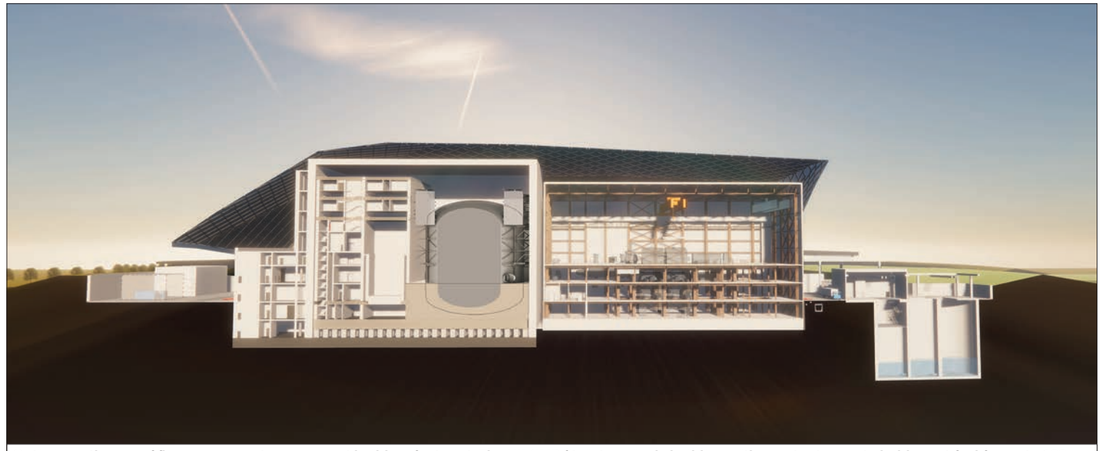
The nuclear island, a critical component of the power station, represents only about 25% of the overall cost. Therefore, to drive down the LCoE it is important to consider the design of the whole plant at the outset. For this reason, the consortium includes organisations from both the nuclear and civil construction sectors including Bam Nuttall, Laing O'Rourke, Atkins, Jacobs, Assystem, TWI, National Nuclear Lab (NNL), and the Nuclear Advanced Manufacturing Research Centre. The current phase of the programme has been jointly funded by all consortium members and UK Research and Innovation (UKRI). UKRI launched the programme in November 2019 with an initial investment of £18 million matched by the Rolls-Royce UK-SMR consortium.

UKRI increased its involvement in SMRs a year later with £215 million investment in the Low Cost Nuclear (LCN) programme, matched by £300 million from private funding sources. The aim of the LCN is to enable the UK to deploy SMR and advanced modular reactors quickly and efficiently. UKRI anticipated that the LCN programme could yield a return £52 billion to the UK economy by 2050 if a full fleet of 16 power stations is built. There could also be a £250 billion export market, creating up to 40,000 high-value jobs and rejuvenating UK manufacturing in the north of England and North Wales.

NUCLEAR ISLAND



The UK-SMR is built around a 'nuclear island' based on proven pressurised water reactor (PWR) technology, using industry standard uranium oxide (UO_2) as fuel. Three centrifugal pumps circulate coolant to three corresponding vertical steam generators, with a total electrical output of around 470 MWe. The design of the nuclear island also includes multiple active and passive safety systems, each with substantial internal redundancy.



Optimising the use of floor space creates a compact building footprint. The UK-SMR fits into a single building with on-site storage to hold spent fuel for up to 100 years before it must be transferred to a long-term storage facility © UKSMR Consortium

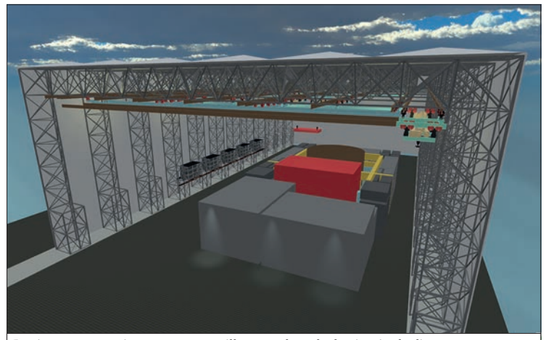
The overall plant design includes several areas of innovation. For example, modularisation of the entire power station enables around 90% of the plant to be factory fabricated and road transported to site for assembly. The whole production process brings together advanced manufacturing techniques, with digital process control. The plan is to integrate this approach, often known as Industry 4.0, with advanced manufacturing methods such as additive layer manufacturing, or 3D printing, of metals, along with 'inspect while weld' techniques and large-scale robotic handling. In this way, we can bring to the nuclear industry techniques that have revolutionised the cost and 'right first time' rate of high-value manufacturing. These innovations, along with process monitoring including the use of Internet of Things and other techniques, will allow the efficient standardisation of the product, module sizes and interfaces. They will also enable factory testing and commissioning of individual modules prior to site assembly. Additionally, wherever possible modules are designed to incorporate 'off-the-shelf' products and to reduce the need to invest in specialist factory facilities.

The modular design aims to reduce the risk of construction delays, which can significantly increase costs and timescales at many nuclear new build sites. The compact layout for the UK-SMR design means that a construction canopy can be used for the first time to cover the entire nuclear construction site. This approach reduces the risks that adverse weather will delay construction. The canopy also provides internal craneage and an adequate construction environment day and night, if required. Many civil construction projects have successfully used this approach.

The compact layout is also designed to protect the reactor against seismic events. Aseismic bearings can isolate the nuclear power station from the ground and any seismic motion. An advantage of this approach is that the bearings can be 'tuned' to a site and its level of seismicity – the size, type and layout – removing the risk of the plant itself needing redesign to meet local seismic conditions.

Digital twinning, building a virtual replica of the project as a way of monitoring progress and simulating the plant, underpins the design, construction and operation of the plant across all aspects of the programme (to learn more about digital twins, see *Creating a virtual replica* on page 16). The system design will be maintained wholly digitally and integrated with analytical models for each element so at all times there will be a virtual plant on which design changes can be tested. As plants enter service, real-time operational data will be added continuously to provide the basis for intelligent maintenance and design improvements. Rolls-Royce has successfully applied these digital technologies on projects like large gas turbines, where engineers take entire digital twins from concept, through performance modelling, design, manufacturing, and on to in-service monitoring. The UK-SMR design has been digitally captured and will continue to be recorded through manufacture and construction to enable a full digital twin of each plant. This will not only allow simulation and optimisation of all stages of the plant lifecycle but is an essential component, enabling the plant to be successfully replicated at scale in other markets.

The fuel for the UK-SMR will use low-enriched UO_2



During construction, a canopy will cover the whole site, including cranes, to allow 24-hour operation and to reduce the risk that bad weather will cause delays © UKSMR Consortium

assemblies with only minor modifications on those used to fuel conventional PWRs. Packaged in similar arrays, the fuel components for the UK-SMR will minimise development risks and costs. This choice means that existing commercial fuel manufacturers can supply fuel and that existing infrastructure for handling used fuel can be simply reused.

The emissions and waste from the SMR's nuclear fuel cycle are clearly important. Over one year, a typical 500 MWe coal-fired power station will burn around 1.6 million tonnes of coal and emit about 2.5 million tonnes of CO_2. Over the same year, a UK-SMR could consume less than 16 tonnes of fuel and produce around 5 m^3 of higher activity radioactive waste, an amount that could fit into the back of a small van. Nuclear energy is the only power source that puts its waste in a container instead of into the atmosphere. Additionally, in line with current UK regulatory requirements, the UK-SMR is designed to store used fuel on site in purpose-built facility for up to 100 years before having to remove it to a long-term storage facility.

AFFORDABLE GREEN POWER

The UK-SMR aims to reliably produce consistent low-carbon power at an affordable price. That it can be deployed at a wide range of appropriately licensed compact sites also means that it could be incorporated into an integrated, decarbonised energy system. Along with their key role as generators for the national power network, SMRs could also provide electricity for hydrogen, synthetic aviation fuel and other e-fuels. They could also have a role providing district heating to nearby towns and cities. This integrated approach means that a plant can be used at maximum efficiency alongside intermittent low-carbon technologies such as wind and solar. Alternatively, SMRs could be deployed remotely, connected to the grid through low-loss transmission technology or simply powering hydrogen or synthetic aviation fuel (SAF) plants where the fuel product can be transported to the point of use.

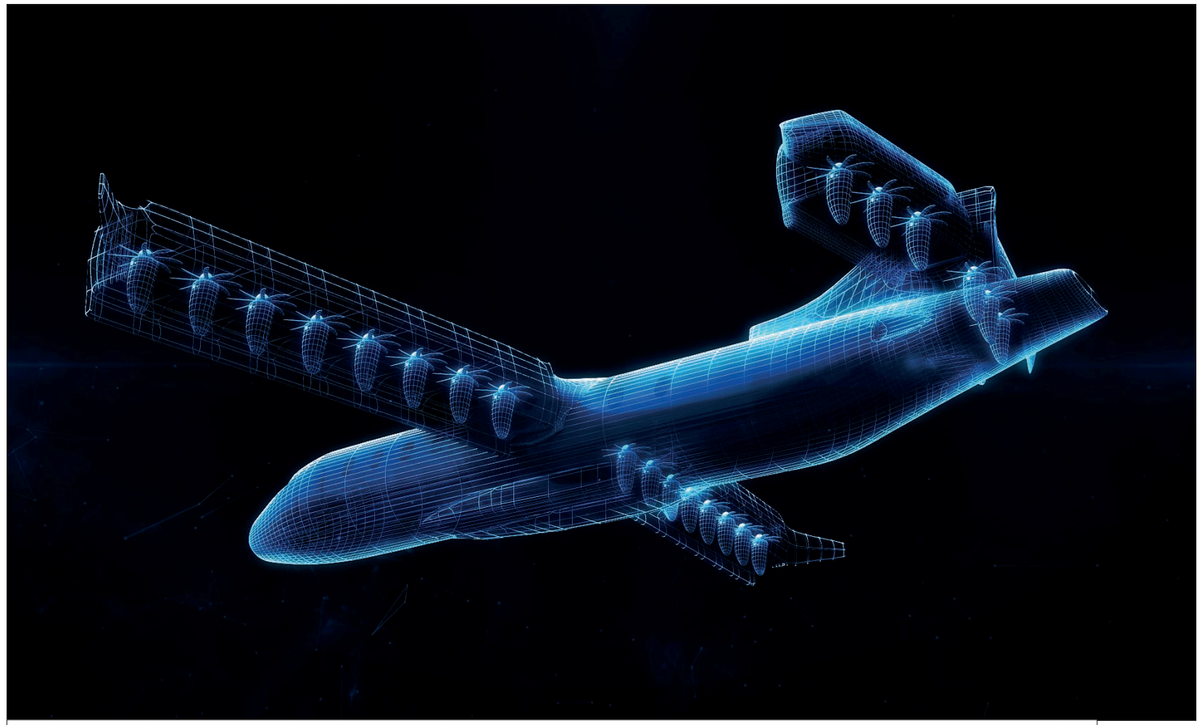
The process of production and assembly of the UK-SMR is designed to be scalable. To accelerate deployment, the factory and power station would be templates for reliable scale up without design changes or affecting quality. Essentially, we could build more factories where required if more power stations are needed. In this way, the UK-SMR could play in important role in the creation of integrated 'energy parks', supporting renewable sources of electricity in the creation of e-fuels for energy storage and transmission. Company nuclear power stations could also open up export opportunities. In the latest of several similar agreements, Rolls-Royce recently signed a Memorandum of Understanding with Fermi Energia to study the potential for the deployment of affordable, compact nuclear power stations in Estonia.

As the work continues, and to keep up the pace of progress, the UK-SMR team is making the transition from being a collaborative consortium to a standalone business, in which Rolls-Royce retains a significant interest, along with other equity investors. Work on the design, with more than 200 major engineering decisions made during the latest phase, has optimised the configuration, efficiency and performance criteria of the entire power station. In the process, it has increased the expected power capacity, without additional cost, from 440 MWe to 470 MWe. The plan is to have the first design to be assessed by regulators and to start the rigorous Generic Design Assessment process, through which the Office for Nuclear Regulation assesses whether the design meets all requirements for a nuclear plant to be operated in the UK, in the second half of 2021. This would keep the consortium on track to complete the first unit in the early 2030s and to build up to 10 by 2035.

BIOGRAPHIES

Sophie Macfarlane-Smith is responsible for the development of global customer opportunities and associated government relationships at Rolls-Royce. She completed a master's in the physics and technology of nuclear reactors at the University of Birmingham and then joined Rolls-Royce's reactor physics team in 1996. She has also had technical and project delivery roles in sectors including submarines, and naval and commercial marine. She has recently achieved her brown belt in Shotokan karate.

Paul Stein FREng is accountable for Rolls-Royce's technology investment and ensuring close alignment with business strategy. He joined Rolls-Royce in 2010 as Chief Scientific Officer and acted as the Engineering and Technology Director for the company's nuclear business for two years. Before joining Rolls-Royce, Paul was Director General, Science and Technology, at the Ministry of Defence. He is a Fellow of the Royal Aeronautical Society and the Institution of Engineering and Technology.



Rolls-Royce used a digital twin for its Intelligent Engine, which allowed its engineers to study and predict the physical behaviours that the engine would exhibit under very extreme conditions and model potential operational scenarios entirely digitally © Rolls-Royce

CREATING A VIRTUAL REPLICA

Digital twins provide virtual replicas of a physical object or system, such as a bridge or an engine, that engineers use for simulations before something is created or to monitor its operation in real time. Stuart Nathan spoke to Mark Girolami, who leads the Lloyd's Register Foundation programme on Data-Centric Engineering at the Alan Turing Institute, where he is also Strategic Programme Director, and Professor Lord Robert Mair CBE FREng FRS, Head of the Centre on Smart Infrastructure and Construction at the University of Cambridge, about how digital twins are transforming engineering.

Did you know?

- Digital twins use real-time data from sensors to monitor a physical object
- Engineers at organisations such as Ocado, Rolls-Royce, NASA, and Ford use them
- They can reduce maintenance costs, improve efficiency and predict future performance
- Digital twins of humans could be created for use in areas such as healthcare and retail

"If you can't measure it, you can't hope to control it" is one of the truisms of science and engineering and is also known as "the one Kelvin got right". It was one of eminent Victorian physicist William Thomson's, also known as Lord Kelvin, favourite sayings and is fortunately more accurate than his confident declarations that heavier-than-air flight was impossible and that X-rays were a hoax. It's also the axiom at the heart of one of the most important technologies currently being implemented in engineering: the digital twin.

The concept of a digital twin has been around for about a decade, but it's only in the past five years that large-scale implementation has begun to happen. An essential component of the developments known as Industry 4.0 or the 'fourth Industrial Revolution', digital twins make the smart connected sensors that are ubiquitous in modern engineering visible – capturing their data and putting it onto a display for process operators to see in real time. This allows them, and by extension the entire enterprise, to observe how their facility is operating, and the influence that the conditions or settings of machinery are having on the output of the plant or physical asset.

There is still some confusion over the terminology of digital twins. It is not uncommon to see a simulation intended for use in the design of a factory or plant described as a digital twin, but Mark Girolami, Sir Kirby Lang Professor of Civil Engineering at the University of Cambridge and leader of the programme for Data-Centric Engineering at the Alan Turing Institute, explains that a true digital twin is not a simulation but a representation. "The most important thing is that it uses real data from operating machinery and live processes to show what is happening," he says.

MONITORING JET ENGINES

Rolls-Royce pioneered one of the earliest and most striking uses of digital twins. The aerospace giant combines the multitude of sensors embedded in its jet engines with machine learning and software analytics to create a virtual replica of the engine in operation, which continually updates itself. It takes in not only the conditions inside the engine but also the ambient environment affecting its operation.

By measuring the engine's condition and ambient environment around it, Rolls-Royce's digital twin enables engineers at the company's operational headquarters in Derby to monitor the condition of an engine in flight, for example between London and Jakarta, with the data relayed back by satellite link, and observe any fluctuations in engine performance that might indicate a component in need of repair or replacement © Rolls-Royce

The machine learning and analytics functions help relate the sensor readings to the component-by-component operation of the engine and identify what is likely to be the cause of performance fluctuation. This allows the company to schedule maintenance of engines before they fail and cause aircraft to be taken out of service, damaging their operators' income. This, in turn, helps Rolls-Royce's business model of selling aircraft operators time in the air, or as the company expresses it 'power by the hour', rather than merely selling them engines. Rolls-Royce calls this strategy the 'intelligent engine'.

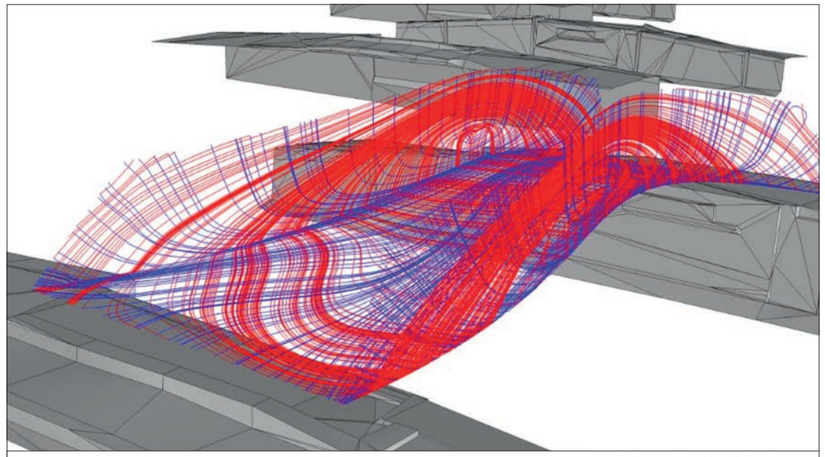
It's the machine learning and analytics aspects of the digital twin that have delayed its implementation. Both depend heavily on computing speed and power, which has only really developed in the past few years. While it would have been possible at any time to merely display sensor outputs remotely – and indeed this has been

standard operating procedure in process plants for many years – the ability to relate these readings to the operation of the asset and use this to predict how output might change is key to the advantages of operating a digital twin.

INFRASTRUCTURE INSPECTION

Rolls-Royce's use of digital twins inspired a much more down-to-earth application of the technology. Professor Lord Robert Mair CBE FREng FRS, Head of the Centre on Smart Infrastructure and Construction (CSIC) at the University of Cambridge, explains: "we wondered if we could get the same sort of results from implementing that technology on civil engineering assets, particularly railway bridges." Static, non-mechanical structures are obviously very different from highly complex jet engines, but in the sense that they need regular maintenance and cause huge disruption if they fail, they share important features.

CSIC put this into practice on two railway bridges in Staffordshire. Traditionally, asset management of railway bridges depends on periodic visual inspection to detect components or structures that may be about to fail. To replace this system, Professor Mair's team installed fibre-optic sensors in a prestressed concrete girder bridge and a steel composite girder bridge, using the data from these to construct digital twins of both bridges. The steel bridge had 108 fibre Bragg grating (FBG) strain sensors on both the main steel I-beams and the transverse I-beams. "The sensors can measure strain and temperature at discrete points along an optical fibre," Girolami explains. "Fibre-optic sensors are lightweight, require a minimal number of wiring cables and provide stable, long-term measurements. When laser light is shone down a fibre-optic cable, the gratings act like dielectric mirrors reflecting only those wavelengths that match the Bragg wavelength. When the fibre optic cable is elongated (or shortened), the wavelength of the reflected light shifts in proportion to this change in strain." The strain is calculated by taking account of the thermal expansion of the glass.



The Alan Turing Institute's programme in Data-Centric Engineering has been developing a 'digital twin' of the 3D-printed bridge in Amsterdam to help analyse the sensor network data, as well as conducting extensive tests of the physical printed material and using statistical methodology to understand more about the material itself © Alan Turing Institute

Trains pass over the bridge at up to 160 mph in both directions. "Every time a train goes over one of these bridges, the sensors register how the structure reacts to all those moving forces and give us huge amounts of data," Professor Mair says. "We can then use the digital twin to tell us whether the structure can stand up to those forces by relating them to the design tolerances of those two different types of girder.

One thing that has been vital to this is a shift to manufacturing those structures under controlled conditions in factories and transporting them to the site to be assembled, rather than casting concrete on site."

The Alan Turing Institute is also involved in the project, analysing up to 12 GB of data per day and relaying this analysis to structural engineers at Cambridge. One of the complicating factors, Professor Mair says, is that the digital twin does not display the raw data from the sensors, but rather derived quantities such as stress and strain. "Establishing the live link between the asset and the twin and ensuring that what the engineers see is directly meaningful is a non-trivial task, and one where we have depended strongly on the Turing Institute team," he adds.

Although the Staffordshire projects have established twins on new assets, Professor Mair points out such capability can also be retrofitted onto existing structures. "One of the important features of the railway network in Britain is that so much of it is Victorian," he notes. "In Staffordshire, we had the advantage of dealing with brand-new structures, but that's very much the exception rather than the rule." In Leeds, he adds, the CSIC was involved with a project to create a digital twin of a Victorian railway viaduct that carried the mainline through the city and into its main station.

"It's a very large structure, it's right in the middle of the city and it looked like it was in bad repair, with very large visible cracks in the brickwork. There was a concern that it would have to be entirely replaced, which would have been hugely expensive and disrupting over a very long period of time. But we retrofitted the same type of fibre-optic sensor that we had used in the new structures in Staffordshire onto this Victorian brickwork, created a digital twin and established that, despite its looks, the viaduct was in fact performing perfectly well and would do for years to come. For

In Clapham, south London, an unusual business occupies tunnels 33 metres underground, originally built as deep-level shelters to protect residents from bombs during the Second World War

a relatively low investment, we showed that there was no need to spend millions of pounds."

UNDERGROUND CROPS

Digital twins are having an effect even below ground. In Clapham, south London, an unusual business occupies tunnels 33 metres underground, originally built as deep-level shelters to protect residents from bombs during the Second World War. Hydroponics farm Growing Underground has filled the complex with banks of shelving holding systems to grow salad leaves and 'micro-greens' – intensely-flavoured, quickly-grown herbs – for London restaurants and outlets including Waitrose and Marks & Spencer. Growing food in the centre of the city greatly reduces the 'food miles' of the products: the farm can cut and package produce and deliver it to New Covent Garden Market within four hours. While the farm was under construction, engineers from the University of Cambridge were installing sensors to construct a digital twin.

In an underground farm, nothing is natural. Instead of sunlight, the plants are supplied with artificial light from LEDs, emitting wavelengths selected to optimise photosynthesis. The flow of water and nutrients into their growing medium is controlled, as is the temperature and humidity of the environment. All these factors influence the yield of the crops being grown in the tunnels; cameras and load cells measuring the weight of the plants provide an indication of how much vegetation is growing.

This made the operation an ideal candidate for digital twin technology, particularly to optimise its energy usage. Lighting, heating and air circulation all rely on electricity, and although the farm produces 12 times more per unit area than the conventional greenhouse and uses 70% less water, it also uses four times more energy per unit area. The farm occupies approximately the same area as a tennis court, but by 2022 is expected to produce over 60 tonnes of produce per year. Its electricity is generated by renewable sources, but to be sustainable it needs to ensure that energy use is minimised while crop growth is maximised. "From day one, the Growing Underground founders, Richard Ballard and Steve Dring bet on data to help them, and we've assisted them from the start of their data journey," explains Melanie Jans-Singh, a PhD student studying energy models and digital twins for urban integrated agriculture, who installed the sensor network in the tunnels.

The network consists of 25 sensors measuring 89 variables, transmitting to eight Raspberry Pi data loggers housed in the tunnels, which send their data to a server in Cambridge and on to an online horticultural data platform. "What the digital twin shows is better than being in the tunnels in person," says Jans-Singh. "It can monitor, learn, feedback, and forecast information that will improve working."

A digital twin helped the farm understand how the tunnel environment was affected by external weather, in particular hot days. This affected the lighting and the fans used to extract and circulate air. Subsequently, integrating forecasting models into the digital twin allowed the system to suggest operational changes for the day ahead and then tell operators how successful these were. "The farm manager checks the dashboard and sensor data at the beginning and end of the workday, so we've set the system to provide a forecast at 4am ready for the first workers arriving at 6am to help with decision-making for the day, and another at 4pm to warn about possible conditions that will happen overnight just before they leave," explains Jans-Singh. "This might mean reducing

OCADO'S DIGITAL TWINS RESTORE ORDER

As previously reported in *Ingenia* ('Hives of activity', *Ingenia* 80), online grocer Ocado uses digital twin technology at two of its automated warehouses. "Digital twins can help us answer 'what if?' questions about the future such as the potential impact of climate change, disruptive changes to systems such as the impact of local energy generation and electric vehicles on the national grid, the impact of new policies or regulatory frameworks and so on," explains Paul Clarke, Ocado CTO, in a post on the blog *Data-Centric Engineering*.

The automated warehouses use robots to pack customer orders into carrier bags placed in plastic crates known as totes. Identifying barcodes on the totes are scanned at junctions between aisles, ensuring that they are following the correct route to fulfil the orders they hold, while item barcodes are used to verify that the correct items are going into their appropriate bags. Sensors around the facility helped detect events such as totes slipping due to variations in friction between the crates and the surface of the conveyor belt in which they were travelling and variables such as mechanical faults that caused delays or diversions.

When planning a new automated warehouse, Ocado first produces a simulation of how the swarm of robots that pick items from storage bins will move around the space. These simulations subsequently evolve into digital twins, handling the 5,000 data points robots produce 1,000 times per second. This totals some 4 TB of data per day per swarms of 3,500 robots in one warehouse. The data is handled by machine-learning systems that perform predictive maintenance, while a digital twin optimises the behaviour of the swarm and updates the parameters of the control system that runs the robotic hive.

South London-based Growing Underground can harvest, pack and deliver produce to central London all within four hours. The use of digital twins at the facility keeps operations running smoothly © Growing Underground/Paul Marc Mitchell (left image)/Martin Cervanansky (right image)

ventilation if the farm is like to be too cold, temporarily adding a heater in a specific location, or trialling different light settings." The twin's users can look at measurements of environmental variables in specific areas, to help them work out why plants might be growing differently in one place to another.

It isn't just yield that the twin helps to optimise. The team is also trying to tweak growing conditions to increase the sugars and starches in the crops, to ensure good flavour and nutritional value.

The Growing Underground team is developing a second site, a disused warehouse that will be able to supply a larger area of London. Here, the live twin feeds into a simulation of this new farm, which the Cambridge researchers are using to help specify equipment and design the layout to keep the warehouse environment stable and minimise energy usage. Jans-Singh is currently working on incorporating machine vision into the farm system so that the cameras monitoring the plants can provide more information on growth levels and colour of the crops.

FUTURE TWINS

The success of digital twins in industry is now beginning to spark interest in whether digital twins could be created for humans. These could be used in healthcare – for example, connecting the sensors on a patient undergoing surgery to a digital twin could help anaesthetists ensure that patients remain in the healthiest condition possible, while intensive care units are also an obvious target. In a less obviously benign situation, data collected by online activity and wearables might be used to construct digital twins of consumer behaviour that could be used to inform strategy for retailers, insurers and other commercial operations.

As a virtual representation of an object or system that spans its whole life, updates using real-time data, and uses simulation, machine learning and reasoning to help decision-making, digital twins give engineers the ability to see how physical assets are working – now and in the future. Therefore, it's no surprise that they are already helping engineering businesses stay ahead of the game.

DIGITAL TWINS IN CARDIAC MEDICINE

A complex version of the digital twin is being investigated for use in improving cardiac medicine. In a paper published in March 2020 in the *European Heart Journal*, a team led by Pablo Lamata of King's College London's Department of Biomedical Engineering, explains how a digital twin could be used to help patients. They combined data from electrocardiograms with mechanistic models, which are based on the electrical activity inside and in between cells in the cardiac muscle and provide a mathematical model to define the heart's electrical activity, with statistical techniques to both improve diagnosis and guide treatments for heart conditions. For example, one metric based on simulations of heart activity and circulation can differentiate patterns of muscle activity, and thereby predict the response to cardiac resynchronisation using a pacemaker.

BIOGRAPHIES

Mark Girolami FRSE is the Sir Kirby Laing Professor of Civil Engineering at the University of Cambridge. Before, he was Chair of Statistics in the Department of Mathematics at Imperial College London. In 2018, he was appointed Lloyd's Register Foundation/ Royal Academy of Engineering Research Chair. As Programme Director for Data Centric Engineering at the Alan Turing Institute, he leads a team of more than 150 researchers, who are working on projects with Network Rail, Rolls-Royce, the National Air Traffic Service, and Transport for London, among many others.

Professor Lord Robert Mair CBE FREng FRS is a geotechnical engineer, Emeritus Sir Kirby Laing Professor of Civil Engineering at the University of Cambridge and a Past President of the Institution of Civil Engineers. He was appointed an independent crossbencher in the House of Lords in 2015 and until recently was a member of its Select Committee on Science and Technology.

Melanie Jans-Singh is a PhD student at the University of Cambridge studying energy models and digital twins for urban integrated agriculture.

Leaves on railway line cause the rails to become slippery, causing trains to experience less adhesion, which can lead to wheelslip when the train is setting off and wheelslide when the train is braking. Several technologies aim to solve this problem © Shutterstock

LEAVES ON THE LINE

Slippery layers of wet leaves on railway lines have been causing train delays for years, and numerous attempts have been made to solve the issue. Geoff Watts spoke to the engineers working on innovative solutions to the longstanding problem.

Did you know?

- Fallen leaves on railway lines cause trains to slip and cause delays
- Leaves and other debris are currently cleaned by high-pressure water jets
- Engineers have developed technologies using plasma, ultrasound, laser, and dry ice to clean rails

Of the reasons put forward to account for the 'operational difficulties' that can disrupt railway timetables, few earn more scorn, derision or even downright disbelief than that of delays caused by 'leaves on the line'. Even the most well-informed passengers may find this explanation – a loss of adhesion between train and track – rather hard to swallow. The scepticism is understandable; when steel wheels press with a force of 30 tonnes/square inch on to small areas of unyielding steel rail, the suggestion that traction between the two can be thwarted by something as fragile and insubstantial as a few leaves is certainly counterintuitive.

The hard, black, thin, slippery layer that forms on the surface of leaf-covered rails subjected to the pressure exerted by a train's wheels is not completely understood. The physics and chemistry of these leaf deposits is still debated, but they comprise a mixture that includes cellulose, cellulose acetate and the amino acid tyrosine. How this bonds so firmly to the metal surface is uncertain, and many questions remain.

The extent to which leaves undermine adhesion has varied over time. The disappearance of steam locomotives in the 1960s eliminated the risk of trackside fires, and vegetation that had that had hitherto been cut back was left to flourish. Leaves then became an increasing problem. More recent troubles with adhesion reflects the lighter weight of modern trains.

The Rail Safety and Standards Board (RSSB), the body charged with delivering a better UK railway system, is looking for an alternative to the current method of tackling the leaf problem, with Network Rail or relevant train operators making a final decision.

NOT LEAVES ALONE

Although by far the most troublesome, leaves are not the only cause of slippery rails. Lubricants dripping from rolling stock, for example, can play a part. Nor is the concern with adhesion a recent phenomenon, says Professor Simon Iwnicki FREng, Director of the Institute of Railway Research at the University of Huddersfield. An interest in the topic goes back to the earliest days of the railway, when some engineers were initially sceptical that steel-on-steel adhesion could generate the traction required to pull any but the lightest loads.

The logistics of real-world testing of railway innovations are unavoidably burdensome and costly, but preliminary studies can be laboratory-based. The University of Huddersfield's rolling contact, adhesion and braking test rig incorporates rails wrapped around a two-metre diameter rotating drum that can handle 10-tonne full-scale wheel frameworks at speeds of up to 125 mph. There are also now several computer models of adhesion that, besides their role in studying adhesion itself, can be used for tasks such as optimising driving performance in low adhesion conditions and evaluating proposed changes to brake systems.

The extent to which leaf deposits reduce adhesion is clear from measurements of the relevant coefficients of friction. The adhesion of a train on dry rails is roughly 0.25. If the rails are wet the figure might fall to 0.15. If the rails are covered in damp leaf deposits it could be no more than 0.015.

Jokes about leaves on the line divert attention from the real cost of leaf-induced delays. The density of traffic on the UK's railway system has roughly doubled in the past 20 years. If the risk of slippage during braking could be eliminated, the gap between successive trains could be reduced, increasing the capacity of the network. The annual cost of delays caused by leaf slip, and of the actions taken by Network Rail to clean the rails, adds up to £350 million. More rarely, but also more dangerously, a loss of adhesion can lead to platform overruns and the greatest of all railway nightmares, the SPAD (or signal passed at danger).

When developing any novel leaf removal system, the initial phases are conducted in the laboratory using short lengths of rail on which leaves have been crushed under high pressure. To carry out systematic tests using real trains running on real rails, testers manually cover as long a length of track as is needed with moist leaves, and then slowly run trains over them as many times as it takes to generate the required deposit. They then drive the train over the leaf-covered section at a set speed and measure the stopping distance with the brakes full on.

The current technology for removing leaf deposits relies on a fleet of trains comprising several wagons that carry large tanks of water and high-pressure spraying equipment. Nozzles spray the water on to the rails at the rate of some 1,000 litres/minute at a pressure of 1,500 bar: sufficient to damage the rail if directed continuously at any one point. The cleaned surface may also be treated with a sand-containing gel that dries as a traction-boosting deposit on the railhead. Every autumn these trains trundle round the network doing the job they've been doing for several decades. But Network Rail would like a more efficient cleaning technology, performed by trains travelling at speeds of perhaps 60 mph.

PlasmaTrack's system can be mounted onto passenger trains and can clean the entire network

PlasmaTrack's technology removes the leaf layer (left) and creates a clean surface (right)

PLASMA TO THE RESCUE

One of the alternatives to current leaf-cleaning methods is plasma. Often described as the fourth state of matter, a plasma forms in a gas subjected to a high voltage, which causes electrons to be ripped away from their atoms to form a superheated soup of positively and negatively charged particles: ions and electrons respectively. The practical applications of plasmas range from fluorescent lighting to welding and, significantly, surface cleaning. PlasmaTrack, the company responsible for exploring this approach to the leaf problem, discovered in archives dating from the late 1960s that researchers working for the former British Rail had already investigated the use of plasmas. Although the technology got as far initial trials it was abandoned, and then forgotten.

PlasmaTrack uses the most readily available gas: nitrogen. It is piped, at pressure, to a delivery system where it is subjected to a high voltage, which produces plasma that then emerges as a jet from a nozzle set a few centimetres above the rail head. The temperature at the plasma's core is around 10,000°C. The rail surface that receives the plasma jet reaches a peak of 700°C – enough to vaporise any leaf material. Because the heating is transient and superficial, the rail itself is left undamaged. Proof of concept laboratory studies using pieces of rail contaminated with leaf deposits demonstrated that the technique is effective.

The nitrogen that the PlasmaTrack system relies on is extracted from air that has been compressed and then scrubbed of its oxygen by travelling through a standard nitrogen generator. Although this adds to the bulk of the equipment, using a generator avoids the need to handle and replace heavy and cumbersome bottles of the gas. Besides tanks to store the compressed air and nitrogen, other necessary equipment includes a power generator, an inverter, the ignition box for triggering the plasma, and a chilling system for cooling the plasma head.

Having shown that a 5 kW plasma jet would achieve the required cleaning, the company's next step was to transfer the system to a vehicle moving on real rails at a test track. The equipment was loaded into a six-metre container mounted on a wagon fitted with the plasma delivery head. This demonstrated that a 15 kW plasma jet was effective in cleaning at speeds of up to 15 mph.

Having completed an 18-month period of feasibility testing, PlasmaTrack set about miniaturising the equipment and fitting it to a prototype road-to-rail vehicle that might be suitable for low-speed leaf cleaning on rural lines. Using a road-to-rail vehicle on a working stretch of track in Wales, it began real-world testing with a 100 kW system moving at speeds of up to 20 mph. The aim now is to treble that.

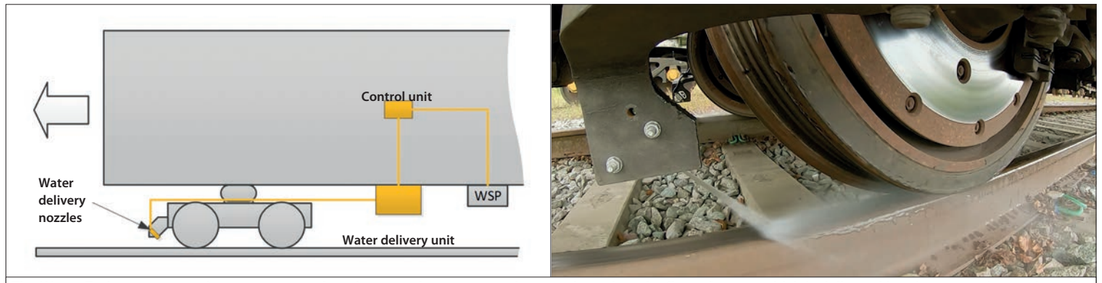
Further reductions in equipment volume should be possible by, for example, replacing the system's own generator with a power feed from the locomotive pulling the wagon. In the future, says Julian Swan, CEO of PlasmaTrack, miniaturisation might allow the equipment to be incorporated into service trains, possibly fitted with several nozzles operating at lower power.

Network Rail has selected PlasmaTrack to demonstrate its high-speed system on live network at 60 mph in autumn 2021 and Network Rail Wales will be using its low-speed road-to-rail system for 10 weeks at the same time.

When it comes to cost comparisons with the existing water jet system, Swan believes that the plasma system will prove "comparable if not better". But he also argues that even if the fuel bills were similar, the plasma system will score higher on speed and effectiveness.

WATER RECONSIDERED

Although train operators looking to replace high-pressure water jets in rail cleaning, a different way of using water is not ruled out. John Cooke and Simon Barnard of Water-Trak based their technology on a



The Water-Trak set up comprises a storage tank and a control system to activate and regulate the flow of water, which is delivered by pipe to a point on the rail just ahead of the train's front wheel. It uses water at a pressure of 7 bar and a flow rate through the nozzle and on to the rail of around 3 litres/minute. The aim is to deposit 1 ml to 4 ml of water on each metre of track

fundamental observation: while leaf residues on a rail cause problems when moist, the loss of traction largely disappears when the surface is either completely dry or thoroughly wet. This led them to wonder if the remedy might be found not in blasting residues off with high-pressure water, but simply ensuring that the rail surface was completely wet. They tested the possibility in a laboratory and showed that this was so.

To test the system on a real train running on real rails the company, like others, first had to create a realistic leaf coating on an appropriate length of railway track. It manually covered rails with moist leaves and ran a train over them half a dozen times to ensure the leaves were firmly crushed on to the rails. To test the effect of the leaves on braking, the train driver applied the brakes in a leaf-covered section of track. The braking distance at the chosen speed of 18 mph averaged out at 97 metres. The test was then repeated with the water system turned on and the braking distance averaged 76 metres. Last October the system was also tested on a service train, racking up some 120 miles.

One criticism might be that while the Water-Trak system restores traction, it doesn't remove the leaf deposits responsible for the problem. According to John Cooke this is not quite the case. Although the passage of wheels over leaves certainly creates the problem, that same passage gradually erodes the residue: a process that is aided by wetting the rail. So, in solving the immediate problem of slippage, it also creates conditions in which normal operation deals with the underlying problem.

ULTRASOUND

Timothy Leighton FREng FRS, Professor of Ultrasonics and Underwater Acoustics at the University of Southampton, also suggests another way of using water: as a vehicle for ultrasound-created bubbles ('A talent for bursting bubbles', *Ingenia* 73). The ultrasound generated at the nozzle is transmitted down several centimetres of the water stream of water, allowing the cleaning action of the bubbles to be brought to the surface to be cleaned.

His system uses a stream of ordinary tap water flowing at 1 to 2 litres/minute through a nozzle about 1 cm in diameter. Under the influence of ultrasound, the walls of the tiny bubbles, a few microns in diameter, found in any flowing water undergo what Professor Leighton describes as "a kind of shimmering, rippling motion". In contact with a dirty surface, the shear forces in the water created by the bubbles are sufficient to dislodge and remove surface contaminants.

The ultrasound is generated inside the water by a piezoelectric sound source and travels through a nozzle down the stream until it meets the surface to be cleaned. So long as the gap between the nozzle and surface is only a few centimetres, cleaning is effective. The set up uses much less water than the high-pressure systems and doesn't blast debris up into the air from where it can fall back and recontaminate the track.

The biggest hurdle is speed. In laboratory and field trials funded by RSSB, and using an early prototype nozzle, cleaning was effective only when the vehicle was moving at a crawl. To be practical, speeds of at least 30 mph would be required, and Professor Leighton believes this is achievable. His spin-out company, Sloan Water Technology Ltd, has developed the early nozzles to a more suitable form.

The bubbles created by ultrasound have enough force to dislodge the debris caused by leaves (top) and clean the rail track (bottom)

LASERS AND DRY ICE

Of the other solutions for cleaning debris from the tracks, a company based in Amsterdam, Laser Precision Solutions, is already marketing a system that relies on a pulsed laser. Ben Medendorp, Head of Finance and Commerce, notes that when the idea of using a laser for these purposes was first suggested it was ahead of its time. It was eventually taken up and commercialised by his company and is already routinely used on one US commuter line.

In the Laser Track system, the paired laser beams, operating at a wavelength outside the visible range, emerge from a box mounted just above the rail. The generator powering the laser is housed in a 6 m container wagon; the rest of the equipment, including the laser itself, is carried on another. Fibre optic cables convey the two beams down to the track. In practice the cleaning is performed by two special trains travelling the network at around 25 mph.

At the University of Sheffield, where he holds a Royal Academy of Engineering Research Chair, Professor Roger Lewis has been using dry ice pellets to remove leaf debris. The pellets are fired at the rail head in a stream of air travelling at supersonic speed through a nozzle placed at a right angle just above the track. Part of the cleaning effect derives from the kinetic energy of the pellets hitting the contaminant layer and breaking it up. Added to this is the small but powerfully explosive effect of pellets at –70°C suddenly subliming to cause an 800% increase in volume in a fraction of a second. The system leaves no solid residues.

The pellets themselves are made using CO_2 captured by other industries such as brewing and fertilisers. Taking all manufacturing and operating into account, Professor Lewis thinks that despite an inevitable release of CO_2 into the atmosphere, the system's overall carbon footprint is favourable to the current water jetting. The space required for equipment amounts to a few cubic metres, which, as he points out, is vastly less than that taken up by large tanks of water.

He and his colleagues initially trialled the system on a road-to-rail vehicle and trailer at about 10 mph. They subsequently tested it at five sites around the UK on different types of track. In 2020 they treated the Tyne and Wear Metro tramway and the West Highland line in Scotland during the leaf fall season. In their next planned trial, they aim to run the system at speeds of up to 40 mph. Lewis's target is to reach 60 mph, a cleaning speed that he believes to be ambitious but feasible.

Professor Lewis' Research Chair, co-funded by RSSB, is in wheel/rail interface low adhesion management. His team is also looking at all aspects of the problem of debris on the track, including the fundamental causes, modelling of friction and optimising current mitigation (sand and traction gel), as well as seeking new solutions.

The Laser Track system, fitted onto a passenger train on a US commuter line

Pellets of dry ice travel at high speeds onto the rails to clean debris

WHERE NEXT?

Modern trains are mostly fitted with wheel slip protection (WSP) systems to alert drivers to any slippage between wheel and track. While many of these solutions focus on vehicles designated for track cleaning, a radically miniaturised system compact enough to fit into a service train could be switched on automatically by a WSP system.

Network Rail and train operators will take cost into account when choosing which anti-leaf technology to consider further. The technologies' various inventors are confident that they can match the current cost of doing the job and even undercut it, though precise figures are not available. Network Rail will have much to consider before it makes up its collective mind how best to fight what it must hope will be the final battle of the leaves.

TUNNELLING BELOW TRAINS

An innovative construction technique has been used to create a 'dive-under' tunnel beneath the East Coast Main Line railway, creating the world's longest single underground jacked structure, and the first ever in the UK to be jacked round a curve. Hugh Ferguson spoke to John Agar and Pieter Esbach, Engineering Manager and Project Director for Morgan Sindall Infrastructure, and Andy Robinson, Director of UK company Jacked Structures.

The 155 m-long concrete portal almost complete, before the start of jacking

Did you know?

- The £240 million Werrington Grade Separation project will increase capacity on the East Coast Main Line
- The new structure should be virtually maintenance-free for its 120-year design life
- The 155-metre-long tunnel is the world's longest single underground jacked structure and weighs more than the Eiffel Tower

Jacked box tunnels are nothing new, as a method of creating an opening beneath a busy road or railway with minimal disturbance. A jacked structure is constructed, normally in reinforced concrete and usually rectangular in shape, adjacent to where it will be located, and then thrust forward horizontally into place using high-capacity hydraulic jacks, while the ground is excavated in front. This allows the road or railway to continue operating overhead or during a very short closure. This method becomes impractical for large or long tunnels since the friction forces become too much for the jacks, and jacking around curves creates an extra order of complexity.

The challenge at Werrington near Peterborough was to replace a flat crossing by diverting a freight line beneath the East Coast Main Line (ECML) at a very acute angle [see 'Why a dive-under at Werrington?']. The Werrington Grade Separation project is part of Network Rail's £1.2 billion upgrade of the ECML and is being built by Morgan Sindall Infrastructure under a design-and-construct contract, with Mott Macdonald as design partner. Tony Gee & Partners is sub-consultant for the jacked tunnel elements, with additional advice from UK company Jacked Structures, whose founder James Thomson is patent holder for the system adopted.

The team decided on a system that involved replacing the conventional box section of the jacked tunnel with a portal – just the two side walls and the roof – and leaving the floor to be cast in situ once the jack was complete. This reduced the weight of the structure and, more importantly, removed the primary source of friction during the slide: between the base of the box and the ground.

CREATING THE PORTAL

This could only be done if there was a firm foundation for the walls of the portal to slide on. Engineers at Morgan Sindall Infrastructure achieved this by first driving two small-diameter tunnels under the railway, precisely on the alignment of the portal foundations. These were then half-filled with reinforced concrete to provide a smooth surface for the portal to slide on, with side walls cast in to help guide the portal round the bend, and they then later act as permanent foundations for the structure.

Travelling formwork for constructing the 11,000 t 155 m-long concrete portal before it was jacked into place © eb7 Immersive

The chosen layout required a 155 m-long tunnel, 9.5 m wide and 5.1 m high with 1 m-thick walls, on a curve of 750 m constant radius. Preparatory works included diverting a river and various services, relocating some of the existing freight track to make space for the new works, and excavating the approach ramps.

Last August, engineers used an earth pressure balance tunnel boring machine to drive the two curved guide tunnels. This type of machine is used in soft ground, and uses the excavated earth to support the tunnel face as it is excavated. Each of the 3.5 m diameter guide tunnels were lined with 'permanent' concrete segments to ensure no settlement of the ECML overhead before the main structure was jacked. Cages of reinforcing bar were inserted inside the tunnels, and the guide path was concreted in.

WHY A DIVE-UNDER AT WERRINGTON?

At Werrington, freight trains from the east (Spalding, Lincoln and beyond) have to join and cross the busy East Coast Main Line (ECML) to connect to the Stamford line that runs parallel to the ECML to the west. Each crossing can block the line for up to 10 minutes, so separating the junction will allow more frequent mainline services, with improved capacity.

A fly-over would have created an eyesore visible for miles around in the flat landscape, would also have had to cross two roads and would have required a costly relocation of high-voltage power cables. A shorter tunnel at a less acute angle would have required a wide sweep of new track for which land was not available. Network Rail's original plan was a 'jigsaw' solution of small connecting sections of tunnel created by sheet-piling and roofing over, each built in a short but disruptive closure of the ECML, with each closure running the risk of over-run if anything went wrong. The curve could have been avoided by jacking a straight structure, but this would have had to be exceptionally wide to accommodate the necessary curvature of the track inside. The ECML could have been carried on three temporary truss bridges while the excavation was carried out underneath, but due to the skew, the bridges would have had to be very long, with massive foundations.

A bored tunnel (or twin tunnels) would have had to be much deeper, with more extensive approach works and additional risk as the site is in a flood plain. A jacked box while keeping the ECML open throughout would have been challenging at such an acute angle and would also have been several metres deeper than the solution adopted, with longer approaches.

Hence, a jacked portal provided the best solution, with most construction off-line, just one short track closure, and minimal risk of unplanned disruption to the ECML. As a single structure, with no joints or bearings, it should also be virtually maintenance-free for its 120-year design life.

The site at Werrington last November showing the East Coast Main Line running southwards towards Peterborough and London King's Cross, the Great Northern Great Eastern freight lines joining at a flat crossing from the left, and the (already diverted) Stamford lines running parallel to the ECML to the right. The curved concrete portal is under construction alongside the freight lines, with the reception area and ramp just to the right of the ECML beyond

The giant concrete portal – weighing more than the Eiffel Tower at 11,000 t – was constructed on the eastern approach, over a reaction slab that included 34 rows of sunken 'pockets' as well as slide path beams on each side linking to those in the guide tunnels. The reaction slab provided a foundation to construct the portal. Cast pockets in the reaction slab accommodated relocatable reaction frames for the jacks to push against. At the rear of the portal, large moveable steel reaction frames were lowered to engage in the pockets and provide something for the jacks to push against, for each stage of the push: every 5.4 m the reaction frames were lifted and relocated in the next pocket. The four large jacks together had a capacity of 5000 t, bearing on a thrust slab – a short 10 m-long section of the eventual tunnel floor between the feet of the portal.

JACKING INTO PLACE

The jacking itself was originally targeted for a track possession in September 2020, but the first COVID-19 lockdown put paid to an already very tight programme. Network Rail had a full complement of works for December, and instead provided a nine-day track possession in January 2021– although a skeleton Main Line service was maintained throughout, by diverting passenger trains to one of the realigned freight tracks.

In December, a short 13.5 m trial push was successfully completed, to test the jacking system before the portal reached the ECML. From soon after midnight on 16 January, the ECML track over the tunnel was lifted together with ballast and topsoil to expose the stiff clay beneath. Then the jacking could commence, with the clay removed by hydraulic excavators operating both within the front of the box and from the surface above. Cutters were fixed to the front walls of the portal, to trim the cut to just 50 mm outside the portal walls.

Two stills from an animation used in training for the construction team before the jack. A: The rear of the portal, with four 1250t jacks slung from the portal roof and attached to a thrust slab spanning between the portal feet at the rear of the structure. The jacks pushed against movable steel reaction frames (foreground) engaged in pockets in the foundation slab beneath. B: The front of the portal during the shove, showing excavators at work and the top of the linings for the right-hand guide tunnel being removed to reveal the slide path with its PTFE pads, on which the steel skidding beams run

As the drive progressed, the top sections of the guide tunnels' segmental linings were removed to open up the new guide track. Low-friction PTFE (commonly known as Teflon) pads were fixed to the guide track at regular intervals to provide a smooth-running surface: the portal ran over the pads on a series of 28 steel skidding beams, each attached to the underside of the portal walls and activated by two lift jacks.

THE BEND

Getting round the bend was an additional challenge, as this had only been attempted once before (in The Netherlands) and that was for a much smaller tunnel. The 'steering' came from a hydraulically linked lateral guidance system: a series of 40 jacks located in slots in the bottom of the portal walls maintaining sideways pressure on the sides of the guide paths.

Resistance to the thrust was expected to have three components: friction of the portal walls' skidding beams running on the slide paths with their PTFE pads; front loads from the cutting edges of the portal walls pushing against the soil ahead; and side friction as the unsupported soil slumped against the walls. The resistance was expected to increase as the tunnel progressed. As it turned out, the front load during jacking was less than expected, and there was no side friction at all: the excavators and side cutters were able to trim the ground accurately, and the unsupported vertical sides of the clay held up well, leaving just a 50 mm-wide gap. The peak thrust required was only 900 t, and two of the four jacks proved redundant.

Steering too went like clockwork. A constant pressure was exerted by the lateral jacks on each side, and this proved sufficient to steer the structure round the bend with very little adjustment.

The only difficulty came with the PTFE pads, which occasionally buckled and needed to be replaced more frequently than expected, causing minor delays. Even so, working 24 hours a day in three shifts, the jack was completed, the portal lowered on to its permanent foundations, the 50 mm gap between the wall and the clay was backfilled with pea gravel and then grouted from inside with cementitious grout through holes in the walls to minimise any future settlement, and the ballast and track re-laid overhead – all comfortably within the nine-day window. The track was handed back to Network Rail with 52 minutes to spare.

With plenty of finishing work to complete, the first freight trains are expected to use the new tunnel in November. Avoiding the delay of crossing freight trains will allow the frequency of ECML high-speed services to be increased from six to eight per hour, but passengers will not see this benefit until May 2022 when the new timetable is introduced – by which time passenger numbers on long-distance high-speed trains may well have risen back to pre-COVID-19 numbers.

The £240 million Werrington Grade Separation project is part of Network Rail's much larger ECML upgrade, a large part of which is renewing track, signalling and overhead line equipment at London's King's Cross station and its approaches.

BIOGRAPHIES

John Agar was key in supporting and helping to develop and lead the design solution developed for the Werrington Grade Separation project. An experienced engineer, John has worked within the industry for several years.

Pieter Esbach has a wealth of experience in leading and delivering complex multi-million pound civil engineering schemes. Committed to driving innovation and working collaboratively, Pieter played an integral role in leading the safe delivery of the Werrington Grade Separation project.

Andy Robinson is a specialist tunnelling engineer with over 30 years' practical, design and management experience in jacked installations on the worldwide stage.

HOW TO MAKE A MOBILE TECHNOLOGY REVOLUTION

2021 marks 30 years since the launch of GSM (Global System for Mobile Communications), which transformed mobile communications across the world. Professor Stephen Temple CBE FREng, who led the UK's part in the initiative, looks at its impact on the journey from 1G to 5G in the way that mobile technology generations are created.

Mobile technology is evolving all the time. In just 30 years, technologies and data speeds have gone from 1G at 1 kb/s to 5G at 4.2 Gb/s, enabling faster internet access and more capacity for everything

Did you know?

- Launched in 1991, GSM laid the foundations for today's global mobile industry
- A new generation of mobile technology (such as 3G, 4G, 5G) is launched roughly every 10 years
- It would have taken 200 years to download the entire eight seasons of *Game of Thrones* over 1G, while over today's mid-band 5G it takes four hours
- A successful new mobile generation needs fully coordinated international collaboration in research, standards, spectrum bands, and network deployment

Every industry must manage technology change: a mix of successes and failures is seen as normal. What is unmatched in any other comparable field of high technology is that, over the past 30 years, not a single generation of mobile technology has failed. Since the launch of the GSM [see 'What is GSM?'] in 1991, all the generations of mobile technology since 2G have been open international collaborative projects.

TECHNOLOGY EVOLUTION

New generations (G) of mobile technology have been launched roughly every 10 years:

- 1979: 1G aimed to generate more telephone capacity for phones in cars. However, car phones were seen as a frivolous use of scarce frequencies and so very few were released. 1G allowed the same frequency to be reused intensively across a country.
- 1991: 2G took mobile 'digital' and the GSM version spread across continents, allowing people to use their mobiles almost everywhere.
- 2001: 3G fused mobile networks with the internet.
- 2009: 4G dramatically ramped up network data capacity. The data explosion, ignited by Apple's iPhone smartphone interface making it easy to access rich content like videos, was overwhelming 3G networks.
- 2019: 5G had three ambitions: the first was higher data speeds, the second was specialist ultra-reliable low-latency networks (for mission critical services), and the third was to ready mobile networks for billions of 'things' to be connected.

With such fast-paced innovation, it is easy to notice when data speeds begin to fall short. A popular way of measuring data speed progress is how long it takes to download the eight seasons of *Game of Thrones* – 70 hours of TV in total, with picture quality equivalent of watching Netflix at 25 Mb/s, resulting in 787.5 GB of data needing to be transported [see 'Typical download data speeds over five mobile generations' below].

However, the frequency values shown in red [in the table] illustrate the fundamental limitation of how far radio waves propagate versus how much data they can carry. This is likely to add to a high data speed 'digital divide' as national 5G coverage for high band could be 10 times less than 5G in mid band, which in turn could finish up to five times less than 5G in low band.

WHAT IS GSM?

GSM was Europe's version of 2G that rose rapidly to become the dominant technical standard for mobile networks across the world. Its pervasiveness and collaboration between GSM mobile network operators made it possible, for the first time, for people to fly to another part of the world and their personal mobile phone just worked when they stepped off the plane. The huge volumes its global adoption generated brought mobile phone prices down so that even the poorest countries could afford them. The scale of GSM made it the standard of choice for innovations: the first Apple iPhone was a GSM mobile. Subsequent mobile generations have been able to start from the global foundation GSM created.

TYPICAL DOWNLOAD DATA SPEEDS OVER FIVE MOBILE GENERATIONS

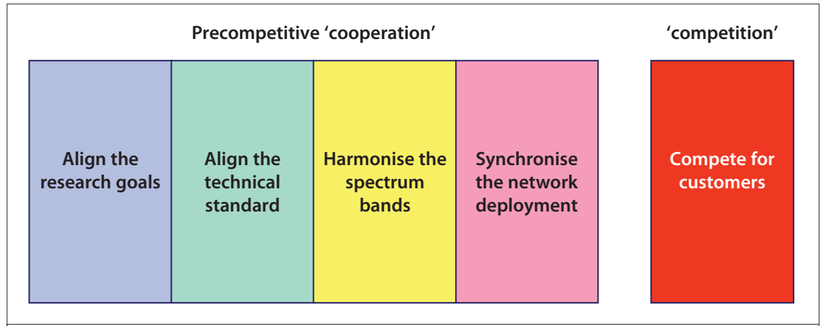
Mobile generation	Assumed mobile data speed	Time to download the entire *Game of Thrones*
1G (modem)	1 kb/s	200 years
2G (GSM)	9.6 kb/s	21 years
2G (GSM/GPRS)	56 kb/s	3.6 years
3G	2 Mb/s	36 days
4G	20 Mb/s	3.6 days
5G @ 700 MHz: (low band)	20 Mb/s	3.6 days
5G @ 3.4 GHz: (mid band)	400 Mb/s	4 hours
5G @ 26 GHz	4.2 Gb/s	25 minutes

CREATING A GENERATION

As well as the evolution of data speeds, mobile technologies have developed significantly over the same time. Wireless technology is a key element in the success of mobile generations and advances in semiconductor technology have also been indispensable. Top-end smartphones now have 512 GB of storage, which is almost enough to store all eight seasons of *Game of Thrones* (in 1997, the impressive 8 MB of storage offered by the Nokia 9000i Communicator would not have been enough for the opening credits).
On the demand side, better resolution cameras and displays are continuously ratcheting up the quantity of data to be transported over mobile networks.

There are four main elements that have to be coordinated to revolutionise a mobile technology generation. The first, which determines the future commercial and societal value of a mobile generation, is consensus building within the research community on the shared goals. The most successful of these have been those that set out to solve the big problems of the time.

The second element is creating technical standards to ensure every new mobile from any manufacturer will successfully work with every new network, in any country.



This figure shows the four elements that have to be brought together to create new mobile technology generations

The global standards body, 3rd Generation Partnership Project (3GPP), unites seven telecommunications standard development organisations. This could prove to be difficult with so many differing opinions and viewpoints, but the engineers involved have worked together to deliver high-quality standards for mobile technology across the last three generations.

The third element is harmonising spectrum bands, the radio frequencies allocated to the mobile industry and other sectors for communication over the airwaves. The disconnect between technology standards and radio spectrum regulation has been the weak link in the mobile network technology innovation model for some mobile generations. In mobile spectrum auctions, governments use an auction system to sell the rights to transmit signals over specific bands of the electromagnetic spectrum. The closest a mobile generation has come to failing was 3G because of an over-heating spectrum auction, where excessive price paid for 3G spectrum led to reduced 3G mobile coverage. Economists had put forward what has now proven to be a flawed theory that auctioning frequencies would place them in the hands of those likely to make the most effective use of them. What attracted governments more was the money that auctions would raise, particularly when competition would prevent mobile operators from recouping the money by raising prices to consumers. However, mobile operators recouped costs by cutting back investment in 3G coverage, leading to a decade of consumer complaints about poor 3G coverage.

The 4G auction was better managed, with a coverage obligation on a low band licence. It will take time to see the impact of the UK 5G auction prices, although the money raised in the first part alone could have paid for 100,000 small 5G base stations.

Why does the price of frequencies matter? The data speeds in the table on the previous page and extent of possible coverage for different frequencies tells us that the biggest single mobile radio engineering challenge over the next 10 years is going to be closing the digital divide and getting 1 Gb/s everywhere. Those 100,000 small 5G base stations could have made a start.

The fourth element is synchronising the network roll-out with development of new devices. Nobody will buy a next-generation mobile if there isn't a next-generation network to connect it to and there is no point in rolling out a next-generation network if there are few next-generation mobiles in consumers' hands. A synchronised roll-out will also secure early-scale economies and falling equipment prices. This was first achieved in Europe when the four largest countries decided that their mobile operators would all sign up to switch on GSM networks in 1991.

Author Stephen Temple shows the first 1G analogue phone to fit in a shirt pocket from his vintage mobile collection

LAYING THE FOUNDATIONS

How did the 'repeat pattern' of a new technology generation roughly every 10 years arise? Some of the 1G network did work well, and an analogue phone that could fit in a shirt pocket was launched in 1986, so GSM had a huge amount of catching up to do. A higher data speed mobile technology was just around the corner and GSM was in danger of being squeezed out. ETSI, the officially recognised standards body in Europe for making telecoms standards, deliberately slowed the advance of a new wider band standard so that it would not compete with GSM. Instead, it was made a third generation by design.

ETSI's expedient invention of 'the mobile generation' turned out to be an enduring valuable tool that laid the foundation for today's phenomenally successful global mobile industry. It also addresses a particular innovation market failure, where nothing can happen unless an entire industrial ecosystem acts together. Its model of coordinating the four elements has delivered huge commercial, industrial, and societal benefits on a global scale. Created for the GSM revolution 30 years ago, the model has secured the success of another three mobile revolutions and is currently providing the confidence for the research community to begin its new journey towards 6G.

MOBILE TECHNOLOGY MILESTONES

Technology milestone	First mobile with the feature	Year
GSM hand portable	Motorola 3200	1992
Game on a mobile	Hagenuk MT-2000	1994
Colour screen	Siemens S10	1998
ARM chip in a mobile	Nokia 6110	1999
Camera phone	Sharp SH04	2000
Capacitive touch screen	LG Prada	2007
4k display	Sony Xperia Z5 Premium	2015
Folding screen	Royole Flexpai	2018

Source: GSMHistory.com

BIOGRAPHY

Professor Stephen Temple CBE FREng joined the Department of Trade and Industry in 1984 a year before the UK launched its 1G mobile networks. He led for the UK in the GSM standards group and has been involved in various ways in 3G, 4G and 5G mobile generations. He recently edited the Institution of Engineering and Technology guide *6G for policymakers* and chairs cluster two of the UK Spectrum Policy Forum.

PROMOTING ENGINEERING

Prince Philip took a great personal interest in the development of engineering in the UK. In 2009, HRH The Duke of Edinburgh wrote for *Ingenia* about the promotion of engineering and the importance of encouraging and developing future engineers. Here, we republish his article, with an introduction from former Editor-in-Chief, Dr Scott Steedman CBE FREng, detailing how the article came into being.

As a young Naval officer, HRH The Duke of Edinburgh developed a keen interest in engineering that continued throughout his life. His support for the concept of a national academy for engineering, distinct from the Royal Society, was pivotal to the foundation of the Fellowship of Engineering in 1976, renamed the Royal Academy of Engineering in 1992. Following a conversation I had with Prince Philip at the Academy Awards Dinner in 2007, he kindly agreed to work on an article for *Ingenia* on the origins of his interest in engineering and technology. During an audience at Buckingham Palace, we discussed his early experiences as a Midshipman in the Royal Navy, when he was required to learn about ship propulsion and steering gear. He explained how he had become intrigued by how things worked through trying to sketch the different mechanical systems that controlled the ship. I asked whether we could publish one or more of these sketches, as this would bring the article to life for readers. He was adamant that his drawings would not be published as he said they were not very good and should not be seen. In the end he relented and his archivist, the late Dame Anne Griffiths DCVO, located his notebook and I chose the few you see on the next page. A second theme that emerged in our meeting was the importance of vocational training and apprenticeship as a route to qualifying as an engineer. He wanted to refer to specific innovations and to name one or two distinguished engineers whom he had met over the years. Communicating by fax, Prince Philip marked up my initial draft by hand and I incorporated his comments over three iterations to produce the article that follows.

Please note, figures quoted in this article are from when the article was first published in 2009

I experienced my first exposure to engineering when I joined the Royal Navy as a Cadet in 1939. We were required to keep a 'Midshipman's Journal' in which we recorded our daily activities from our instructional courses to life at sea as Midshipmen. My journal includes several engineering drawings – which shows that I must have been paying attention to that part of the course.

The Navy has, of course, its own branches of professional engineers to look after the complicated propulsion, weapons and domestic machinery in a warship but their successes and tribulations are, equally, very much the concern of the Executive branch. Without the engines, and all the other machinery, a warship would not be able to fulfil its duties. This applies just as much to the nation as a whole. The complete infrastructure of national life is in the hands of engineers.

When you come to think of it, the contribution of British engineers, particularly from the 18th century onwards, is quite remarkable: mines, canals, dams, railways, bridges, sewage works, and the very earliest machine-driven ships. Not only in this country but all over what was the British Empire, and in many other countries around the world; much of this was achieved by self-taught engineers.

As has so often happened to other professions in the past, the engineers very soon formed themselves into specialist institutions to ensure that their members achieved, and maintained, proper professional standards. There are currently 36 such bodies in the United Kingdom.

It was only in 1962 that any attempt was made to bring the various branches of engineering into any sort of collaboration. Thirteen of the major engineering institutions formed themselves into the Engineering Joint Council, which was granted a Royal Charter in 1965, and became the Council of Engineering Institutions (CEI).

Without the engines, and all the other machinery, a warship would not be able to fulfil its duties. This applies just as much to the nation as a whole. The complete infrastructure of national life is in the hands of engineers

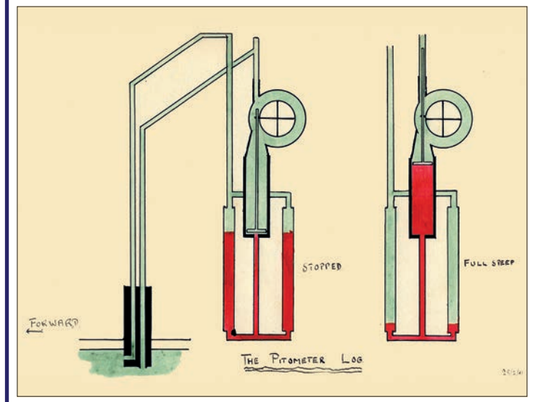
For some reason, which I cannot recollect, I was invited to become President of this new Council. One of the main reasons for creating the CEI was the need to tackle the thorny problem of establishing the appropriate qualifications required to be recognised as a Chartered Engineer in any of the engineering Institutions.

CREATING A NATIONAL ACADEMY

It was also about this time that the status of engineers in society as a whole became a lively topic for discussion. The suggestion was that engineers did not enjoy the same respect as scientists, academics and other professions. This led to the proposal that a body along the lines of the Royal Society should be established for distinguished engineers. Indeed, Professor Meredith Thring, of Queen Mary College, proposed the creation of a Royal Society of Engineers.

This idea did not find much favour with the Royal Society itself, which, instead, proposed to elect more engineers to its Fellowship. It seemed to me that this was equally unsatisfactory, since the engineers would always be in a minority. Any solution would also have to have the support of the CEI. I therefore proposed that the Council itself should establish a Fellowship of Engineering, with Fellows elected from across the whole engineering profession. This came into being on 11 June 1976, when 126 of Britain's leading engineers gathered at Buckingham Palace for the inaugural meeting. Lord Hinton,

FROM A MIDSHIPMAN'S JOURNAL



Engineering drawings showing a Capstan Engine and Pitometer Log, from HRH Duke of Edinburgh's Midshipman's Journal. By kind permission

as Chair of the CEI, became President. This body gradually distanced itself from the CEI until in 1992 it decided to become completely independent and change its title to the Royal Academy of Engineering.

MAINTAINING STANDARDS

The creation of the CEI seemed to trigger the creation of a whole new set of engineering bodies. First came the Engineering Council UK, which was required to regulate the qualifications for entry, and progress through the engineering profession. This was followed in 2001 by the creation of the Engineering and Technology Board, which was formed to promote the vital role of engineers and engineering in society.

One of the serious bones of contention for the CEI was the problem of establishing a clear line of professional advancement from operative, or apprentice, to the jealously guarded title of Chartered Engineer.

The present situation is that the Engineering Council recognises three levels of professional qualification: Chartered Engineer (CEng), Incorporated Engineer (IEng), and Engineering Technician (EngTech). It lays down the educational and professional qualifications needed to achieve these designations. For CEng, the Engineering Council require an educational base equivalent to Level 6, master's degree, and for EngTech, the educational base should be equivalent to Level 4/5, typically HNC/HND. Over the last five years, the proportion of engineers registering as CEng has gradually dropped to below 70%, while those registering as IEng has been steady at around 10%, and those registering as EngTech has risen to over 20%.

Within the engineering industries, there appears to have been a growing anxiety about the recruitment and training of apprentices. It has been suggested that the decline in apprenticeships may well be due to the conversion of so many technical colleges into polytechnics and universities. However, it is also possible that the decline in the number of young people seeking apprenticeships is related to the consequent huge growth of university places, the pressure on young people to seek places in universities, and the great variety of less demanding subjects being offered.

A generation ago, only 8% of school-leavers went to universities. The figure today is 42%. The result is that, out of a school-leaving population of some five million, there were only about 20,800 Level 2 engineering apprentices who completed their training in 2007–08, while the very modest total of some 15,000 Level 3 advanced engineering apprentices completed their training in 2006–07.

On 11 June 1976, HRH The Duke of Edinburgh hosted the inaugural gathering of the Fellowship of Engineering at Buckingham Palace. He is flanked by Earl Mountbatten of Burma (left) and Lord Hinton of Bankside (right), who became the Fellowship's first President

Prince Philip is shown a surgical device that re-aligns fractures of the tibia by members of an engineering team from Staffordshire University. He met the finalists for the MacRobert Award at the Royal Academy of Engineering's Awards Dinner in June 2007

BECOMING AN ENGINEER

One of the common objectives of all the engineering institutions, the Royal Academy of Engineering, and the regulating bodies, is to encourage more young people to take up engineering at the level appropriate to their educational qualifications. The fact remains that engineering is the driving force behind all technological advances, and that it plays an immensely important part in the improvement in social conditions. Furthermore, engineering is probably the greatest wealth creator in our whole society.

I am also convinced that young people are more likely to start a career in engineering if they can see a clear line of professional advancement right through from an unskilled operative, or an enthusiastic amateur, to the status of Chartered Engineer. There are encouraging signs. The technician entry route is proving increasingly attractive, and now accounts for about 20% of the annual registrations with the Engineering Council. However, the total number of prospective engineers, who by following the direct route to registration as a Chartered Engineer through university courses remains static at around 5,000 to 6,000, year-on-year.

The present system certainly ensures a thorough grounding in engineering for all those who have a burning ambition to become professional engineers but I suspect that it may not attract those who enjoy using their manual skills to make things, or even just to repair things.

Many of our pioneering engineers started without any formal training but they had a passion, and a talent, for invention and development. There can be no doubt that opportunities are still there but the system does not seem to be able to cope with the 'hands on' enthusiast, who has no immediate interest in academic qualifications. The challenge is to entice them on to the ladder of professional advancement. Better skills and wider knowledge enable greater achievements.

PIONEERS IN ENGINEERING

I think that a classic example of such a native genius is John Harrison. Born in 1693, the son of a carpenter, he became a self-taught clockmaker, who, by 1762, had designed and built such an accurate marine chronometer that it could be used by ships to determine, for the first time, their longitude on long ocean passages. The same sort of initiative is alive today.

In 1969 Ronald Hickman wrote to tell me that he had designed and built an 'all-purpose workshop bench', which he called a 'Workmate'. His problem was that he could not find anyone to manufacture it. We eventually persuaded the firm Black & Decker to take it on and it was launched in 1973. It immediately gained a Design Council award and it has remained a bestseller ever since. This year, 30 years after he patented the original concept, the winner of the 2009 Prince Philip Designers Prize is Andrew Ritchie for his, almost single-handed, design and manufacture of the highly successful Brompton Folding Bicycle.

There are also examples of distinguished engineers who have climbed the professional

Prince Philip meets engineering students from Imperial College on his visit to the Constructionarium at Bircham Newton in 2006. The Constructionarium enables students to spend a week building sizeable scale model versions of existing structures onsite © Imperial College London

As the ever-growing human population consumes more and more of the earth's natural resources, it is going to take all the ingenuity of inventors, engineers and designers to maintain the rate of improvements in the developed societies and to bring better standards of living to more and more people in the less prosperous countries of the world

ladder and made a distinguished contribution without following a university education. Doug Oakervee FREng, who recently retired as Executive Chairman of Crossrail, and is a past President of the Institution of Civil Engineers, started his career as an apprentice joiner in 1957. Through night school and day release he obtained an HNC and HND. During his career he has been responsible for great engineering works, including the construction of Hong Kong's new Chek Lap Kok airport. His career illustrates how valuable a combination of academic and practical skills can be to achieve success in major engineering projects.

As the ever-growing human population consumes more and more of the earth's natural resources, it is going to take all the ingenuity of inventors, engineers and designers to maintain the rate of improvements in the developed societies and to bring better standards of living to more and more people in the less prosperous countries of the world. If this is to be achieved during the 21st century, the challenges for the professional institutions and the Academy will be to make sure that bright young people, whatever their background, who aspire to do something creative and fulfilling with their lives, can achieve their ambition through engineering.

SOUND MOORINGS FOR A RENEWABLE CAREER

For Dr RV Ahilan FREng, a career that started in offshore oil and gas has turned him into a champion for renewable energy. After all, offshore production has created plenty of technologies that benefit wind, tidal and wave power as they displace carbon-emitting hydrocarbons.

Even in the 1990s, Rajapillai (RV) Ahilan's offshore engineering projects had to take account of climate change. Now Ahilan sees research into wave energy as a potential source of technologies for other areas of marine engineering. Since the start of his career, Ahilan has provided technical advice to operators of just about anything that moves in the marine world. Ahilan and his colleagues have advised operators moving oil and gas rigs around the world, people with cargo stranded in the Suez canal and a cruise liner operator with a vessel that ran aground off an Italian island. He recently became Chief Energy Transition Officer at ABL Group following the merger of AqualisBraemar and London Offshore Consultants (LOC). In his new position Ahilan is "addressing energy and oceans, or energy and maritime", with 900 people working out of 39 countries. The role has taken him increasingly into renewable energy, adding advising operators of offshore wind farms to a growing portfolio of renewable

technologies. As Ahilan points out, offshore renewable technologies such as wind turbines, wave energy and tidal power all need engineering skills that would be familiar to those who created and operated offshore oil rigs.

EDUCATION

It was more by chance that Ahilan ended up as an engineer with a degree in civil engineering. Born in the northern Tamil part of Sri Lanka, his parents were great believers in education. His father was a pathologist and his mother taught English. Ahilan had other ideas, and engineering was not among them back then, he admits. "I was always very much interested in maths and its applications."

Influenced by a cousin who had returned from England as a Chartered Engineer, Ahilan travelled from Sri Lanka to Leeds to study civil engineering. There, a second key influence was John Fox, an "inspirational teacher" says Ahilan. "The world does not give enough credit to teachers," he adds. "Your teacher makes a fantastic difference to the future of your life." Fox taught fluid mechanics at Leeds. "As a result, I got excited about fluid mechanics. He made me think it was the most important subject in the world."

Student projects were an early introduction to what fluid mechanics could do in real life. "I did a fascinating project in my final undergraduate year, on pressure transients in oil pipelines." By then he was already beginning to think that it might be interesting to work in oil and gas. "This was the era where oil and gas was in its pomp."

Ahilan's interest in fluid mechanics led to a PhD at the University of Cambridge in ocean engineering, focused on sediment transport and wave action. Again he brings up the importance of teachers. "I have been very lucky with all of my teachers," he adds. "One thing they teach you very well at Cambridge is not to teach you. You have got to figure it out for yourself, with a few nudges here and there."

Ahilan's research combined building theoretical models with experiments to confirm their validity. He investigated what would happen to sediments in very high wave action that moved the sediments, a real issue when trying to work out what would happen in coastal erosion and around offshore structures. "Sediment is a very strange mixture," he explains. "It is neither solid nor fluid. Sediment transport is more of an art than a science."

OFFSHORE

With a PhD completed, it was natural to look for a job in offshore oil and gas. There was also the opportunity to venture into uncharted depths, intellectually as well as literally. Civil engineering had been around for a long time, with the burden of history and codes and standards developed over many years. "Moving offshore gave you the ability to construct new things or new concepts, and to realise those new concepts," says Ahilan. Oil and gas discovery and development were still developing areas of offshore engineering, with fewer set ideas about things. "The subject that I got conned into believing was the greatest subject in the world meant that I got into offshore oil and gas. People were willing to listen to new ideas, willing to start from first principles to solve problems."

It was at Cambridge where a careers adviser suggested that Ahilan should talk to one of the consultants in offshore engineering, Noble Denton. Advised that the company liked to do things from first principles, Ahilan's career path was set. "I got very excited about that and applied to join them." When he started work at Noble Denton, he was asked to look at offshore platforms where there was seabed erosion.

The effect of sediment recently made global headlines, when there were attempts to move sediments to free a large cargo carrier blocking the Suez Canal. While this maritime challenge did not land on Ahilan's desk, ABL Group was asked to advise on the fate of containers stuck on the stranded vessel. The company frequently gets involved in recovering vessels or salvaging wrecks. "We get appointed as an independent party who can look at the whole problem without fear or favour when competing interests are at play in distressed situations."

One of the biggest projects Ahilan's firm was involved with was the grounding of the Costa Concordia off the Italian island of

Dr RV Ahilan in Singapore in 1984, shortly after starting at Noble Denton

Giglio. "Within an hour, we got called by the protection and indemnity club that insured the vessel." There then followed five more years of work, to help to contain the costs and to recover the ship from the grounded location.

INDUSTRY STANDARDS

Asking Ahilan to describe his own most interesting engineering project takes him back to his early days in offshore oil and gas, when he helped to establish the standards for jack-up oil and gas rigs. "I saw the abyss of my career, and I saw the peak within the playing out of that particular project," he explains.

Before a drilling company could move a rig on to an oilfield, it had to satisfy the requirements of the insurance coverage. In the early days of offshore exploration, insurers didn't know where to begin with these new monsters, which Ahilan describes as "both a structure and a machine". So the insurers called in their engineering consultants at Noble Denton. There was a massive dispute in the early 1980s about the criteria for approving an offshore jack-up rig, Ahilan explains. "I don't know who had the wisdom to volunteer me," he jokes, "but I was volunteered to develop a proposal on how to resolve this issue." He was brought into an industry-wide group to develop a methodology that everyone could sign up to.

Ahilan came up with an approach that didn't get very far. "I got ambushed by a major international oil company that completely disagreed with the proposals that we were putting forward." Still only in his late 20s, Ahilan took this rebuff hard and even contemplated leaving his job. The next day, the oil major asked Ahilan to drop by. The company wanted to oversee the outcome and the idea of an industry approach went out the window. "They invited us to do the work directly for them," he explains.

After that first phase, with the company on side, the Noble Denton approach went on to become an industry project. Ahilan returned to the fray when it was time to turn the collective result into an industry code that should apply for jack-up rigs to achieve consent. "I was then involved in developing the methodology for structural reliability analysis that eventually resulted in the safety factors that are in the current standards used for jack-ups."

The oil company that originally rejected his proposal eventually told Ahilan that it liked what he had done and that it had helped it to understand what the different safety factors might imply for the safety of such platforms. "I thought it was a good win," he adds. "That was probably for me the most enjoyable project and probably the thing that established my reputation in the industry."

This was not Ahilan's first foray into writing codes. In the wake of the Piper Alpha disaster in 1988, when a fire destroyed a production platform killing 167 people, he was called in to advise on one of the many issues that arose in the subsequent inquiry. The codes behind the engineering of mooring systems of floating structures, he explains, hadn't taken into account slowly varying second order forces. The UK's Department of Energy invited Ahilan to contribute to the guidance of mooring development, which led to him participating in and then convening the ISO group that created the industry standard. He credits this work as establishing him as the go-to engineer for the development of safety factors for design codes.

It was also around that time that Ahilan began to see how engineers might have to accommodate the impact of climate change. In the early 1990s he worked as an advisor to Shell, on an installation in the Norwegian North Sea that turned out to be ahead of its time. "It is the first example that I can recall, and it may have been the first

The irony is not lost on Ahilan that a champion of renewable energy has a passion for cricket and fast cars, like his six-year-old Maserati Quattroporte, but he is quick to point out that he was also an early owner of a Tesla electric car

example ever, of recognising the impact of global warming in sea-level rise. We used an additional sea-level rise in the calculation to figure out what sort of clearance we should have between the still-water level in the North Sea and the underside of the deck on which people will be living and working. It was installed in 1996 but was designed to last for 70 years."

RENEWABLE ENERGY

Ahilan talks of his career as being in two parts, starting in engineering and moving increasingly into executive roles.

As a senior executive in GL Noble Denton, Ahilan had managed teams of engineers and mariners in shipping and oil and gas. When asked to run GL Garrad Hassan, the renewables company, there was, he admits, muttering among the renewables engineers. As Ahilan puts it, he sensed that they were asking "what does he know about renewables?" In the event, he reckons that there is no greater enthusiast for renewables than a convert who may well be more passionate than some of the people who were there in the first place. After all, the skills needed to make offshore renewable energy a mainstream engineering business have much in common with putting oil rigs on the seabed or ensuring that the operators of ocean-going vessels get the advice that they need to run their businesses. This has enabled him to push the growth strategy for renewables.

The challenge for Ahilan when he went into renewables was to make it commercial. "I have always argued that renewables will be the way forward but it cannot be the way forward if you're expecting people to wear hair shirts in order to move forward or have to go cap in hand for subsidies all the time. So let's put our mind to making sure that this is commercially astute, socially astute, in order for it to thrive." He uses an engineering rationale to explain his approach. "As an engineer I find it somewhat symmetric, to be able to use energy at the pace at which we receive it rather than use in a century what has been in place for millions of years. That is why I am passionate about driving the growth of renewables. The sustainability of it will absolutely trump everything else."

UNIVERSITIES AND RESEARCH

Asked to list other career highlights prompts Ahilan to talk about his involvement with universities. He maintains links with the University of Leeds with a personally sponsored lecture at the Leeds Institute for Fluid Dynamics named in honour of the academic who sucked him into fluid mechanics, John Fox. Leeds is, he points out, the only centre for doctoral training in fluid mechanics in the UK.

Ahilan also chairs the Marine Technology Trust, a 20-year-old charity that supports undergraduate students who need help to complete a project in industry in just about any aspect of marine engineering. "It is not

a large trust," he explains, "but it makes a difference to the people who are unable to do their undergraduate projects."

Ahilan's current support for academic engineering also takes him to the frontiers of research in renewable energy. He was a keen supporter of two of the eight projects that recently shared £7.5 million from the Engineering and Physical Sciences Research Council (EPSRC) through its support for wave energy converters. Ahilan will chair the group of industrial advisors for the WavE-Suite project led by Qingwei Ma, Professor of Hydrodynamics at City, University of London. The project plans to address the lack of tools for assessing the ability of wave energy systems to survive extreme marine conditions. Professor Ma says Ahilan's "extensive and wide experience in general offshore engineering and offshore renewable energy, and his knowledge in marine hydrodynamics put him in an irreplaceable position to give us invaluable suggestions and guidance from a point of view of offshore engineering practitioner."

Ahilan takes a business view of the prospects of wave energy from where he sits in the world of marine technology. "I am not even convinced of wave and tidal energy commerciality within the next 10 years," he says. "If I look at 2050 even, I think that the wave and tidal energy contribution to the grid is going to be sub 10%, maybe even one percentage." Although he is convinced that the research is important, in the same way that it was worth landing on the Moon. "It is not going to transform the energy system, but what it might do is to transform the technologies that are available for application to all sorts of other things. It is getting to the cutting edge." And that cutting edge will apply to the maritime technologies that have been Ahilan's domain since he was seduced into fluid dynamics as an undergraduate.

ELEVATING THE STANDARDS FOR OIL RIGS

RV Ahilan played a key role in writing the engineering codes for the safe operation of the jack-up rigs that were essential to the development of the UK's North Sea oil and gas

Jack-up rigs are the life blood of offshore oil and gas exploration and development, moving from site to site as companies investigate new prospects and prepare for the arrival of production platforms that are built to spend years on one site. In the early days of the North Sea's oil boom, the development of jack-up rigs raised a new challenge. How could the industry certify their safety in deployment and operation?

Ahilan was called in when the industry was trying to come up with a collective approach to addressing those questions. Building a jack-up rig, says Ahilan, is not like designing a fixed platform. "During the build of a production platform, you are calculating but if you need to you can put in a little bit more steel. With a jack-up you have got to absolutely make sure that it was light enough to float so that it can be moved between drilling locations."

After he had eventually persuaded the oil and gas industry to accept his approach, Ahilan had a shock. "I had to shed deterministic thinking, drummed into me throughout my university education." Instead, Ahilan explains, he had to apply probabilistic analysis. He had to abandon the usual engineering approach, with calculations that considered not only the properties of the materials and the possible loads on them, for example from waves that are likely to occur once in a century, but also the uncertainties in them.

When engineers design structures for anticipated conditions, a static rig for example, they can put various known values into a calculation. They know that no structure can be guaranteed 100% safe and that there are risks involved in any design. Engineers handle those uncertainties by simplifying them into a set of safety factors written into industry codes. This is where Ahilan carried out probabilistic analysis to derive those safety factors, laying the foundations for the codes that engineers would use when designing jack-up rigs.

For every structure, he explains, there is a finite probability of failure. "It doesn't matter what structure it is, just because you meet the safety factor does not assure you the safety forever. All you are trying to do is to reduce that finite probability to a level that society is comfortable with. Then the question arises how do you know that you have done that? That is where the codes come in. That is where people who generate codes have to perform these analyses in a probabilistic way and come up with failure chances that society is implicitly accepting."

Ahilan is quick to point out that engineering is essentially a team pursuit. "I don't want to claim that I wrote the code," he insists. "I led the project that derived the safety factors," he explains. "It then had to be put into a code. If there was one person who was most responsible for coordinating and putting that code together for the Society of Naval Architects and Marine Engineers in the US and now adopted into ISO, it was Mike Hoyle. He is a very good friend of mine."

CAREER TIMELINE AND DISTINCTIONS

Born, **1960**. Studied civil engineering at the University of Leeds, **1977**. Studied an MS in civil engineering at the California Institute of Technology, **1980**. Studied a PhD in engineering fluid mechanics at the University of Cambridge, **1981**. Engineer at Noble Denton, **1984**. Managing Director, Noble Denton Europe, **2000**. EVP, GL Noble Denton, **2009**. President, GL Noble Denton Americas, **2011**. President, GL Garrad Hassan, **2012**. EVP, DNV GL Renewables Advisory, **2014**. Group CEO, LOC Group, **2019**. Fellow, Royal Academy of Engineering, **2020**. Chair of Trustees, Marine Technology Trust, **2020**. Chief Energy Transition Officer, AqualisBraemar LOC, **2021**.

EDIBLE PACKAGING

Half of plastic packaging is used once and thrown away. Notpla has developed sustainably sourced seaweed packaging to hold liquids, which decomposes in less than six weeks.

Notpla, a replacement for plastic packaging, began as a student project for Rodrigo Garcia Gonzalez and Pierre Paslier as part of their master's in innovation design engineering at Imperial College London and the Royal College of Art. They wanted to develop an edible packaging that did not add to the plastic waste problem.

Notpla aims to significantly reduce plastic waste with its edible plastic-like material that holds liquids. For those that don't want to eat the sachet, it can be composted at home and doesn't contaminate recycling with microplastics.

Inspired by the way nature encapsulates liquids using membranes, for example in fruit, the pair made the first prototypes in their kitchen in 2013. The resulting product, Ooho, is made from brown seaweed and is edible, biodegradable and vegan.

They tried a few options, rejecting cellulose and tapioca, before settling on seaweed. Brown seaweed is one of nature's most renewable resources, growing up to 60 metres tall at a rate of up to 1 m per day. It doesn't compete with food crops for land, does not need fresh water or fertiliser and actively contributes to de-acidifying our oceans. Seaweed is also regularly used in food production – for example, a spherification technique uses seaweed to create fake caviar. Rodrigo and Pierre tried enlarging these caviar bubbles, and after many prototypes, ended up with transparent, edible large bubbles.

The Ooho edible and biodegradable packaging is used for beverages and sauces. Oohos can replace plastic cups and bottles at festivals and sporting events. After their first video of Ooho went viral in 2013, they joined Climate KIC, Europe's largest funded accelerator focused on climate innovation. They collaborated with chemists and chemical engineers from Imperial College London to test Ooho at running events, festivals and takeaway shops. Ooho was trialled for removing single-use plastics from the Virgin Money London Marathon, where 36,000 Oohos replaced bottles. At festivals, Oohos have been used for water, juice and even cocktails. The team realised that the product could also work well for sauces and condiments for the takeaway industry, and have partnered with Just Eat to trial this.

Notpla, so called Not Plastic, is made from one of nature's most renewable resources, brown seaweed. (Front right) before being turned into edible packaging (back left) © Notpla

One of the largest challenges the team experienced was creating an edible packaging that wouldn't impact the flavour, as initial products had a strong seaweed flavour. It took the chemists and engineers several iterations before they managed to create a membrane with a neutral flavour.

The seaweed-based technology can also be used to challenge other applications of plastic, such as the thin layer of plastic in many cardboard food boxes. Notpla Coating is naturally biodegradable and provides a grease-proof and water-resistant barrier for paper products. It developed a coated box made of pure cellulose, which has no additives in the pulp, contrary to typical takeaway box, and has a seaweed coating. The team are now working on a flexible film to package dry products that are currently in plastic sachets.

For more information, visit **www.notpla.com**

HOW DOES THAT WORK?

LATERAL FLOW TESTS

Millions of people each week are taking lateral flow tests to detect COVID-19, enabling them to get a result in just 30 minutes.

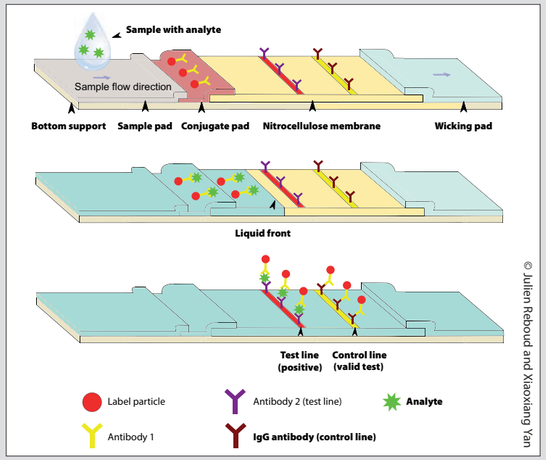
Most medical diagnostic tests are about finding a needle in a haystack. With infectious diseases, even just a few pathogens in our bodies can wreak significant havoc, and these are very small – viruses can be around 1,000 times smaller than the width of a hair. To find them and understand the cause of an illness, one must capture only the pathogens, remove everything else and reveal their presence. In the analogy of the haystack: blow all the hay away so that only the needle remains and it shines in the sunlight.

In some cases, this analysis can be done using lateral flow tests, which can perform all three steps – capture, purification and detection – in a few minutes, using just a strip of paper held in the hand.

The format is based on two main phenomena and is used widely in medicine. The first phenomenon is fluid transport through the paper's porous matrix, also known as wicking. As spilt water expands on a paper towel used to mop it up, a liquid sample, such as blood or saliva, can also flow in a strip of paper. The paper 'pumps' the flow, always in the same direction, wetting the dry parts in front of it. By placing components in succession on the paper, they will encounter the sample, and the pathogens it potentially contains, one after the other in a controlled sequence.

The lateral flow strip is not actually a single piece of paper but a sequential arrangement of carefully engineered porous materials, called pads, each with a specific function. The first pad receives the sample and can have different pore sizes. For example, blood contains many cells, which often create disruptions in the flow as the sample moves through the strip. This sample pad can comprise of pores that are smaller than the cells, enabling the pathogens to pass through but retaining the cells like a filter. The flow through the rest of the pads is finely tuned using the size and surface properties of the fibres, which are often made of nitrocellulose. Fibres with a hydrophilic surface and relatively large pores between them allow the sample to flow faster than if the pores are smaller with more densely packed fibres. The manufacturer can control the test's duration and the time that the necessary biochemical reactions take on the strip. The final absorbent pad acts like a sponge to receive the sample. The more liquid it can hold, the more sample the strip can process.

The second phenomenon captures the pathogens by specifically binding different molecules together. The technology often reuses a natural immunity defence mechanism in living organisms, based on the binding of antibodies to intruders. These molecules latch onto the intruders in a tight lock-and-key fashion: the key (the antibody) only binds to one lock (the pathogen) and nothing else in the biological sample. By placing an antibody on the paper, it can capture the pathogens as they pass, transported by the liquid flow from the wicking. The flow then continues to wet the paper.



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A second antibody carrying a coloured bead reveals the pathogen's presence: as it binds to the pathogen, now stuck in a particular place on the paper, beads collect in a line, which becomes visible to the naked eye. There are many more beads than pathogens, so unbound beads carry on, moving to a second location where a different particle captures them and creates a second line. The second, control line simply attests that the test has functioned properly. Two lines indicate the pathogen's presence. If there is only one line, the test has worked and there was no pathogen.

Analysis on such a simple, low-cost strip of paper can provide important information outside of hospitals, at home, in the GP's office, or in resource-limited settings such as low- and middle-income countries. The fast response time also enables quick informed decisions about treatment, increasing the chances of overcoming the disease.

BIOGRAPHY

Dr Julien Reboud is a senior lecturer in biomedical engineering at the University of Glasgow. He helps engineer new medical diagnostic devices for use in low-resource settings in Africa.