INNOVATION IN ENGINEERING: TURNING IDEAS INTO NEW BUSINESS.

Institution of MECHANICAL ENGINEERS

Presidential Address 2021
Peter Flinn MA MBA CEng FIMechE

Improving the world through engineering

In this Presidential Address, I reflect on the factors which led me to choose a career in mechanical engineering and I summarise the key points of my career, much of which was concerned with taking ideas and turning them into reality. I then move onto a summary of my learning on these topics as expressed in the book I published in 2019. In the final two sections, I consider the role of engineering innovation in this changing world and how the Institution of Mechanical Engineers might increase its influence for the good of society as a whole. Given that the Institution is now almost 175 years old, I also provide some historical perspective to our current and future work.

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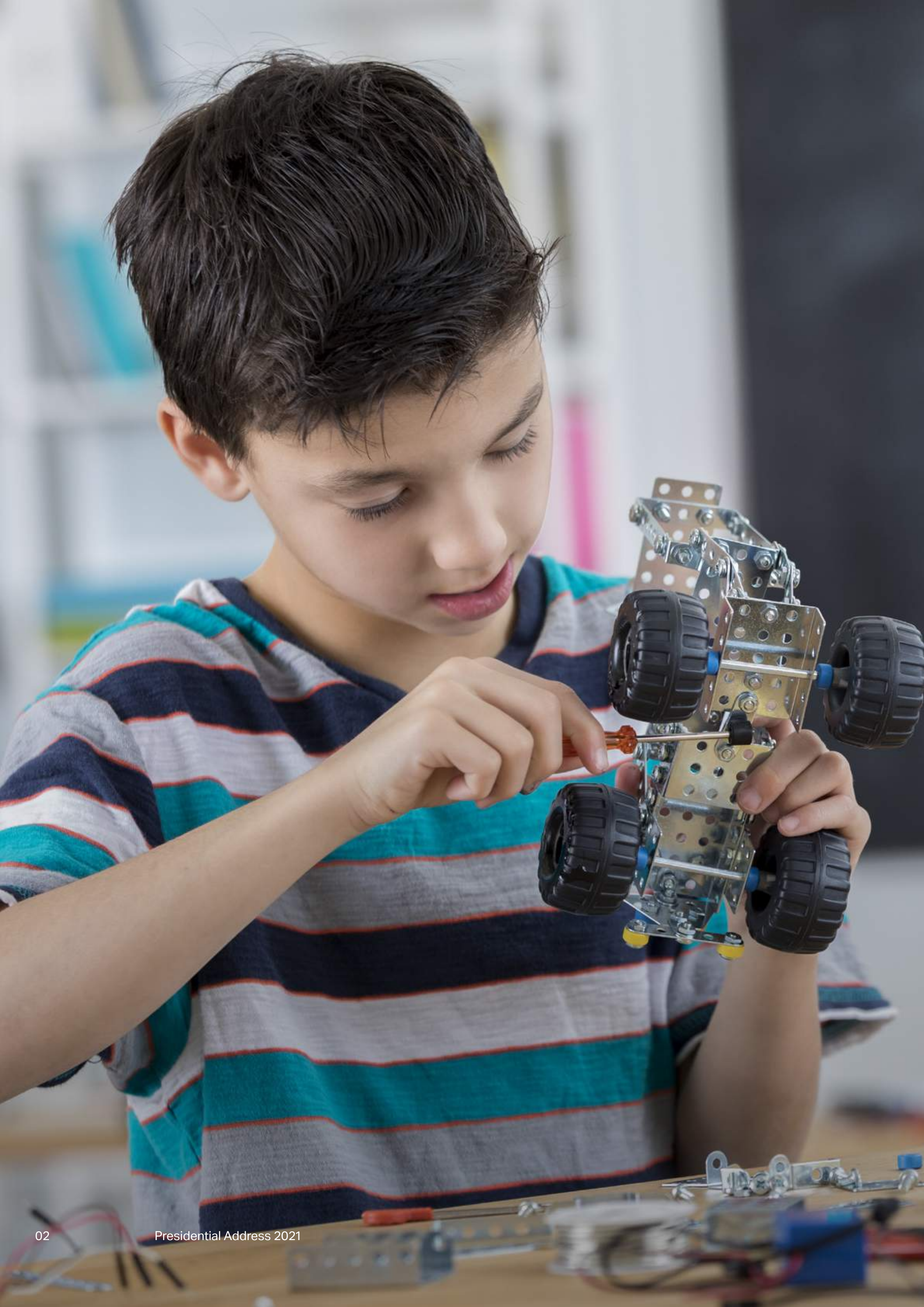


01 INTRODUCTION

In this paper, I begin with some words about how I became interested in my vocation – engineering – and move onto what I covered in a rather varied career. My main learning was how to turn ideas into reliable products and I outline how this can be achieved. I then say something about my views of how this Institution could move forward in a time of major societal challenges and rapidly developing technology but also bringing in the 175 years of perspective that the Institution can offer.

Unusually perhaps, 'engineer' was a familiar word to me during my early years. My father had been in the Royal Engineers as a private soldier during the Second World War, serving in North Africa and Italy. Being born soon after this war, and frequently meeting his old comrades, I formed the impression that engineers were people who got things done. It was a period when Meccano, Mamod steam engines and cut-away drawings in the Eagle comic were part of everyday life. It was also a period when the ability to fix things was a daily necessity. Hence, I had a positive and practical image of engineering from my earliest days.

02 EARLY YEARS AND EDUCATION

Engineering Books

Then, when I was eleven, I was fortunate enough to win a school prize, a book, I actually wanted something on train-spotting but this was considered unsuitable. Instead, I was given Men, Missiles and Machines by Lancelot Hogben. I still have the book and am still impressed with the drawings of pyramids being built, atoms being split and pictures of what we would now call renewable energy.

Next year, at the age of twelve, I asked for and received Six Great Engineers by JG Crowther. My fate was obviously sealed by this point. The six engineers, whose biographies are given in the book, included Charles Parsons and Christopher Hinton whose associations with this Institution are well known. In fact, the portrait in the book of Charles Parsons bears an uncanny resemblance to the picture in our Parsons Room on the first floor and, when in meetings there, I often think back to when I first saw it in about 1960.

Mechanical Sciences

During my teenage years, I messed about with bikes, radios and cars so it was no surprise when, again of my own volition, I chose to do engineering at university – or Mechanical Sciences as it was known at Cambridge. Before I 'went up', I had eight months to spare; these days young people would expect to tour the world in such circumstances but, in those different times, I took a job as a laboratory assistant at a gas plant in Blackpool. Extremely smelly, it produced town gas from coal and, experimentally, gas by reforming LPG. At lunch times and at the age of 18, I seemed to be in charge of the plant.

The Cambridge course itself was quite theoretical and mathematical although the engineering labs had some impressive kit which today would be subject to stringent safety requirements. I covered a very wide range of engineering topics – mechanical, electrical, civil and nuclear – and felt that everything was based solidly, if mathematically, on first principles. That led on to my first job in the aerospace industry, of which more later.

Business Education

I had always wondered about acquiring a business qualification – it seemed to me that any engineer who couldn't understand business and finance would be fighting with one arm tied behind their back. When I was working in Scotland, the opportunity arose to do an MBA on a part-time basis at Strathclyde Business School so I took the plunge and completed it over a 3 year period, including a mini-thesis on the economics of flexible manufacturing systems.

Then, in 1989, my company nominated me for the International Senior Management Program at Harvard Business School. It was a 2–3 month/6 days per week intensive course based entirely around case studies. There were either 2 or 3 cases per day and students were called at random in the class sessions to give 5 minutes on 'what would you do?' in the circumstances of the case. Very often, the head of the company in question would then come along and say what actually happened and whether it was successful, which sometimes wasn't the case. We had inputs from Nike, Asahi Breweries, General Electric and Pilkington's, to name a few. We also had a few overview lectures from well-known names such as Michael Porter. Overall, it broadened my business perspective enormously as well as tasting another Cambridge – this time Cambridge, Massachussetts.

03 **CAREER**

Developing & Making New Products

I spent the best part of forty years developing and making engineering products and providing services to support them. I worked for four companies over this period: British Aircraft Corporation (now BAE Systems), Leyland Trucks, ABB, now all parts of publicly-quoted companies and Vectra Group, an SME owned at the time by a private equity firm. Starting on basic design and development work on projects such as the Anglo-French Jaguar, I gradually acquired more responsibility and had about 15 years as a general manager/managing director with profit responsibility in manufacturing-related businesses employing 1,000+ people and with turnover of up to £100m. There was a strong international flavour to the work and a wide variety of experiences – see below.

Setting Up New Organisations

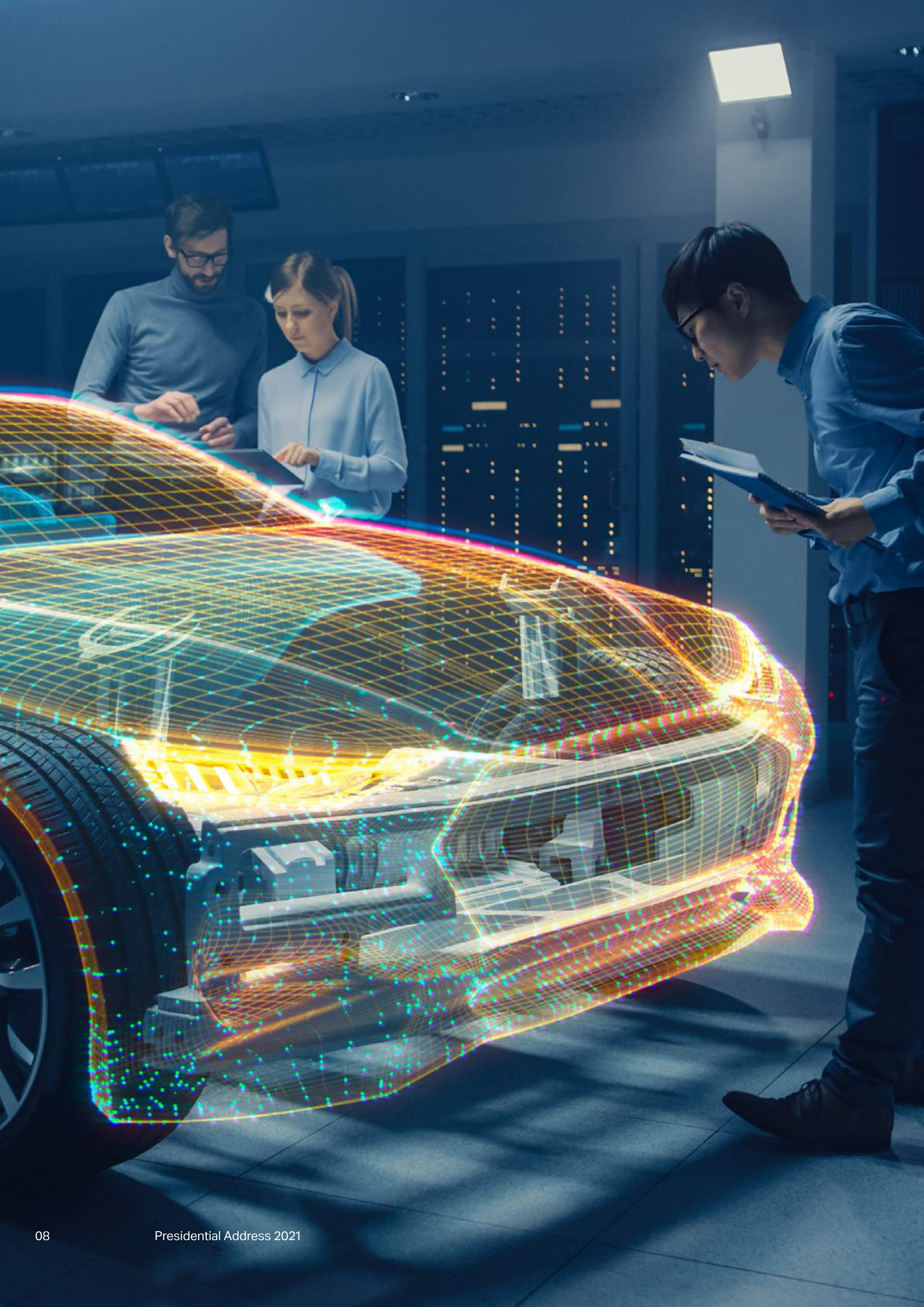
I then had about ten years working at the interface between business, government and universities. This all happened by accident. I was appointed to act as the Project Director for setting up The Manufacturing, Technology Centre at Ansty near Coventry, an organisation now thriving. This led on to a similar role for the Aerospace Technology Institute, also thriving, and to much of the start-up work for the Catapult Network, especially in manufacturing. Although the subject matter of all these organisations is technology and engineering, the work to establish them was a mixture of the political, financial, legal and commercial. All needed clarity of purpose and vision to carry them through scepticism and doubt during their early stages.

What Did I Learn?

I've always felt that I've had a very varied career that has provided a broad perspective as I've had to:

- Learn how to develop products and make them reliable and cost-effective
- Beg for money
- Travel to foreign parts
- Cross picket lines
- Be summoned to House of Commons Select Committee hearings
- Become an expert in company, employment and contract law
- Recruit people and make people redundant
- Takeover businesses and be taken over
- Work with 50+ nationalities
- Set up new organisations from scratch with the appropriate infrastructure
- Deal with fraud, theft and unacceptable behaviour
- Learn how to build a team
- Meet royalty

Overall, these and many others are the skills that any competent manager needs to acquire in order to get things done!



04 INNOVATION – THE COMMON FACTOR

The Common Factor

Looking at my experience in the round, much of it seems to have little to do with engineering, the subject I originally studied. But this should not be a surprise as engineering is all about turning invention and technology into something useful and that means interacting with the real world. If there is a common factor, it is in the constant pursuit of innovation, whether that be innovation in technology, products, services, organisations or processes.

What is Innovation and Why Is It so Important?

Those with a classical education will recognise 'innovation' as a Latin word derived from the verb 'novare' – to refresh or renew. However, it hasn't always held today's meaning. In the 16th and 17th centuries, innovators were religious heretics with strange and unacceptable ideas. Edward VI, for example, in 1548 issued 'A proclamation against those that doeth innovation' and threatened them with 'his highness indignation… imprisonment, and other grievous punishementes'. (Edward was 10 years old at the time).

But Sir Francis Bacon (1561–1626) had other ideas in his 1625 essay 'Of Innovations'[1]. He stated that: "He that will not apply new remedies must expect new evils; for time is the greatest innovator." His context was innovation in government which was generally regarded with deep suspicion at the time.

The modern and much broader meaning may have had its origins in the seventeenth century but its widespread use in its present form is essentially a twentieth century phenomenon. And this derives from innovation's importance in promoting economic growth.

Economic and Business School Thinking

To understand this connection between innovation and growth, two of many stand-points are summarised below.

Going back some years, the Austrian economist Joseph Schumpeter (1883–1950), a professor at Harvard Business School, was a great student of long-term economic development.

He concluded[2] that long-term growth was sustained by waves of 'creative destruction' based around innovations. Whilst these innovations might destroy the value of established companies in the short-term, they ultimately resulted in greater overall growth.

Peter Drucker, a personal favourite and always very pragmatic in his views, identified innovation as a powerful force but one which arose more from analysis and hard work rather than pure inspiration. He identified[3] seven sources of innovation of which new technical knowledge was one – and the one which was the longest to develop, had the highest casualty rate and was the most unpredictable. He and others also pointed out that technical innovations often represented the coming together of multiple technologies, involved a lot of team-work and might happen in multiple locations at the same time.

The points above, and those from other students of innovation[4], confirm the powerful but somewhat unpredictable role of major new engineering solutions. These are points which the Institution should bear in mind when it is asked to advise or comment on engineering policy matters.

Innovation at Its Most Powerful

Our natural tendency when considering innovation is to think about the headline-grabbing 'Top 10' developments. We think for example of Thomas Newcomen and his early 18th century steam engine which, via Watt and the Stephenson's, eventually brought about huge social and economic development in the 19th century through railways, steam ships and power generation – all from a system that was originally designed to pump water out of mines. Although Newcomen is usually credited with the idea, others were working on it at the same time.

Similarly, the transistor that came to the fore in 1947 through the work of William Shockley's team at the Bell Laboratories in New Jersey has subsequently brought about huge changes – technical, economic and social – that were previously unthinkable.

When we think of innovation, it is natural to think of these high-profile developments, plus others such as electrical power, the internal combustion engine or the telephone as further examples. Similarly, it is hardly surprising that governments the world over put money into what they hope will be the next major breakthrough. At the same time, there is a long catalogue of revolutionary ideas whose impact, whilst useful, was far from major.

Small Scale Ideas

The reality, of course, is that most engineers spend their working lives 'doing' innovation that results in modest but useful improvements. But the effect of these improvements cumulatively is huge. That is why a Model T Ford in 1908 cost about the same in real terms as a modern car[5] despite the latter being immeasurably faster, safer, more fuel efficient and more comfortable. Similarly, computers have shrunk from the size of a house (in 1945) to the size of a pin, air travel is much safer and cheaper, and golf clubs hit the ball so much further (in the right hands).

Spending on Innovation

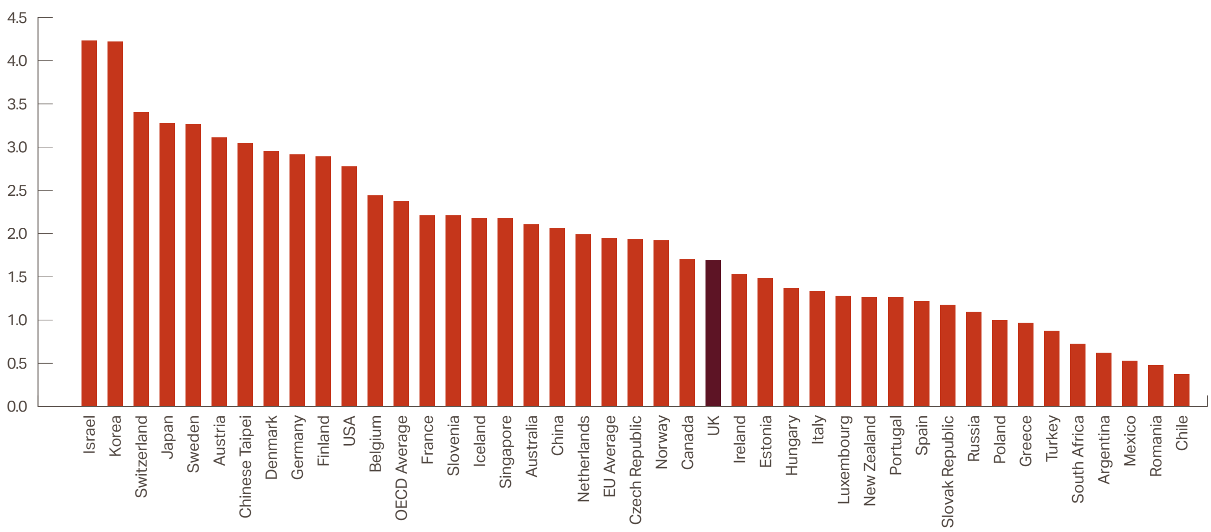
In the developed world, nations typically spend between 1% and 4% of GDP on 'R&D' (**Figure 1**)[6]

R&D in this context means activity of the type that engineering, pharmaceutical and manufacturing companies typically carry out[7]. It might be considered a rather narrow definition of 'innovation', excluding as it does much of the innovation carried out in service companies.

As another indicator, in 2018 3.3m patent applications were filed world-wide and filings have been growing at c. 5% p.a. for some time (**Figure 2**)[8].

Hence, innovation just on these rather narrow measures, is big business in its own right, comparable in size, for example, to food manufacturing in the UK. But its real value is in the competitiveness it provides to the products or services in which it is subsequently embedded. Research into the economic returns from investment in R&D suggest between 10% and 30% p.a. for the private returns for the company[9] concerned and between 40% and 100% when spill-overs to other organisations and sectors (social returns) are taken into account. The returns from any one particular investment are much more uncertain, of course.

Figure 1: Spending on R&D as % of GDP by country[6]



Government Intervention

For these reasons, governments the world over support innovation. Recent economic modelling in the UK[10] suggested that increasing R&D spend from the current, modest 1.7% of GDP to 2.4%, close to the OECD average, would have the effect of gaining an extra 1.3% to 2.9% GDP growth over an extended period and would have a disproportionate effect on export performance. We also see in the UK direct encouragement of innovation through initiatives such as Innovate UK, the Catapult network, the Aerospace Technology Institute, the Advanced Propulsion Centre, and R&D tax credits.

Encouragement From IMechE

Our Institution has, in its own modest way, played its part in encouraging innovation through:

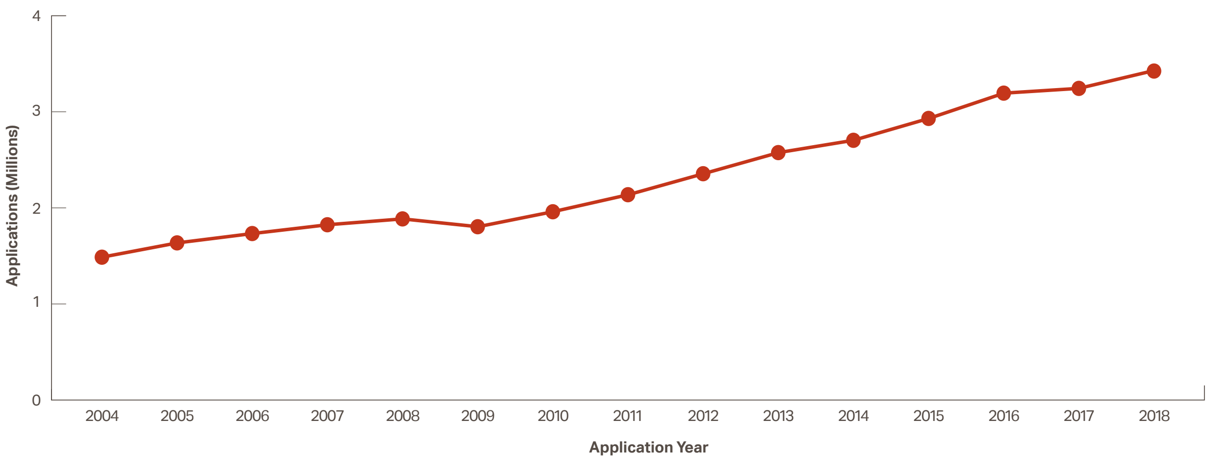
- The Manufacturing Excellence/TMMX Awards – since 1982, and for the last 5 years in conjunction with The Manufacturer magazine, the Institution has been involved in a high-profile awards scheme which encourages, as the name implies, excellence in product and process innovation;
- The Stephenson Fund[11] – investing c. £1.7m of Institution funds in 11 early stage companies operating in a variety of industries – space, sensors, internal combustion engines, nuclear fusion and catalysts, for example;
- Student and Apprentice Challenges – 5 competitions which encourage practical innovation in the fields of home automation, rail, autonomy, design and motor sport

As well as encouraging innovation per se, these activities provide opportunities for members to participate in and learn from innovation in action.

Innovation Overall

So innovation is good for everyone and very much the stock-in-trade of engineers in their everyday lives. But is it easy?

Figure 2: Patent applications worldwide 2004–2018[8]



05 PRODUCT DEVELOPMENT– THE ENGINE OF INNOVATION

The Importance of Making Things Work

As hinted above, technical innovation is a powerful but difficult activity. Arguably, this is because expectations are so high. It is difficult to replicate the standards set by established industries such as cars, aircraft and consumer goods in terms of cost, safety, reliability and ease of use. However, there has been relatively little coverage of the processes by which engineering products are created and developed to meet these expectations – hence the book I published in 2019[12].

Figure 3: Managing Technology and Product Development Programmes: A Framework for Success

The Role of the Engineer – Entrepreneur

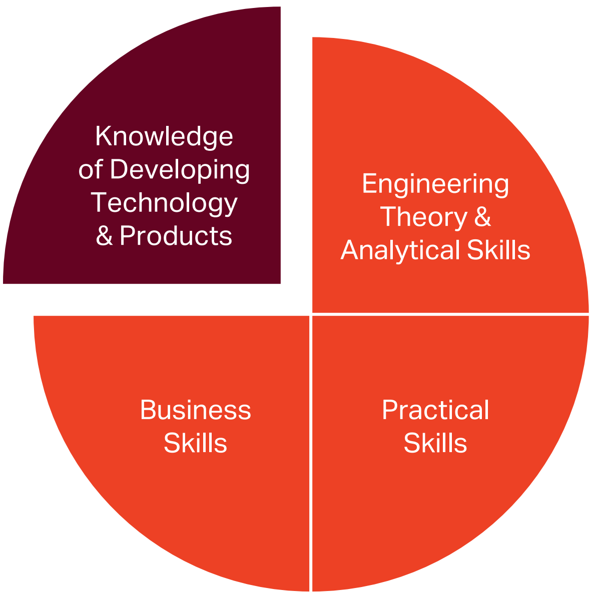
These processes use the design, analysis, and other skills that are taught academically. However, the means by which technology is turned into designs and subsequently to launch of reliable products is something that a new engineer has to work out for him or herself – a process that can often take a full decade if the environment is complicated.

Quoting again Peter Drucker, his 1985 essay[13] drew attention to this topic: 'We know how to train people to do technology such as engineering or chemistry. But we do not know how to endow managers with technological literacy, that is, with an understanding of technology and its dynamics… Yet technological literacy is increasingly a major requirement for managers.'

The purpose of my book was to fill this gap, as illustrated below.

The intention was to provide a framework that can be used to describe how new technologies, and then products, are created.

Figure 4: Engineering knowledge & skills



Core Development Process

The development of technology and products can be considered as a process, albeit one that is not used repetitively, as would be the case in manufacturing. Each project is somewhat different and the timescales in some industries, such as aerospace and defence, can be measured in decades. There are at least three distinct phases to this process, which can be described broadly as research, technology development, and product development.

The process can be unpredictable, especially in the early stages. When new ideas are being formulated, it is difficult to draw up future timescales and programmes as a series of logical steps, except in the most general sense. This is less the case with the later, and more expensive, stages of product development where classic project management methods can be applied.

There is therefore no magic formula for generating ideas and turning them into successful products. However, broad rules can be followed, and some of the principles of lean thinking, as used in manufacturing, can be usefully applied.

The day-to-day process of engineering is essentially an iterative, learning activity. Ideas are formulated, tried, analysed, and tested. The work also draws on previous experience, requiring an active input from seasoned engineers. Products, or the research and technology development coming before them, can be considered to have a high level of intrinsic risk in their early stages, reducing as more development work is undertaken. The cost of remedying these risks is very low in the early stages, no more than amending a drawing, but is very high if the product is in the prototype stage or, even worse, in service.

The thoroughness of this process determines the eventual reliability of the end product. New firms find it difficult to match the reliability achieved by established companies, derived from their facilities, methods, and experience.

Figure 5: The core development process

TECHNOLOGY READINESS LEVEL										
1	**2**	**3**		**4**	**5**	**6**		**7**	**8**	**9**
Idea	Lab Dev.	Proof of Concept		Rig Test	Lash Up Demo	Full Scale Demo		Prototype	Pre Production	Production
LAB / WORKSHOP RESEARCH										
			Concept Demo							
				TECHNOLOGY DEVELOPMENT						
							Full Scale Demo			
								PRODUCT DEVELOPMENT		

Technology Maturity

The concept of 'technology maturity' is a vital element of the understanding of engineering development. New technology, unfortunately, does not jump out of the box ready to go. In fact, the opposite is true: making technology work at the levels of cost and reliability expected by twenty-first century customers is a long process.

To develop this concept further, a mature technology is one that works reliably when in the customer's hands and can be manufactured consistently at the appropriate cost. It will be used in a range of applications by a number of companies. An immature or underdeveloped technology is the opposite of these and will frustrate the end user.

The idea of a technology maturity scale came first from NASA in the 1970s when NASA was trying to understand why certain programmes overran and others did not. It eventually developed a nine-level system, each referred to as technology readiness level, or TRL. This approach has been widely adopted across a range of industries and supports good decision-making: for example, whether to incorporate a new technology on a new product programme, which technology developments to pursue, and whether to invest in a start-up company.

Methods are available for numerical assessment of readiness, and these are useful in providing an objective understanding of the maturity of an idea, and hence what to do next. Quite frequently, certain aspects of new technologies are well developed but other areas are weak.

In principle, advancement of technology readiness is achieved by undertaking increasingly detailed analysis and testing with increasingly representative test material in an increasingly realistic environment. The process for doing this work can certainly be made more efficient, but all phases of maturity have to be worked through. The TRL, and associated manufacturing, scales give a common language for this process and can be used as a means of communication with nonexpert parties such as general managers or investors.

Aligning Technology With Business Needs

New engineering technology can be developed almost in isolation, but there is then much less chance that it will result in a successful economic outcome. It therefore makes sense, in the early stages of technology development, to think through how that development might be manufactured, sold, and supported, and how it might compete in the marketplace. Just a simple assessment, when a technology is at TRL 2 or TRL 3, will ensure that the development is heading in the right direction. Apart from anything else, this will make future funding more likely whether the development is in a university laboratory or in a company environment.

The idea must, however, be seen in the context of the competition and must have strongly differentiating features and/or must appeal to a very well-defined target market unless it is able to compete on price alone. The latter is possible where the development is taking place in an already strongly cost-competitive business but a new entrant will find it difficult to compete on cost.

This then raises the question of identifying the customer. In some situations, there may be a single, clearly identified purchaser; in others, there may in effect be multiple customers, or the effective purchaser may be an engineer who specifies what will be bought. Identifying the true buyer is essential, and it may not always be obvious who that person is.

If a new technology or product is being developed within an established company, the route to market will already be in place. Where it is being developed in a start-up, there are several ways forward, ranging from developing own manufacture and sale to selling the idea to another business. Understanding the routes forward will, sooner or later, be essential.

Another decision concerns how the idea will be sold: will there be just one product design or will multiple options be needed to satisfy the customer base? Or will each application have to be engineered slightly differently? The ability to satisfy a range of customers is essential.

The product must also be capable of economic manufacture. This means, at a strategic level, employing methods of manufacture that a firm can access, either through its own resources or through its suppliers. At the operational level, it means optimising the details of the product so manufacturing and assembly are easy – difficult-to-manufacture parts invariably have quality problems. This process then extends to service and disposal.

It can be seen from these points that, far from being an isolated activity, technology development needs high levels of collaboration to be effective.

Planning the Work

Engineering covers a wide range of activities, from small-scale technology development projects to very large product delivery programmes. All forms of projects benefit from at least a basic level of planning – it's a question of how much detail and where the emphasis should lie.

For a small project, these in total need be no more than half-a-dozen pages; for a very large project, hundreds of pages will be necessary. The process of compiling these documents may be as valuable as the output itself.

Projects can be categorised according to their complexity and level of uncertainty. Simple but uncertain projects, such as early research work, need only the most basic planning, with approximate timescales and a small number of key milestones, but still taking periodic stock of progress, especially as new learning is revealed.

Large, complex projects clearly need very detailed 'classic' project planning and professional management. Before starting such projects, the technological risks need to be brought down to acceptable levels by preliminary technology development work. Otherwise there is a danger of such projects becoming both complex and highly uncertain: a recipe for expensive problems.

In summary, new technologies and products are delivered through projects: time-bounded activities with specific objectives. As technology advances in maturity, these projects become more structured, more complex, and more commercially-focused, with an expectation by investors that results will be achieved. The basic disciplines of project management are valid at all phases of development: the 'fuzzy front end' through to multimillion-pound commercial projects.

Creating the Concept

Arguably, the most interesting part of engineering is having ideas and turning them into new product concepts. This phase of work brings together future market needs, new technological possibilities, and economic viability. As with other phases of work, early-stage development is an iterative mix of creating ideas, matching them with gaps in the market and testing whether the solution is likely to work financially.

Some ideas will simply be incremental developments of those that exist already, such as small-scale improvements on last year's product. Much less frequently, radically new ideas emerge and create markets that just don't exist currently.

Ideas can come from a variety of sources: company engineers or salespeople, long-range technology forecasts such as technology roadmaps, other sectors of industry, research engineers in universities, start-up companies, suppliers, or private individuals. Research has shown that three factors tend to determine the success of new products:

1. The superiority of the product in terms of the features it embodies
2. The extent to which customer needs have been investigated in detail
3. The amount of effort invested in early-stage product development

Customer data gathering, in detail, and customer understanding are clearly major factors at this stage.

Early-stage technical work forms the foundation of future development: it develops a concept that will appeal to customers. It must also identify critical issues and risks and do sufficient work to show they can be overcome subsequently. A parallel and realistic financial evaluation is a further, important element of concept development.

This is also the stage where intellectual property (IP) protection should be put in place. It could take the form of patents but could take other forms such as copyright and trademarks.

Concept development suits a small, multifunctional team environment – the work is not easily subdivided and is fast changing. Formal documentation of the work is helpful in as a means of capturing what has been done and as a discipline to ensure that the concept has been fully thought through with no inconsistencies.

Identifying and Managing Risks

Whilst generating a new concept represents the most interesting phase of development, the enthusiasm for the new must be tempered with a counter-balancing consideration of the risks that something novel might introduce. Risks can take many forms, from a simple failure to work as planned through to outright catastrophic failure.

Within this context, the risk management approach identifies all possibilities of failure and evaluates them according to their likelihood and the severity of their consequences. Action is then taken in proportion to these factors. It is through this approach that consumer products such as cars have such high levels of reliability, and hazardous activities, such as flying at 500 mph at 35 000 ft, are regarded as everyday occurrences.

The root causes of risks and failures are relatively straightforward, and include design-related issues, defects introduced through manufacturing, mechanical failures, electronic component failures, and software design malfunctions. The aim of much engineering development is to minimise the likelihood of these occurring, noting that complete freedom from risk is unattainable.

There are several well-established ways of evaluating risk, such as failure modes and effects analysis (FMEA) and fault tree analysis (FTA), first used in the 1950s and 1960s. Industries in the public eye, such as nuclear, aerospace, process, and oil and gas, are very strong in this area, having suffered some serious catastrophes such as Flixborough, Challenger space shuttle, and Piper Alpha. These industries have built on the basic methods and introduced quantitative approaches that estimate numerically the likelihood of failure and evaluate the consequences in numerical terms.

These methods are becoming wider in their application as more products and systems become dependent on software and control systems for their safety - 'functional safety', as it is called.

These thoughts must also be tempered by what is practicable and economical. The ALARP concept (as low as reasonably practicable) has been developed to identify which risks are just unacceptable, which can be discounted, and which should be brought down to acceptable levels. Of course, what is considered unacceptable is becoming stricter over time.

Risk identification and management is one of the primary mechanisms for embodying the lessons of the past and learning from the failures of the past is central to the engineering process.

Validation

Engineering validation is concerned with the analysis, modelling, and testing activities, which are used to minimise engineering risks and ensure a reliable product. It covers validation of performance, legal compliance, product life, response to extreme conditions, and reliability. Whatever form of validation is used, problems are identified, causes understood, and solutions tested – essentially, a process of learning. All new developments need a thorough and well-planned validation programme to achieve competitive reliability.

Analysis by engineering calculation, based on theory, is the starting point and is readily applied in the early stages of programmes. Most theory is available as pre-programmed software. More detailed mathematical models are then used to take analysis to a higher level of complexity and detail, examining complete products, systems, processes, and their performance. The success of both analysis and modelling is very dependent on the correlation that can be built up with real life. Modern software makes it very easy to create realistic-looking models and hence the illusion of accuracy. Companies build up this correlation over time, usually in the form of development codes which results in very accurate simulation methods. Start-up organisations will have to develop this capability over time and must take care not to be overconfident .

Trialling by physical testing is the ultimate assessment of a new product and the closest to real life. However, the realism of modelling methods has progressed to the point where physical testing is used as a means of confirmation rather than development. It should be noted that physical prototypes are often the first time that all a complex product's systems come together, and hence their unexpected interactions can be understood. Performance testing is relatively straightforward but life testing needs accelerated methods.

Where the product is very low volume or a one-off, prototyping may be difficult or impossible. The sold product must then go through a commissioning period which must be carefully managed to achieve customer satisfaction.

Later in development programmes, numerical measurements of reliability can be made if a statistically significant number of products can be made by production methods and operated in realistic conditions – product reliability is set by the thoroughness of the development programme and is not inherent in the design.

Engineering Delivery

'Delivery' results in a formally-defined product that can be manufactured with confidence, sold, operated, and retired. The output is information, almost certainly in digital form, such as drawings, bills of material, and specifications. The engineering function acts as the originator and custodian in most organisations of this data and 'owns' the information, applying formal issue control to it in line with quality management requirements. The data, however, will have been created collaboratively within the organisation and represents an important corporate asset.

In contrast perhaps to the more creative aspects of technology and product development, this is a detailed and exact form of activity, which provides the basis for making known and traceable products.

This activity covers TRLs 7–9 and MRL 5 and upwards. It consumes the majority of the resource and cost of the development programme through detailed design, modelling, prototype manufacture, and test work. Given the amount of resources consumed and the number of activities undertaken, it requires careful planning of the key milestones.

There will still be some learning and iteration during this phase of work, but it will be containable if the product specification and technology have been properly researched in earlier phases. However, with inputs from design engineers, manufacturing engineers, suppliers, and other parties, close team- work is needed, backed by responsive but formal change control.

Detailed management responsibility should be delegated to team level, where most of the new information originates and where solutions to problems can be found. Co-locating multifunctional teams on either a periodic or permanent basis can have a big effect on the speed of the work. Good systems in terms of progress tracking, learning points identified and closed, and accessible product databases have a similar effect.

Specialised resources can be troublesome bottlenecks. These could take the form of specialist engineers, managers for sign-off, analytical resources, or test facilities. Conscious management of bottlenecks is recommended, there being a trade-off between utilisation and throughput time, with high utilisation causing surprisingly long queues of work.

Completing this phase of work, a formal sign-off process should ensure that all requirements have been met, all learning points closed, all reviews completed, and legislative requirements met. The product may then be 'released' without conditions or it may be concluded that a conditional release can be given pending completion of certain tasks.

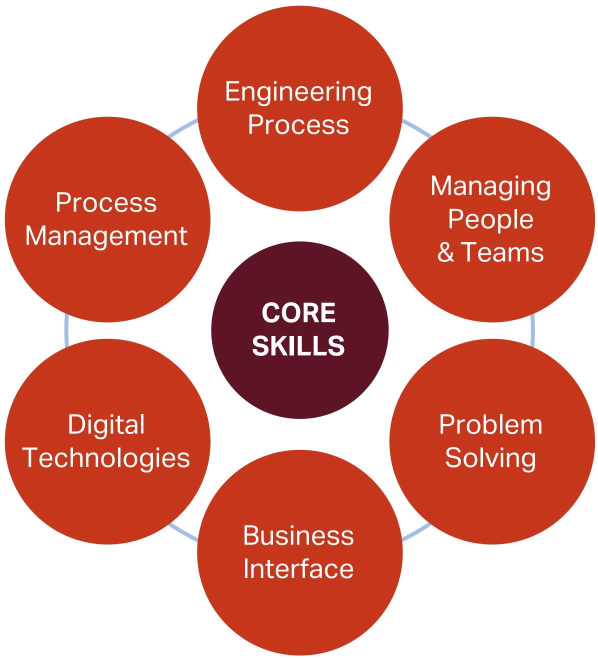
This is an important decision point at which an organisation commits to volume production and all that it entails.

Concluding Points

The process outlined above does not guarantee a successful outcome but it gives a much better chance of turning ideas into reliable, cost-effective products.

For engineers taking part in or leading such processes, the skills required are wide-ranging and a mixture of technical, managerial and inter-personal.

Figure 6: Engineering core skills



06 INNOVATION IN THE FUTURE

Those are some thoughts about how innovations can be turned into reliable, cost-effective solutions. Before asking 'what does the future hold for innovation?', it's worth reflecting on what has happened to technology and innovation since the founding of this Institution.

Technology Since 1847

This Institution, in its almost 175-year history, has experienced at least three industrial revolutions and is arguably experiencing a fourth, driven by data, intelligence and analytics.

It has seen annual production of cars, aircraft, phones, domestic appliances and electricity rise from nothing in 1847 to, in 2019[14]:

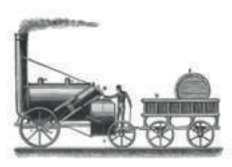
- Cars – 92.8m
- Aircraft – 50k
- Phones – 1.5bn
- Washing machines – 140m
- Electricity – 25,000 TWh (25 x 10^{15})

This process of growth was driven by new technology and new products which were successful in meeting the customer demand created by the wages those customers earned by working in the industry producing the products – a form of virtuous circle. And they have become increasingly affordable through improvements in efficiency, productivity and capital intensity, most successfully within open, market economies.

At the same time, the world has improved immeasurably in other respects, despite opinions to the contrary. For example, the world's health[15,16,17] has improved radically, as measured by:

- Life expectancy, improved from <40 in 1847 to 73 currently world-wide
- Infant mortality, improved by between 10x and 20x
- Extreme poverty, reduced from 90% of the world's population to <10% despite the population growing from 1.2bn to 7.8bn over that period.
- Some 'killer' diseases largely eliminated, eg polio and smallpox

Figure 7: Industrial revolutions

				
Revolution	**First**	**Second**	**Third**	**Fourth**
Approximate Timescale	1760–1840	1880–1910	1965–1995	2000–
Features	• Coal • Steam engine • Railways • Mechanisation and factories • Iron production	• Electricity • Steel • Mass production • Large corporations	• Semi-conductors • Computing & software • Internet • Automation	• Digital manufacturing • Virtual Modelling • Embedded computing • Artifical intelligence and autonomy

This is not to say that everyone has benefited equally but few could argue that the world has not improved since 1847 and much of that improvement is down to technology and engineering.

At the same time, we have the uncomfortable fact that CO_2 concentration has risen from 284ppm in 1847 to 412ppm in 2019[18]. Global temperatures have risen by 1.0 to 1.2C, methane concentrations have increased from about 800ppbn to 1800ppbn, and 8m tonnes pa of plastic is going into the ocean.

6.2 Current and Future Challenges

Engineering was painting on a blank canvas in George Stephenson's time. Nowadays, partly as a result of that success and partly for other reasons, the world is a more complex and demanding place. It continues to face challenges and whether those challenges are greater or less than those in 1847 is a matter of debate!

In this context, the United Nations has identified 17 sustainable development goals covering a wide range of topics[19].

Many of these challenges were there, in worse form, in 1847 but were accepted then as facts of life. Five of today's 17 goals are of particular relevance to engineers:

- Goal 6 - clean water and sanitation
- Goal 7 – affordable and clean energy
- Goal 8 – decent work and economic growth
- Goal 9 – industry, innovation and infrastructure
- Goal 12 – responsible consumption and production

These points are well known and align with a recent survey of Institution members who asked that policy work should concentrate on four areas:

- Climate change mitigation and adaption
- Delivering net zero (i.e. adding as much greenhouse gas to the atmosphere as is removed from it)
- Future transport systems
- Education and diversity.

They also align with the fact that many national governments have committed to net-zero carbon targets by c. 2050.

Figure 8: UN Sustainable Development Goals

6.3 Technology and Engineering Solutions for the Future

Given that the R&D spending across the world is approaching $1.0tn pa, it is hardly surprising that an amazing range of technologies are under development, offering potential solutions to the challenges noted above.

To the extent that it is possible to summarise the main areas of activity in world-wide R&D, arguably it covers four principal topics:

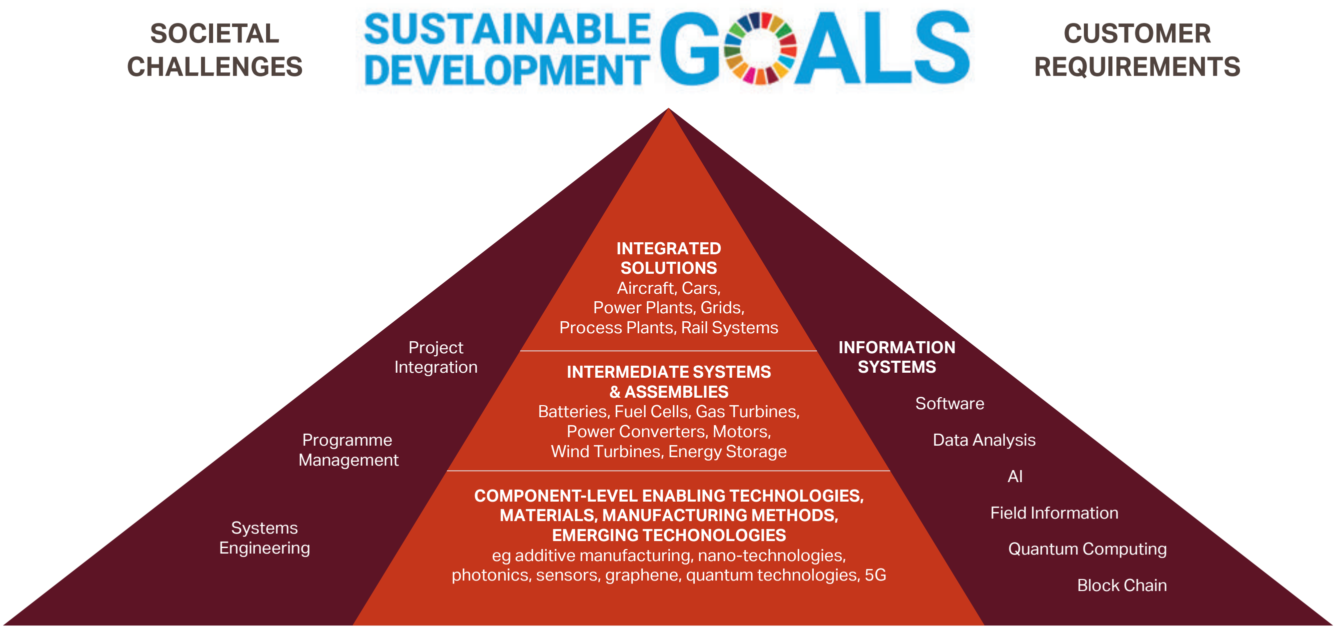
1. The physics, chemistry and engineering of new materials, methods and components
2. Data technologies - sensing, data analysis, machine learning, intelligence, and connectivity including the Internet of Things
3. Biological and bio-medical solutions
4. Integration technologies - systems engineering, software, simulation

Together, these form a 'technology supply chain' (**Figure 9**).

The enabling technologies are at the bottom of the chain and the integration activities are at the head of the chain. And integrated systems can only proceed to the extent that under-pinning technologies permit, a fact that was appreciated 200 years ago when steam engine technology could only proceed at the pace that, for example seals, would permit. Today, it is argued that quantum computing is restrained by progress in lasers and cryogenics technologies.

What is often under-appreciated is that to address societal challenges through new systems requires substantial and difficult integration activities – of physical technologies, software, and systems engineering.

Figure 9: The technology supply chain



But Are We Doing Enough?

With these points in the background, societal pressures are strongest in the developed world to solve the most pressing problems in the shortest possible timescales. In response, governments are becoming more interventionist and regulatory. Their instincts also seem to be more protective towards their own countries, to the extent that that is possible within the constraints of open economic systems where it is very difficult to 'buck the markets', as one former prime minister observed.

One area where, at least in the UK, government is becoming more active is in technology development.

Recognising that the UK spends (only) some 1.7% of GDP on R&D compared with an OECD average of 2.4 % (and up to 4% in certain countries such as Israel and South Korea), a target of 2.4% by 2027, and 3% in the longer term, has been set.

It could be argued that R&D spend does not represent innovation in its totality but most R&D is concentrated in manufacturing industry so it is a good indicator of innovation activity in engineering more generally.

When current UK R&D spend is examined in detail[20], it becomes apparent that it is split:

- Industry and business – 68%
- Higher education, especially universities – 24%
- Government incl. UKRI – 7%
- Private, non-profit organisations – 2%

The industrial and business component of this spend is then concentrated in 6 areas:

- Pharmaceuticals
- Automotive
- Aerospace
- IT services
- Software
- Technical testing and analysis

To a certain extent, this also aligns with venture capital funding[21] of technology work where the bulk of the UK 2019 spend went into:

- ICT, computing, software and electronics (50%)
- Biotech and healthcare (23%)
- Business products and services (15%)
- Chemicals and materials (7%)

The point to note here is that governments will find it difficult, even if they want to, to increase overall R&D or innovation spend through their own resources in universities or government bodies. With over 2/3 of R&D spend being in business, countries rely on industry to achieve policy objectives, which is quite right given that governments have a rather patchy record in 'picking winners'.

The other question which this analysis raises is whether the spend is in the right areas versus the challenges faced by society. In the UK, just over 50% of equivalent CO_2 emissions come from transport and energy generation[20]. Whilst transport technology seems well represented in UK technology development, energy generation is less prominent in the UK figures than might be expected – small scale 'modular' nuclear reactors being an example of an area which could receive more attention.

Will These Actions Produce the Desired Results?

Whilst governments can increase their funding of research and development activities to encourage the solving of these challenges, the bulk of innovation work is carried out in industry where the laws of economics prevail. Companies and venture capital funds will invest in innovation to the extent that returns will accrue and hence meet the objectives of shareholders, who are often pension funds and personal savers – our money!

From one point of view, we could be optimistic because returns from investment in innovation can be high, but as noted previously, are risky and that risk aversion is reflected in the fact that only some 5%–10% world-wide of venture capital funding is going into climate-change companies, green start-ups and public listings.[25,26] whilst investment is piling into much later-stage companies such as Tesla.

In fact, there is no shortage of funding available for later-stage investment. Firms raised some $3.6trn of new funding in 2020 and the world's 3000 most valuable non-financial companies were sitting on $7.6trn of cash[27] during this difficult year. These figures should be seen in the context of a world 'GDP' of c. $80trn.

In terms of the additional investment needed to meet societal challenges, which the UK's Committee on Climate Change has estimated as an additional 1% of GDP above the normal annual spending of 15% –24% of GDP, there would seem to be plenty of funding available provided adequate returns can be achieved.

This then introduces the other dimension of government activity in the area of market intervention where subsidies or pricing mechanisms can be used to encourage appropriate solutions until costs are driven down to the point where those solutions become economically self-sustaining. And some areas such as electric vehicle charging networks may be just too risky for wholly private investment.

The overall point is that progress in meeting societal goals is dependent on the technological developments being 'joined up' both technically and economically.

The Changing Nature of Technology Development

A further point concerns the changing nature of innovation and engineering and the way that components are built up into complete systems. At the level of components and sub-systems, software, sensing and intelligence are increasingly built into what might normally be regarded as mechanical systems. Whilst mechanical systems benefit from 175 years of practical development, and hence understanding of how reliability is achieved, software has only 30–40 years behind it and is therefore less well understood from a reliability perspective.

As those sub-systems are then integrated into higher level systems – which could be a complex finished product such as a car or aircraft, or could be some form of network, such as a smart grid or a railway-signalling system – integration of the elements becomes a major challenge, with all its requirements relating to functionality and safety. Further requirements relate to connectivity to the operating environment, data analysis and the way this might be used to support the business model where the product might be sold as a service rather than a one-off sale plus service.

System integration is usually under-estimated in complex engineering projects, e.g. Crossrail, and is certainly under-estimated with national-level initiatives, e.g. the introduction of electric cars, and this is a political problem as much as a technical one.

Concluding Thoughts

The analysis above shows that demand for innovative engineering solutions can only increase, noting also that many of the world's challenges can only be solved by engineers, a fact that is sometimes over-looked. However, in the context of the progress that has been made since 1847, one should be optimistic that solutions will be found in a timely manner to the challenges we now face, provided that the solutions are managed in a holistic manner, integrating all the relevant factors.

07 IMPLICATIONS FOR THE INSTITUTION AND ITS STRATEGY

The Purpose of IMechE

Of particular importance, then, is the effectiveness of engineers in undertaking innovation and hence addressing societal challenges.

At its founding in 1847, almost 175 years ago[23], the purpose of the Institution, ie what it stands for, was stated to be 'to meet and correspond and by an interchange of ideas respecting improvement in the various branches of Mechanical Science to increase their knowledge and to give an impulse to invention likely to be useful to the world'.

It is notable that, from the outset, the Institution has had two distinct aims:

- To help engineers develop and 'increase their knowledge'
- To help society through 'useful' engineering

Over time, the words used have evolved. At the time of the granting of the Royal Charter 90 years ago in 1930, it was stated in Clause 7 of the Charter[24]: 'The objects and purposes for which the Institution is hereby constituted are to promote the development of Mechanical Engineering and to facilitate the exchange of information and ideas thereon and for that purpose.'

Nowadays, we use the phrase: 'to improve the world through engineering' as our statement of purpose.

Whilst these words might be described as the external purpose of the Institution, internally, its role continues to be to help engineers in their personal development, their careers and their general effectiveness as rounded individuals who can go on to fulfil the purpose to the best of their ability. This is clearly key to addressing the challenges discussed previously.

The Changing Nature of Engineering

As noted in Section 6, the nature of engineering solutions is changing radically. It could be argued that, for about 2/3 of this Institution's 175-year existence, engineering followed the traditional disciplines of mechanical, civil, electrical and so on, with education, training and development following those disciplines.

The distinctions now are much more blurred. Solutions cover multiple disciplines, and all are over-laid with software, control systems, data and intelligence. Key features of engineering today include, as well as 'normal' engineering:

- Integration of embedded software and control systems in components and sub-systems
- Connectivity to units in the field
- Ability to collect, process and analyse large amounts of field data
- New business models where products and systems are sold as services with performance guarantees
- Integration of multiple sub-systems into complex networks
- Management and integration of complex, multi-facetted projects
- Potentially, autonomous and/or learning systems
- Assurance of safety and reliability in these environments

In addition, engineering is finding its way increasingly into bio-medical and healthcare fields and may, further ahead, include the integration of biological with more traditional engineering systems.

Improving Engineers' Effectiveness

Relating these points to the Institution's value proposition to members, the work of the Institution is currently built around four priorities:

- Maintaining professional standards
- Supporting and developing engineers
- Securing the future of the profession
- Encouraging and disseminating knowledge and invention

Arguably, all these activities need to be changing and developing continuously to reflect the points noted above, covering for example:

- How accredited degree courses should develop to reflect the broadening nature of engineering
- How the Institution's programme of events, webinars, and courses can help engineers develop their technical, business and management knowledge and skills
- How to communicate to younger people the vital role engineers play in solving the world's challenges
- How the Institution influences government and society more generally on the role engineering plays in societal challenges

Our Role as a Source of Impartial Advice

On the final point concerning the wider influence of the Institution, the membership possesses valuable knowledge not just about the technicalities of future solutions but how they can be developed into reliable, high-volume and cost-competitive answers to society's needs.

We can comment on:

- New, enabling technologies and where they might be applied, how and when they might develop, and a realistic assessment of their true potential;
- System solutions addressing major challenges and how they should be constructed so that all elements of the system are thought through as a coherent whole with no gaps;
- Management and software integration issues which need to be taken into account to create on-time, reliable solutions

Collectively, we possess the ability to influence how political or societal decisions are taken to achieve the best answer.

08 **CONCLUDING POINTS**

I started this paper by describing how I became interested in engineering and, subsequently, chose to pursue a career in this field. I was fortunate to have a varied career that was concerned more with business, organisational management and finance than pure engineering but always with engineering principles in the background, acting as the ultimate sanity test.

I have given my views about how ideas can be turned into working reality, an under-rated activity but one which is vital if we are continue to improve living standards through reliable, cost-effective, safe and efficient products that meet customers' needs internationally.

I then turned to future challenges and how we, as engineers, can help society address them, which I think we need to do more of. This led on to the role of the Institution in developing engineers and influencing the future direction of technological development.

I have emphasised the need for pragmatism in the work of engineers so the over-riding theme of my address might be summed up by the comment made by a certain Arthur M. Wellington as long ago as 1887, 'an engineer can do for a dollar what any fool can do for two.' – our role is to develop practical, robust and cost-effective solutions!

09 ACKNOWLEDGEMENTS

The views expressed in this paper are very much my own, built up over the c. 50 years of my engineering career, including some 30 years of active involvement in this Institution.

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Finally, the references on the following page have provided useful supporting facts and opinions.

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