THE FUTURE OF INTERNATIONAL COLLABORATIVE ENGINEERING.

Institution of MECHANICAL ENGINEERS

A Manifesto

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Improving the world through engineering

> The need for cross-sector, cross-discipline and cross-border engineering collaboration has arguably never been so acute.
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Synopsis

As COVID-19 vaccination programmes begin to take effect in an increasing number of countries around the world, and national strategies for post-pandemic economic recovery shift from formulation to delivery, it is timely for engineers to reflect on the experience, learnings and knowledge acquired during the past two years and what it might mean for the work of the profession.

Such a stock take enables an understanding to be gained of not only what has been learnt and what new insights have been acquired, but also what elements of successful practice have evolved whilst meeting the challenges of the pandemic, and which of those to take forward to help the profession tackle other major global challenges.

In this paper the Institution of Mechanical Engineers (IMechE) contributes to such an exercise by exploring the nature of engineering collaboration prior to, and during, the pandemic; considering its future role in the profession; and articulating a manifesto for increased collaboration in tackling society's major 21st Century challenges.

Introduction

Collaboration is at the core of what sets humans apart from other species and has been a key contributor to humanity taking a dominant position amongst living things on the planet. The ability to communicate with each other and organise into collaborating collectives to achieve mutually beneficial goals and outcomes, initially in areas such as food and water acquisition, shelter, protection and tool development, and later transport, trade, commerce and health, has transformed us from hunter gatherers to participants in a modern civilisation that today spans the globe.

In this context, most early humans were engineers to one degree or another, gaining and sharing knowledge through mimicking, copying, duplicating, and practicing collaborative working skills from the beginning[1,2]. However, more recently in time, as engineering developed into a well-defined discipline within society, and the engineer emerged as a distinct class of professional practicing therein, formalisations of collaboration ensued, and the practice became recognised as a subject in its own right.

This policy paper from the Institution of Mechanical Engineers considers the future of collaboration within the engineering profession, specifically international collaboration in a post-pandemic world. It explores the collaborative tradition in engineering; how engineers have, and do, collaborate; what the key challenges to international collaboration are and how to address them; and what the profession can do to ensure future engineers have the knowledge and skills necessary for working collaboratively to help society solve the pressing environmental, health and socio-economic challenges of the 21st Century.

A 21st Century trend towards isolationism

The geopolitical landscape of the world is changing rapidly as was most recently highlighted by the global response to the COVID-19 pandemic, in terms of the national positions that emerged; the alliances that formed to apportion blame; and the partnerships that formed to seek socio-economic-political-health solutions to the emerging crisis[2,3], and the impacts of these changes on the work of the engineering profession are being felt by engineers of all disciplines across many sectors.

Since the close of the second world war, and throughout the second half of the 20th century, a key characteristic of engineering activity was large-scale national and international collaborative efforts, driven by the military-industrial complexes of the cold war's opposing sides or the rush to deliver energy and a plethora of new consumer goods to 'western world' populations growing in affluence. At that time, engineers in roles from research and development through to selling and servicing could, during the course of their careers, expect to be involved in partnerships of a civil, military, public sector or commercial nature, bringing together big and small nations from around the world to drive innovation and deliver results.

However, with the collapse of the Soviet Union in the 1990s and the new millennium came a new world order, the repurposing of former cold war military alliances along with their associated military-industrial complexes, economic uncertainty and an increase in the threat of terrorism worldwide, and a slow but pervasive emergence in recent decades of a deeply nationalist sentiment in many countries[2,4]. The latter leading to trends in isolationism, protectionism, trade wars and an overall reduced appetite for international collaboration: for example, witness the recent developments in the United States[2,5]; the increasing tension in the US-China[6] and Australia-China[7] relationships; and the Russian Federation's increasingly assertive global position[8], as well as the emergence of right-leaning political developments in a myriad of European countries[9].

These geopolitical trends were consolidated further during the early months of the COVID-19 pandemic as in the Spring of 2020 nations around the world closed borders, imposed 'lockdowns', turned inwards and focussed critical infrastructure and resources on meeting domestic needs for food, water, energy, healthcare and household income, often at the expense of overseas relationships, aid and support. For example, nearly 80 countries imposed restrictions on the export of medical supplies during 2020 (disproportionately impacting low-middle income countries [LMICs])[10]. Indeed, apart from a small number of outstanding examples or international collaboration in vaccine and medical equipment development, testing, manufacture and distribution (two of which are highlighted as case studies in the next section), based largely on existing private sector relationships, the collaborative landscape of the pandemic response has been primarily domestic in nature and characterised by the emergence of a form of 'vaccine nationalism' in countries across the globe[11].

> Engineers have, as a profession, traditionally collaborated formally and informally on many levels.

How do engineers collaborate?

The geopolitical reality of today is that a small number of economically powerful and resource rich nations of the world have the technical and human capability to undertake large-scale, complex, public and private sector funded science, engineering and technology-based programmes largely in isolation of other nations. The remaining 190+ countries do not. Yet such programmes are often not only of considerable importance to a nation's socio-economic and health outcomes, in the decades ahead they will become vital to their ability to tackle a myriad of challenging and increasingly chronic problems such as air quality degradation; the demise of ecosystems and natural resource depletion (with implications for food, energy and water supply); adaptation to climate change impacts including extreme weather events, seasonal shifts and sea level rise; and the emergence of future epidemics, pandemics and related health crises.

Solving these problems will demand large-scale systems level responses across multiple sectors, technologies, supply chains and geographies. It will require the engineering profession to integrate underpinning scientific, social and economic knowledge into complex, holistic, systems level approaches involving many technical and non-technical disciplines working together collaboratively to achieve global goals. In short, tackling worldwide challenges will require worldwide collaboration in direct contradiction of the current trends towards nationalism and isolationism. It is therefore vital that the engineering profession comes together around the globe to advocate for collaboration, work towards reversing isolationism, and ensure that engineers at all stages in their career journey have opportunities to gain the knowledge and skills necessary for successful multi-discipline, multi-sector, multi-nation collaborative engagement.

Engineers have, as a profession, traditionally collaborated formally and informally on many levels, not only with colleagues in the organisations that employ them, whether public or private sector, civil or military, but also within and across industrial sectors and national boundaries. They have done this either in their employed capacity or as volunteers participating in professional bodies such as the IMechE, by sitting on domestic and international standards committees, and in the development of engineering design codes and guides to good practice. High profile, complex and challenging international engineering collaborations include the international space station, the ITER fusion energy project and the Large Hadron Collider (LHC). Others with a more parochial national focus include examples such as the USA's Apollo moon missions and the UK's exploitation of North Sea oil and gas resources. In the field of publicly funded research programmes, engineers across academic and industrial sectors also have a long track record of collaboration aimed at achieving national and internationally relevant research outcomes, for example in the European Union (EU) funded Horizon 2020 programme (now superseded by the Horizon Europe programme) and the UK's more bilaterally focused international Newton Fund.

Innovating new ways of collaborating for vaccine manufacture in a global pandemic

During the peak of the pandemic, Fuji Film's site team were involved in a project to increase their facility's throughput by a 3-time batch rate to support the manufacture of the Novavax COVID-19 vaccine candidate[12]. The inception of the project involved the customer and technology partners, suppliers and regulators around the world. Starting any major project requires extensive coordination and planning and in large corporations well tested processes facilitate this critical first step. However, doing this during a pandemic, where all the teams were geographically distributed and individual team members were working from home, required a radically different approach to 'business as usual'. Successfully delivering such a complex and multifaceted project entirely through remote working facilitated by virtual meeting channels and collaboration software would, only 2 years ago, have been regarded as 'the impossible'. Yet, the necessity of the pandemic's challenges made this a reality and an accepted way of working.

To build teams needs human interaction and initially this was not a characteristic of collaboration that was easy for Fuji to translate into a virtual world. However, as the speed of collaboration and familiarity with technology tools increased, the barriers fell away, and progress was rapidly made. Building on experience and skills in the project teams, trust was established as individuals learned to use IT to effectively communicate, and with designs progressing and reviews being successfully held the group bonded around the common goal, to help deliver a vaccine to combat the global spread of COVID-19. Supply chains were engaged early and became a key part of the process, contributing to a "can do" collaborative work ethos.

In parallel with preparation for manufacture, scientists were producing the process to make vaccines at scale and this simultaneous working offered the ability to have assurance of the candidate vaccine throughout the project. An accepted view of risk was taken by all stakeholders, teams were given permission to fail as a trade-off against speeding up the time to manufacture and this created an environment for innovation.

The ability to run multiple scenarios to achieve the process definition while the facility capacities were being increased allowed the team to achieve a 10 month "start to manufacture ready" status of the manufacturing asset.

It is important to note that this approach was achievable because the facility in which the drug substance was to be manufactured was already operational as a GMP (Good Manufacturing Practices) certified asset. The time to increase capacity in such a facility is significantly lower than the time to construct an entirely new plant. By increasing capacity of a manufacturing asset, the support functions are also required to adapt and expand, new equipment requires reliability assessment and establishing asset records, warehouse capacity reviews are needed, and cold storage needs must be considered.

The results of the collaboration included:

- more than 30 new GMP qualified items of equipment specified, procured, installed and commissioned in 10 months;
- new cold storage installed in a qualified state;
- more than 20 skilled people recruited and on-boarded;
- site construction teams mobilised to work in a COVID secure manner;
- QA documentation produced, reviewed and approved for GMP manufacture;
- reduced time to manufacture and tech transfer of customer proteins into GMP manufacture;
- a reduction in carbon emissions due to reduced travel, both domestically and internationally;

and achievement of the project's overall goal of a manufacturing batch rate increase of x3.

The team's legacy is a previously unthinkable way of collaborating globally to achieve high standards of engineering design and build for vaccine manufacture. By recruiting and training skilled people, they have also created a foundation of engineering skills in the life sciences sector in their region. The opportunities are many and they are proud as a team to have been part of the COVID-19 response.

Large-scale complex collaborative programmes, which often involve many geographically dispersed participants, large major companies, world-class universities, and national government departments/agencies, are often driven by national and international strategic agendas, both military and civil. On the other hand, many start-ups and small to medium sized companies (SMEs) are driven to work on projects collaboratively through lack of funds, lack of access to investment finance and limits on physical resources in terms of people, materials or equipment, or to fill identified knowledge gaps that are acting as a brake on development and, importantly, to realise innovation. Collaboration is often a key ingredient to the success of a start-up or SME, but even in large, established, vertically integrated private or state companies, collaboration with partners who are external to the corporation can be essential to driving innovation, through exposure to new ideas, approaches and thinking. Strategic use of collaboration by commercial players to gain knowledge, technology or know-how, or to gain market entry or ownership of emerging market space before it matures, is a common foundation for engineering collaboration.

Collaborations can be voluntary, in that those wishing to collaborate choose their preferred collaborators, or as is often the case with public money, particularly from international bodies, 'forced' by funding criteria which require certain 'quotas' to be achieved in order for projects to be eligible for consideration (such as, for example, an industrial/academic/public partner mix; geographical location mix of the collaborators; or percentage of a work programme that must be allocated to participants, etc.). This 'artificial' or 'forced' form of cooperation can result in sub-optimal collaborations taking place between partners who are largely unknown to each other, have no track record of collaborative working together, and might not necessarily be each other's first choice as partners for a project. It can also lead to widely dispersed teams composed of collaborators with significant differences in culture, history and political systems, working inefficiently and ineffectively together over considerable geographical distances and a range of time zones.

The most efficient, effective and successful engineering collaborations are typically those where the overall goal or mission of the work, such as tackling a major global challenge, or striving to be first to market with a new technology or product, or solving a specific environmental, health or social problem, is what brings the collaborative group together. In such cases, as illustrated by the two examples presented in this section, the goal or mission motivates the group to remove barriers to collaboration and overcome constraints to collaborative working in order to achieve targets and even exceed them. In such groups the partnership composition is unlikely to be pre-ordained by participant 'quotas', but established based on recognised complementary specialisms, knowledge and skills, and pre-existing or desired working relationships. High levels of goal or mission alignment and a sense of a common worthwhile purpose drives high levels of motivation to overcome cultural and historical differences and mis-aligned political systems. Like all forms of collaborations, engineering collaborations are less about technology and more about people, human interaction and behaviour.

Engineers collaborating successfully with a shared goal to deliver UCL-Ventura

The first COVID-19 cases were detected in the UK on 31 January 2020 and by March of that year admissions to intensive care units (ICUs) across the country were increasing rapidly. The UK had one of the lowest numbers of ICU beds per capita in the developed world (6.6 beds per 100,000 inhabitants compared to 34.7 in the USA[13]) prompting urgent multisector efforts to scale up manufacture of ICU technologies. The Institute of Healthcare Engineering at University College London (UCL), which provides a cross-Faculty interface for engineering, medical and clinical scientists across the University and partner hospitals, responded to the need by assembling an expert team, codenamed UCL-Ventura[14], composed of mechanical engineers and intensive care specialists from University College London Hospital (UCLH).

The medics in the UCL-Ventura team were in close contact with colleagues in China and Italy whose experience showed that mechanically ventilating patients soon overwhelmed healthcare systems. By comparison, early experience from both countries indicated that non-invasively ventilating patients via continuous positive airways pressure (CPAP) could alleviate around 50% of patients from progressing to mechanical ventilation, with further clarity provided through subsequent randomised controlled trials[15]. This improved patient outcomes and preserved precious healthcare resources (ICU beds, trained staff): CPAP patients are not sedated, recover faster, require less intense medical support, and the devices are easier to train healthcare workers to use.

However, in early 2020, alongside many other medical technologies the UK was experiencing an acute national shortage of CPAP devices. These were largely sourced from overseas and restrictions on the export of medical products had been imposed by a substantial number of countries worldwide[10]. Consequently, there was an urgent need for a simple CPAP device that could meet regulatory standards, be mass-manufactured at speed, and easy to train healthcare workers to use.

To succeed in designing and mass-manufacturing a CPAP device within weeks, the UCL-Ventura team needed manufacture capability to complement existing engineering and clinical expertise. UCL Mechanical Engineering had a longstanding educational partnership with Mercedes AMG High Performance Powertrains (Mercedes HPP), who design and manufacture Formula 1 racing car engines, and their engineers immediately joined the team.

The UCL-Ventura team reverse-engineered an off-patent CPAP device, the Philips 'WhisperFlow', a purely mechanical device based on the Venturi principle which takes pressurised oxygen from a supply port, entrains air, and provides an air-oxygen mix at a tuneable flow rate and oxygen concentration to the patient (Mark I). Given the unprecedented demand on hospital oxygen supplies, the team subsequently optimised the air-entrainment port design and accompanying breathing circuits (the tubing, valves, filters and mask which connect the CPAP to the patient) to improve patient comfort and reduce oxygen utilisation by up to 70% (Mark II)[16].

The Mark I prototypes were ready for hospital testing within 100 hours of the first team meeting and gained emergency approvals from the Medicines and Healthcare Products and Regulatory Agency (MHRA) within 10 days; the Mark II device followed 3 days later. Ultimately, the UCL-Ventura team achieved six MHRA emergency approvals including two oxygen concentration monitors, one CPAP hood and one pressure monitor (all essential technologies constrained by global supply chains). Each device involved partnership with industry from a range of sectors to enable design and mass-manufacture, including SMEs (for example Oxford Optronix and Thanos Medical) and established larger companies (Avon Security and Mercedes HPP).

The UK Department of Health and Social Care commissioned 10,000 devices which were delivered within a month of the first meeting. To meet demand, Mercedes HPP repurposed their Brixworth factory for manufacturing devices at a maximum rate of 1,200 per day. Partnering with an automotive logistics company G-TEM, Venturas were deployed to around 130 NHS hospitals.

To contribute to the global humanitarian effort, the Ventura team released their full design and manufacturing instructions through a zero-cost license, alongside technical and clinical training materials[17]. The license has been downloaded more than 2000 times across 105 countries. By Spring 2021, around 20 countries had completed the journey through download, manufacture, testing, regulation and hospital deployment, with at least 25,000 devices manufactured spanning Peru[18], Mexico, Paraguay, Ecuador, Pakistan, India, South Africa, Iran, and Ukraine.

This uptake was enabled through close collaboration with international organisations and government teams, which also supported international donations to further countries. For example, UCL-Ventura devices were supplied non-profit to Uganda and Palestine working with the International Medical Education Trust 2000 (IMET2000); Mercedes Benz South Africa donated 1000 devices to South African hospitals; and the UK government donated over 1200 devices to India and Nepal[19].

The rapid, global impact of the UCL-Ventura programme was enabled by long-standing collaborative partnerships which were both multidisciplinary and multisector, alongside clear identification of the global mission and clinical need, regulatory advice and active government cooperation. The partnership also benefitted long-term investment in multidisciplinary science and engineering, and in joint infrastructure for research and translation across Universities and hospitals (eg via the NIHR). Finally, the non-profit approach engendered trust, enabling new partnerships spanning healthcare, industry, academia, government and regulators to be built at speed and coalesced under a common goal. Whilst there remain significant barriers to innovation at pace in a global crisis, the knowledge, learning and insights gained through the Ventura experience should underpin future approaches.

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Information Communications Technology tools both help and hinder engineers working collaboratively.

Addressing the key challenges of international collaboration

Regardless of whether the collaboration is voluntary or artificially forced, and despite the learnings of the pandemic experience, developments in Information Communications Technology (ICT) tools both help and hinder engineers working collaboratively. On the positive side, they can help by enabling the swift and easy transfer of documents and files, as well as through facilitating collaborative working on engineering in real time across multiple dispersed sites and geographies. However, in in other areas, such as written electronic communications, they can be detrimental to progress by creating substantial, and sometimes significantly damaging, misunderstandings that may have the potential to impact negatively on financial and time resource budgets, possibly leading to cost overruns. Such misunderstandings can be particularly prevalent in international collaborations, where language interpretation issues, differences in social cultural norms, and nuanced communications culture often exist.

The use by international collaborators of a common language such as English can only partially solve the problem, in that non-native speakers translate from their mother tongue to English and though people from different nations use the same English vocabulary, the words may carry different meanings from the perspective of the individual speakers. As a simple example, in some cultures it is common to say 'yes' out of a sense of politeness and obligation, regardless of whether, from an Anglo-American or European perspective, the answer is actually 'yes'. Likewise, for others saying 'no' is equated to 'losing one's face' and so the use of the word is avoided, with clear implications for the efficiency of collaborative working.

Although there is no wholly satisfactory substitute for physical face-to-face communications, as we have learnt during the pandemic the use of video conferencing and less formal ICT tools, such as 'live chat' and video phone apps, particularly by a younger generation of engineers for ad-hoc interactions, can contribute significantly to mitigating against communication misunderstandings. However, even here nuanced communication culture can create difficulties, particularly with regards to the use of body language. For instance, consider the Indian cultural norm of a shaking head conveying agreement, whereas in an Anglo-American and European setting the interpretation of such a movement by the listener would be the opposite.

Similarly, social media tools can help with breaking down cultural barriers, but they can also have the opposite effect by leading to increased polarisation through reinforcing existing prejudices and cultural tensions through what is often termed an 'echo-chamber' effect. From an industrial perspective, standardisation of the ICT tools used for collaborative working in engineering might make a useful contribution to addressing these communications related challenges, as there are currently a plethora of options available and different organisations and geographies have preferences for different tools, adding an unnecessary layer of complexity and confusion which heightens the risk of misunderstandings.

Lessons learnt in IT communication through meeting the engineering education challenges of the pandemic

In the Spring of 2020, when all taught course provision abruptly transferred online, Brunel University's staff experienced a rapid learning curve as they adjusted to communicating and collaborating with engineering students exclusively via the internet. In common with many educational establishments around the world, not only did staff and students need to quickly learn how to effectively use a variety of new software-based meeting platforms (and functionality protocols such as 'raising a hand', screen sharing and muting / unmuting etc), the entire approach to teaching delivery had to be adapted. For example, rather than providing straight-through lectures of 2 hours duration, the course content had to be adapted for delivery in "bite-sized" chunks more aligned with online attention spans and student engagement methods had to be devised based on the "chat" and polling tools embedded in platforms.

Another challenging and unanticipated barrier to communicating effectively arose because of the need to adhere to General Data Protection Regulations (GDPR), in that staff could not insist but only encourage students to switch their cameras on during online sessions. This made teaching difficult as the loss of visual feedback meant that lecturers could not readily gauge how content was being received. Anecdotal evidence suggests that confident students were actively engaged regardless, but that shyer students were able to easily hide, or indeed opt out of online sessions entirely, choosing instead to study through recorded lecture provision. Tutorial sessions and collaborative learning also posed a particular challenge. Whilst in the humanities such sessions are mostly discussion based, those in engineering mainly involve practice exercises in physics-based analysis and mathematical design calculations. Online white-board facilities were found to work just as well as those in the tutorial rooms, but the inability of staff and cohort peers to "look over a student's shoulder" to see exactly where they might be struggling, a core element of tutorial learning in engineering, substantially hindered collaboration in learning.

Counter intuitively, laboratory sessions were transferred online with reasonable success by being filmed and combined with group discussion sessions. The learning experience was impaired only to a very small degree, but the "hands-on" experience so essential to the development of engineering skills did suffer, particularly regarding dissertation projects due to labs and workshops being closed. However, overall, staff feedback was that many students rose to the challenge, collaborating effectively with their supervisors and wider project stakeholders in a highly professional manner. These students will be an asset to their future employers, bringing with them honed communication and collaboration skills. It is the shyer students that may have suffered detrimental impacts and require further skills development assistance as they enter the workforce.

One significant positive outcome of the pandemic experience was an increase in the opportunities available to include industrial expertise in teaching provision to aid the professional development of students. With most engineers working from home during the various national "lockdowns" and having been through similar steep learning curves regarding the use of online platforms for communicating and collaborating, as well as the issues of travel time being effectively removed, the willingness of experts to participate increased and students were able to gain insight into a diverse range of topics and case studies, thereby preparing them better for their transition into the profession.

Beyond communication, differences in societal and workplace culture and a lack of awareness of these differences is a key challenge in managing effective international engineering collaborations. For example, there are corporate level issues that can arise from different national approaches to the sharing of intellectual property (IP), because of different cultural perspectives on property rights and confidentiality, and at the operational level issues can emerge that are related to day-to-day working relationships across the collaborative team. Having a team leader in place (either at the project or corporate leadership level, depending on the nature of the collaboration) with the skill set necessary to recognise this issue and manage it efficiently is a core ingredient to success. However, in countries where engineering leaders are chosen primarily on their technical prowess and little emphasis placed on their people management and social skills, such as in Germany and Japan, this is not so straightforward. Such skills include having an ability to perceive sensitivities and build teams accordingly, as well as create working environments that help engender mutual awareness of, and respect for, cultural differences. This is not just about being cognisant of different cultures and understanding their behavioural norms, but also having insight and appreciation for how other cultures collaborate within their own cultural environment.

For instance, some cultures have a strong element of consensus building and decision making that underpins collaborative activity, whereas others are more strictly hierarchical with top-down leadership and decision making confined to a small group of senior managers. In Norway's societal culture for example, in deference to the community it is not normal to promote oneself, whereas in Anglo-American culture 'self-selling' is positively encouraged. This difference in national character could lead to employee development issues in collaborative project work involving a UK or American leader with Norwegian team members, where the latter are overlooked for job promotions, career development and continuous professional development (CPD) opportunities relative to their UK or US team colleagues, because they conceal their personal talents, abilities and achievements rather than promote them.

Leaders of teams or organisations collaborating internationally should also be cognisant that issues of cultural differences and behavioural norms are not only geographical, but also generational. Engineering work has traditionally been, and in Anglo-American, European and many Asian cultures still is, very much a hierarchically organised activity and young engineers, who are often more adept at international relationships and communications than more senior engineers, are often constrained by working practices and attitudes of a system shaped by an older generation. Japan provides a particularly poignant example in this regard. Effective leadership must recognise such limitations and take action to enable and empower those constrained to contribute more effectively to the collaborative environment.

There are a range of approaches that leaders of international collaborations can take to help engender cultural awareness, understanding of different behavioural norms, and respect for differences. These include for example facilitation of international exchanges of personnel and the convening of physical face-to-face workshops. The latter can be particularly effective if residential in nature and held at the start of a collaborative project (ie a project 'kick-off' workshop), at critical points in the lifetime of a project (ie at delivery milestones), and at times when significant issues or problems arise (ie brainstorming 'solutions focused' workshop). Such workshops provide focussed opportunities for team members to become aware of differences, understand them, and develop relationships in both managed and informal unmanaged environments, through working and socialising together.

Beyond the provision of appropriate ICT tools, personnel exchanges, and focused collaborative workshops, at all levels and at multiple points in an engineer's career journey education, training and skills development is fundamental to helping the profession address the human challenges of international collaboration. The key question is, therefore, are engineers being adequately prepared for participation in such collaborative working, particularly within the context of the multitude of pressing international challenges global society faces in the 2020s and beyond? And if not, how can the profession ensure that they are?

> The knowledge and skills that can help engineers perform effectively in international collaborative working are first and foremost people centred.

Preparing engineers for international collaborations

The knowledge and skills that can help engineers perform effectively in international collaborative working are first and foremost people centred. For example, language skills are useful, not only for communication, but also because individuals gain cultural awareness in the learning process, through insights embedded in the language itself as well as in the situational context of the practice exercises. In this way, language use can often help facilitate an understanding of the behavioural norms of the people in societies where it predominates. More broadly, there is a need to help engineers develop skills for engaging with and working in international collaborative teams, particularly those useful for establishing and managing relationships across cultures and disciplines (for example, when working with legal teams, social scientists, anthropologists, historians, botanists, political scientists, marketing communications experts, etc.) and understanding the context and societal framework within which their work sits. The latter is particularly important as the profession's practice is littered with examples of technically excellent engineering projects that failed to move beyond the drawing board, or faced significant societal challenges, because of a lack of attention to culture, the societal context within which the proposed solution was to be placed, and public engagement. Projects such as Stuttgart 21, Berlin Airport and Tokyo International Airport at Narita provide good case studies in this regard.

At the beginning of the engineering career journey, all engineering students should be given a grounding in the issues that can arise because of cultural differences and misunderstandings, as well as the methods, tools, approaches and strategies to avoid and mitigate against these – such as physical face-to-face project workshops and the sensitive use of ICT technology. CPD training might similarly offer such content for practicing engineers already in the workforce and there is clearly a role in this for Professional Bodies, such as IMechE, Verein Deutscher Ingenieure (VDI), Institution of Professional Engineers Japan (IPEJ) and Engineers India.

For these more experienced learners and those studying at Masters level, the development of team leadership and corporate level leadership skills might take a much deeper dive into the knowledge, skills and techniques required to engender and deliver successful collaborations internationally.

In the case of college and university programmes, academics involved in engineering education, particularly those focused on research activities, are often engaged in collaborative working which can include participation in international collaborative projects of varying complexity, size and reach. These academics, along with Industrial Guest Lecturers and Visiting Professors, should be empowered to share their experiences of collaboration, both successful and not so successful, with students and provide case studies of lessons learnt, along with advice and guidance on collaborative activity. However, academic teaching and industrial guest lecturing can be constrained by the engineering programme curriculum, which in many cases is extremely full.

Collaboration in the curriculum

In the UK the Engineering Council[20] is charged with setting the standard for the practice of engineering and in this regard, through being a signatory of the Sydney and Washington Accords[21,22], its requirements are typical of those for the profession globally. Compliance with the Accords demonstrates that the UK's accreditation process is compatible with the standards of the International Engineering Alliance (IEA)[23] and that the mandatory learning outcomes meet or exceed the required thresholds. Additionally, the Council has also demonstrated alignment with the EUR-ACE® framework[24] of the European Network for Accreditation of Engineering Education. As such, the UK provides a good case study candidate for considering the teaching of collaboration knowledge and collaborative working skills in accredited curricula.

The UK's 'Standard for Professional Engineering Competence, UK-SPEC'[25], as published by the Engineering Council, forms the basis of the learning outcomes presented in the Council's 'Accreditation of Higher Education Programmes' (AHEP) handbook[26] and these must be demonstrated for the award of 'Accredited Programme' status. The latter includes courses that lead to Foundation degrees, Bachelors, Masters and Doctoral degrees, and equivalent qualifications, and provide some, or all, of the educational element for eventual registration as either an Incorporated Engineer (IEng) or Chartered Engineer (CEng). The requirement of the AHEP handbook are applied in practice by the UK's Professional Bodies licenced by the Engineering Council: The Professional Engineering Institutions (PEIs).

As an example, in the case of mechanical engineering, the IMechE is responsible for accrediting degree programmes at around 70–75 Universities (approximately 1,000 unique degrees) and publishes an 'Academic Accreditation Guidelines' document[27] for the use of staff and volunteer members involved in the accreditation process, as well as the Universities themselves. The guidance is derived from the generic output standards that apply to all accredited engineering degree programmes, as set out in the AHEP, and the decision about whether or not to accredit a programme is made on the basis of delivery against the specific requirements of the learning outcomes being evidenced.

A review of the AHEP defined learning outcomes, and IMechE's interpretation of these in the Institution's Academic Accreditation Guidelines, reveals no specific articulation of a requirement to develop understanding, knowledge, know-how, skills, or awareness in relation to collaboration or collaborative working, neither within the discipline itself or in the context of multi-disciplinary, cross-discipline or international relationships. The curriculum of engineering programmes at all levels of qualification is already very full, so adding an additional specific learning outcome requiring the teaching of collaboration specific subject matter would prove very challenging.

The timescale involved in making such an intervention in curricula is also problematic in that the Engineering Council's AHEP document is generally updated on a five-year cycle with the next opportunity to review and propose changes being in 2024–5 at the earliest. In the rapidly evolving globalised world of today, and in the context of the global challenges that need to be urgently tackled, potentially four or more years is a long period to have to wait for the opportunity to change learning outcomes and curricula. Given that a further period of several years would elapse before the changes were fully adopted and integrated into academic programmes, it could conceivably be beyond 2030 by the time the first graduates influenced by the revised learning outcomes entered the engineering workplace. In the case of many of society's current international challenges and their projected impacts, not least tackling climate change, biodiversity loss and mass extinctions, 2030 may conceivably be far too late.

Rather than seeking to change curricula it may, therefore, be more effective to focus change initiatives on integrating the development of knowledge and skills for international collaborative working into existing modules. Alternative ways of teaching and learning could play a role in this regard, facilitating collaborative and interdisciplinary work which breaks down existing 'siloed thinking' and the strict division of subjects. Intervention points in the curriculum might include group working exercises, such as those often associated with modules in design or project management, and in dissertation assignments or project work.

Further review of the AHEP learning outcomes reveals those that might be interpreted as having scope for interventions to address subject matter pertinent to international collaborative working and these are presented in **Table 1**. The collaborative working aspects of many of these learning outcomes might logically and appropriately be achieved through project related activity, particularly in group project assignments and multi-disciplinary cross-department group projects. Indeed, there is a precedence in the AHEP handbook for achieving some learning outcomes though group work and most accredited degree courses now contain some group projects where students work cooperatively to achieve a joint outcome.

Table 1: AHEP Learning Outcomes with scope for integrating teaching of collaboration knowledge and skills.

AREA OF LEARNING	LEARNING OUTCOMES
Design and innovation	**Incorporated Engineer** **F5** Design solutions for broadly defined problems that meet a combination of user, business and customer needs as appropriate. This will involve consideration of applicable health and safety, diversity, inclusion, cultural, societal and environmental matters, codes of practice and industry standards. **B5** Design solutions for broadly defined problems that meet a combination of societal, user, business and customer needs as appropriate. This will involve consideration of applicable health and safety, diversity, inclusion, cultural, societal, environmental and commercial matters, codes of practice and industry standards. **B6** Apply and integrated or systems approach to the solution of broadly defined problems. **Chartered Engineer** **C5** Design solutions for complex problems that meet a combination of societal, user, business and customer needs as appropriate. This will involve consideration of applicable health and safety, diversity, inclusion, cultural, societal, environmental and commercial matters, codes of practice and industry standards. **M5** Design solutions for complex problems that evidence some originality and meet a combination of societal, user, business and customer needs as appropriate. This will involve consideration of applicable health and safety, diversity, inclusion, cultural, societal, environmental and commercial matters, codes of practice and industry standards. **C6** Apply an integrated or systems approach to the solution of complex problems. **M6** Apply an integrated or systems approach to the solution of complex problems.

Note

F = Foundation degrees, Higher National Diplomas and equivalent qualifications.

B = Bachelors Top-up degrees, Bachelors degrees, Bachelors (Honours) degrees and equivalent qualifications accredited for IEng.

C = Bachelors (Honours) degrees and equivalent qualifications accredited for CEng.

M = Masters degrees, Doctoral programmes, Integrated Masters degrees and equivalent qualifications accredited for CEng.

AREA OF LEARNING	LEARNING OUTCOMES
The engineer and society	**Incorporated Engineer** **F7** Evaluate the environmental and societal impact of solutions to broadly defined problems. **B7** Evaluate the environmental and societal impact of solutions to broadly defined problems. **F9** Identify, evaluate and mitigate risks (the effects of uncertainty) associated with a particular project or activity. **B9** Use a risk management process to identify, evaluate and mitigate risks (the effects of uncertainty) associated with a particular project or activity. **F10** Adopt a holistic and proportionate approach to the mitigation of security risks **B10** Adopt a holistic and proportionate approach to the mitigation of security risks. **Chartered Engineer** **C7** Evaluate the environmental and societal impact of solutions to complex problems and minimise adverse impacts. **M7** Evaluate the environmental and societal impact of solutions to complex problems (to include the entire life-cycle of a product or process) and minimise adverse impacts. **C9** Use a risk management process to identify, evaluate and mitigate risks (the effects of uncertainty) associated with a particular project or activity. **M9** Use a risk management process to identify, evaluate and mitigate risks (the effects of uncertainty) associated with a particular project or activity. **C10** Adopt a holistic and proportionate approach to the mitigation of security risks. **M10** Adopt a holistic and proportionate approach to the mitigation of security risks.

Note

F = Foundation degrees, Higher National Diplomas and equivalent qualifications;

B = Bachelors Top-up degrees, Bachelors degrees, Bachelors (Honours) degrees and equivalent qualifications accredited for IEng;

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M = Masters degrees, Doctoral programmes, Integrated Masters degrees and equivalent qualifications accredited for CEng.

AREA OF LEARNING	LEARNING OUTCOMES
Engineering practice	**Incorporated Engineer** **F15** Apply knowledge of engineering management principles, commercial context and project management. **B15** Apply knowledge of engineering management principles, commercial context, project management and relevant legal matters. **F16** Function effectively as an individual, and as a member or leader of a team. **B16** Function effectively as an individual, and as a member or leader of a team. **F17** Communicate effectively with technical and non-technical audiences. **B17** Communicate effectively with technical and non-technical audiences. **Chartered Engineer** **C15** Apply knowledge of engineering management principles, commercial context, project and change management and relevant legal matters including intellectual property rights. **M15** Apply knowledge of engineering management principles, commercial context, project and change management and relevant legal matters including intellectual property rights. **C16** Function effectively as an individual, and as a member or leader of a team. **M16** Function effectively as an individual, and as a member or leader of a team. Evaluate effectiveness of own and team performance. **C17** Communicate effectively on complex engineering matters with technical and non-technical audiences. **M17** Communicate effectively on complex engineering matters with technical and non-technical audiences, evaluating the effectiveness of the methods used.

Note

F = Foundation degrees, Higher National Diplomas and equivalent qualifications;

B = Bachelors Top-up degrees, Bachelors degrees, Bachelors (Honours) degrees and equivalent qualifications accredited for IEng;

C = Bachelors (Honours) degrees and equivalent qualifications accredited for CEng;

M = Masters degrees, Doctoral programmes, Integrated Masters degrees and equivalent qualifications accredited for CEng.

Gaining collaborative experience in the "real world" alongside undergraduate study

Potential routes to gaining collaborative skills outside of the academic institution include 'Sandwich Courses' at both degree and sub-degree level (these are characterised by the inclusion of periods of 'industrial experience', which may last several months or a year, and have long been recognised in the UK as contributing to the maturity of students and their ability to work with others), student sponsorship by industrial companies with summer placement, and international internship opportunities. In many countries, for instance the UK and India, the latter are reasonably common as a feature of degree programmes, but elsewhere there is substantial scope for increased participation in such activity. For example, there has traditionally been little cultural appetite for international engineering placements or internships in Japan and in the case of Germany only 9% of the student population that went overseas on placements in 2016 were engineers[28]. In this regard, it should be noted that in Germany such 'practical experience' placements ('Praxissemesters') currently have a strong focus on developing expert practical knowledge rather than gaining international experience or skills in collaborative working.

The International Association for the Exchange of Students for Technical Experience (IAESTE)[29] is an example of an organisation that connects employers and higher education institutions globally through facilitating career-focused professional internships abroad. In addition to the international technical experience, students enrich their outlook via complementary social and intercultural activity programmes and international networking opportunities. The combination prepares participants for international collaboration in industry in their future careers by overcoming any anticipated or perceived cultural barriers in the framework of a pleasant exchange experience.

Additionally, there are opportunities to develop collaborative skills in initiatives offered outside the curriculum by the PEIs and other similar organisations. In the case of IMechE's own offerings, the Engineering Design Challenge[30] aims to complement the academic curriculum and present participants with the opportunity to demonstrate their design skills and innovative ideas in an environment that is outside of that in which they study. In this regard, the initiative gives first- and second-year undergraduates a taste of the 'real world' of engineering and involves the design, creation, presentation and demonstration of a device to a strict technical specification, within a set time frame. Participation is as much about developing collaborative and communication skills as enriching technical ability and the competition has taken place in countries as diverse as the UK, China, Pakistan and UAE.

Although the teaching of knowledge for collaboration and the development of skills for collaborative working are not specifically required by the AHEP, innovative provision can be accommodated within the framework of learning outcomes and there are indeed good examples of their innovative integration in engineering programmes. The Open University's 'Team Engineering' module (T885)[31], a compulsory 30 credit component in their Postgraduate Diploma in Engineering, Master of Engineering (MEng) and MSc in Engineering courses being one such example. The module description includes key references to "aims to develop the essential professional engineering skill of working with others"; "requiring cooperative development of the knowledge and skills needed"; "learn about functioning effectively as a team"; and "collaborative team working tasks which are an essential feature of the module". The module includes distance learning, which effectively mimics industrial collaboration across many sites, and two residential school sessions that each run over three days, one at the start of the project and one prior to project report production, thereby echoing the points made above regarding the need for physical face-to-face workshops where possible as part of the collaborative process.

In another approach, University of Wales Trinity St David mimics industrial collaboration by exposing engineering students through group project work to the challenges of working with partner collaborators who are from non-engineering disciplines. For example, this has included a cohort from engineering collaborating with students from an arts-based product design programme to design an electric motorcycle, and on another occasion, collaborating with a cohort studying logistics to consider manufacturing supply chains and product distribution.

Similarly, whilst no longer offered, Brunel University's former 'Special Engineering Programme' was set up to develop engineering managers of the future. In addition to combining both electrical and mechanical engineering disciplines with management, it included industrial placements as well as foreign language studies. Students studied a number of technical modules in the selected language, both at Brunel University itself and during a semester at an affiliated European University. With their polished international skills these graduates were highly desired by industry.

Further afield, in the teaching of 'Entrepreneurship', IIT Bombay (Mumbai, India) deliberately brings student cohorts from different disciplines together, including medicine, biotech, electrical and mechanical engineering, to simulate a company start-up environment with collaborative working for the development of medical devices. Likewise, in Germany, the development of cross-subject engineering programmes, such as "industrial engineering", also provide an example of how to design courses that include relevant skills, knowledge and competences from different fields of study and thus create opportunities in the profession for those who are not only interested in the technical aspects. The German labour market has reacted positively to this development, as the nation's industrial sectors are very much in need of such generalists.

Professional Bodies for engineering across the globe need to find more examples of successful initiatives in the teaching of knowledge for collaboration and collaborative skills, particularly within an international context, to raise awareness of what can be done and advocate for similar innovation within the constraints of the curriculum. However, despite such innovations in the application of the AHEP learning outcomes, it needs to be recognised that not all those with the skills to become technically competent engineers will have the aptitude for acquiring the people skills necessary for effective collaboration. In this regard, the focus shouldn't be on ensuring that all engineers have the attributes, orientation and skill sets for collaboration but on ensuring that within the engineering profession there are practitioners with the right skills and behaviours in the right place at the right time. For example, an individual who is a deep subject matter expert may not necessarily have high levels of societal awareness and the interpersonal skills required for collaboration, but that shouldn't mean they get 'excluded' from collaboration.

The emphasis should be on creating an international professional environment that values equally both the deep subject matter expert and the more generalist 'socially adept' collaborative engineer, along with engineering managers and team and corporate leaders with the ability to recognise these different attributes and deploy them efficiently, effectively and optimally. By becoming a broader profession and accepting people who are less interested (though of course still capable at a fundamental level) in the technical, we can build more diverse teams which facilitate cooperation, ultimately reducing the risks of financial and time resource overruns in international collaboration.

“”
The importance of international collaboration has never been so apparent.

The need for international collaboration strategies

In a world that is now entering a prolonged phase of economic stimulation for a post-pandemic recovery while simultaneously needing to tackle both the inequity in the global distribution of COVID-19 vaccines[3] and a myriad of other pressing global challenges, such as extensive biodiversity loss and ecosystem collapse; intensifying and more frequent impacts of climate change; and widespread air, water and land degradation, the importance of international collaboration has never been so apparent. Given the reality that many of the technologies, processes, interventions, and structural changes required to deliver a successful outcome to a broad range of these issues will demand engineering based industrial and business collaborations, either private sector, public sector, or in public-private partnerships, the need for cross-sector, cross-discipline and cross-border engineering collaboration has arguably never been so acute.

Within the context of the recent global trend towards nationalism and isolationism, it is critically important that economically powerful nations with strong traditions of engineering collaboration, such as the UK and those in the EU, show clear leadership in international collaborative working across all business and industrial sectors of the economy. This is particularly the case in technical areas that can help drive clean growth; deploy clean technologies; implement sustainable and net-zero carbon approaches; deliver innovation in adaptation to climate change; and build international, national, local and individual resilience against external shocks. The COVID-19 pandemic, and its widespread impact on individuals, communities, industries, businesses, public services and the economies of nearly every country in the world, serves as a poignant reminder of the need for the latter. Collaboration in engineering and collaborative working in international consortium amongst nations, both big and small, will be essential to ensuring the delivery of the innovative, sustainable, affordable, maintainable, safe and localisable engineered solutions fundamental to meeting society's pressing 21st Century challenges. Government led strategies embedded in national and international policy, and delivered through a myriad of cross-department, cross-sector, cross-discipline policy interventions, will be needed to encourage these collaborations to emerge and to nurture, support and sustain them.

The creation and implementation of international collaboration strategies at national policy level, which address the socio-economic and technical development requirements of a given country in the context of major global challenges, need to be instigated from a holistic, whole systems level perspective. Critically, they must also integrate sustainability at their core. With a strong international collaborative tradition and a focus on clean, sustainable growth, the UK and the nations of Europe are well placed in this regard to show leadership in advocating globally for a reversing of the trend towards isolationism, as well as to begin the process of reaching out to nations large and small for the creation of engineering based industrial, business and public sector collaborations. Collaborations that not only fill national gaps in knowledge and skills, and address the national strategic needs of consortium partners, but do so within a global challenges framework.

To support such strategies the UK and nations of Europe need to deeply embed teaching of the knowledge and skills for collaboration and collaborative working in their engineering education and training systems. As evidenced in the sections above, this can be achieved through innovative approaches to curriculum delivery that build on existing mandated learning outcomes. The Professional Bodies for engineering have a major role to play in this regard, by means of the process of programme assessment and accreditation, as well as more broadly via their influential position as significant drivers and providers of CPD. In short, the Professional Bodies need to show leadership in the preparation of engineers at all stages in their professional journey to meet the challenges of effective and efficient international collaboration.

The Professional Bodies are well placed to take a leadership role in catalysing innovation in the delivery of the knowledge and skills that will underpin successful multi-discipline, multi-sector, multi-nation collaborative working.

Recommendations

The Institution of Mechanical Engineers recommends that:

1. **Governments develop and implement international collaboration strategies that drive industrial, business and public sector collaboration to meet the 21st Century's major global challenges.** Tackling the world's most pressing 21st Century challenges will involve complex, holistic, systems level approaches delivered through programmes integrating many technical and non-technical disciplines working together collaboratively to achieve sustainable outcomes. For most counties in the world the economic and technical resources required to design and implement such programmes are not nationally available, and even if they were these challenges need worldwide knowledge sharing and action to solve. Strategic international collaboration across the full spectrum of science, research, innovation, development and practical on the ground implementation by industry, business and the public sector, offers opportunities to address national knowledge and skills gaps, meet national socio-economic goals and deliver sustainable international solutions.

2. **The Professional Bodies for engineering need to lead the preparation of engineers at all stages in their professional journey to meet the challenges of effective and efficient international collaboration.** To facilitate the successful design and implementation of sustainable global solutions to the world's major challenges, it is vital that the engineering profession as a whole comes together worldwide and advocates for collaboration, works towards reversing isolationism, and ensures that engineers at all stages in their career journey have opportunities to gain the knowledge and skills necessary for international collaboration. Through their processes of curriculum assessment and accreditation, their position as an industry-academia bridge, and their significant provision of CPD, the Professional Bodies are well placed to take a leadership role in catalysing innovation in the delivery of the knowledge and skills that will underpin successful multi-discipline, multi-sector, multi-nation collaborative working.

3. **Industry, business, and the public sector must recognise the importance of international collaboration in tackling major global issues and empower managers to support their engineers in meeting the challenges of collaborative working.** Having an empowered team leader in place with the skill set necessary to both recognise and efficiently and effectively manage the challenges of international collaboration is a core ingredient to successful multinational projects. Such skills include having an ability to perceive cultural sensitivities and build and manage teams accordingly, as well as create working environments that help engender mutual awareness of, and respect for, cultural differences and alternative behavioural norms. It is essential to successfully tackling the major global issues of the 21st Century that industry, business and the public sector alike recognise their role in the implementation of sustainable international solutions and put increased emphasis on identifying and supporting employees with the potential to develop these leadership and management skills, as well as empower their effective use.

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