Global Engineering Innovations in response to the Coronavirus Pandemic

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ABSTRACT

Engineering innovations have developed quickly and been more important than ever before with the urgent demand for technical solutions to respond to the global pandemic in 2020 and 2021. This paper presents the extraordinary breadth of new technologies that were developed and implemented across the world, by leading engineers and engineering institutions in every continent, including India, and in the shortest possible time. These included the development of new vaccine technologies including breakthrough m-RNA technology, agile and advanced manufacturing processes such as 3D printing, the use of Artificial Intelligence and the development of new diagnostic tools to detect the coronavirus, the development of vaccine manufacturing and cold chain logistics for vaccine delivery and software technologies for geo-spatial mapping, communication and analysis of the virus spread and progress of vaccinations. The importance of these advances and their impact on populations around the word is enormously significant especially for the health and well-being of billions. The World Federation of Engineering Organisations is committed to building capacity for all engineers, to understand these technological advancements and their implementation,in all parts of the world, essential for sustainable development and to ensure that no one is left behind.

Keywords: COVID-19; Innovation; Pandemic; AI; 3D Printing; World Federation of Engineering Organisations

INTRODUCTION

The spread of the coronavirus and the global pandemic of 2020 that followed, galvanised scientists and engineers into developing and delivering innovative solutions to deal with the virus and its impacts in a wide range of ways. Engineers have always been recognised as being ingenious and the word ‘engineer’ itself comes from the Latin Ingenium which is also the root of ingenuity and which means innate quality and especially mental power. This mental acuity has been on display like never before with remarkable developments that are benefiting millions today and will continue to deliver benefits for decades to come. Leading engineers and engineering institutions in every continent, including the Indian Institute of Technology (IIT) Bombay and Imperial College, University of London, both institutions where I studied chemical engineering, have been at the forefront of breakthrough research, developing innovations to detect, control, track and prevent the spread of the corona virus in the shortest possible time. Engineers have been recognised as the hidden heroes of the pandemic [1]. Many leading institutions, such as Imperial College London, have developed an integrated approach, across various disciplines, to fast track innovative ideas and bring them to fruition[2]. This paper explores some of the technologies that have underpinned the response to the pandemic and enabled the global response.

WORLD FEDERATION OF ENGINEERING ORGANISATIONS KNOWLEDGE SHARING AND CAPACITY BUILDING

As the peak body for professional engineering institutions internationally, the World Federation of Engineering Organisations (WFEO) has some 100 national, international and regional/ continental members representing more than 30 million engineers. Our members reported the work of engineers round the world in response to the pandemic. For example, the Maltese Chamber of Engineers, our National Member of Malta, reported the work of their members in developing respirators, face masks and other solutions, winning awards for these innovations [3]. The Institution of Civil Engineers (ICE), our UK National Member, in partnership with the Infrastructure Client Group, released a White Paper that examines the impact of the pandemic on the future shape of infrastructure systems in the UK [4]. Our National Member from Portugal, The Ordem dos Engenheiros de Portugal (OEP) developed a series of initiatives aimed at preventing the COVID-19 pandemic and mitigating its consequences [5].Our National Member for France, produced information for 3D printing of face masks and our Associate Member, TH Georg Agricola University produced face protection, door openers and much more for the Metropole Ruhr, using 3D printing [6]. The National Member for India, The Institution of Engineers (India), is producing a special publication on the work of engineers in addressing COVID-19, where this article is being published.

WFEO has developed an information portal to disseminate knowledge on engineering responses to COVID-19 to its members in 100 nations representing 30 million+ engineers. The goal is to share knowledge between developed and developing countries, train users and develop institutional capacity, all essential for sustainable development through engineering, a key strategic objective of the Federation [7]. WFEO has also developed a knowledge hub with links to important engineering information from public health departments and engineering organisations around the world, to facilitate the sharing of engineering information and innovations internationally[8]. The portal showcases the importance of engineering as a key lever for sustainable development, which has also been recognised by the United Nations [9].

VACCINE DEVELOPMENTS AND BREAKTHROUGHS

The global pandemic itself spread rapidly as a result of international travel made possible by modern aircraft technology developed by engineers. The coronavirus spread from Wuhan, China, to more than 140 other countries in just three months as travellers crossed the globe in a few hours. By comparison, the bubonic plague spread the Black Death from China to Italy in the course of some sixteen years, between 1331 and 1347.However, engineers and scientists have also been the source of solutions. For example, scientists developed a treatment for malaria by extracting quinine, from the bark of the Andean cinchona tree. In the 1980s, a number of antiviral medicines were developed and turned the HIV infection that had affected millions, from a nearly certain death to a chronic and controlled infection. Engineers have been essential in the manufacture of these medicines and their distribution. This has resulted in the eradication or control of many diseases, including in India such as tuberculosis, tetanus, typhoid, malaria and poliomyelitis [10].

The development of vaccines to respond to the coronavirus has been no less remarkable. It usually takes about 10 years to develop and approve a new vaccine. The mumps vaccine took four years [11]. Yet not one but several coronavirus vaccines have been developed in less than one year.

Advances in genomic sequencing enabled researchers to discover the viral sequence of coronavirus in January 2020, just 10 days after the first reported cases in Wuhan, China. Worldwide co-operation and funding by governments contributed to the rapid development of vaccines. In the U.S., Operation Warp Speed (OWS) partnered with multiple institutions, including the National Institutes of Health (NIH) and the Centres for Disease Control and Prevention (CDC), to develop, manufacture, and distribute the vaccines. OWS invested in multiple companies and vaccine platforms at once, increasing the odds of success. The European Commission also funded several vaccine candidates and worked with others in pledging $8 billion for COVID-19 research. The UK government Vaccine Taskforce contributed to vaccine research for the Oxford/AstraZeneca vaccine [12]. The World Health Organisations reports 180 vaccines in development as on 13 July 2021 around the world [13].

India also is in the race to manufacture and distribute the coronavirus vaccine.COVAXIN®, is India's indigenous COVID-19 vaccine,developed by Bharat Biotech in collaboration with the Indian Council of Medical Research (ICMR) - National Institute of Virology (NIV) [14]. The Novavax vaccine is being produced by the Serum Institute of India (SII).The government has also ordered 300 million doses of another vaccine from Indian firm, Biological E. At June 2021, India had given more than 260 million doses of three approved vaccines - Covishield, Covaxin and Sputnik V and approved Indian pharmaceutical company Cipla, to import the Moderna vaccine [15].

The extraordinary drive to develop COVID-19 vaccines was like a moonshot —and producing a vaccine in just over six months after the first vaccines were authorized for use, delivering more than 3 billion doses around the globe, is a remarkable feat of engineering [16]. Engineers had a key role, developing Artificial Intelligence tools to identify key vaccine candidates in a very short time [17]. The methods are also important to develop vaccines to mutations of the virus, ensuring the best possible vaccines are quickly identified.

Engineers have also played a key role in developing m-RNA technology to fast track the development of a new category of vaccines. Moderna, co-founded by two chemical engineers, Noubar Afeyan and Robert Langer, developed m-RNA vaccines that can be manufactured and distributed more efficiently. While conventional vaccines require vast resources to make large amounts of proteins, Moderna's technology can produce mRNA much more quickly in smaller manufacturing plants, and the human body becomes the protein factory. Moderna m-RNA vaccines were ready for human trials in just 63 days, an extraordinary achievement **(Figure 1)** [18].

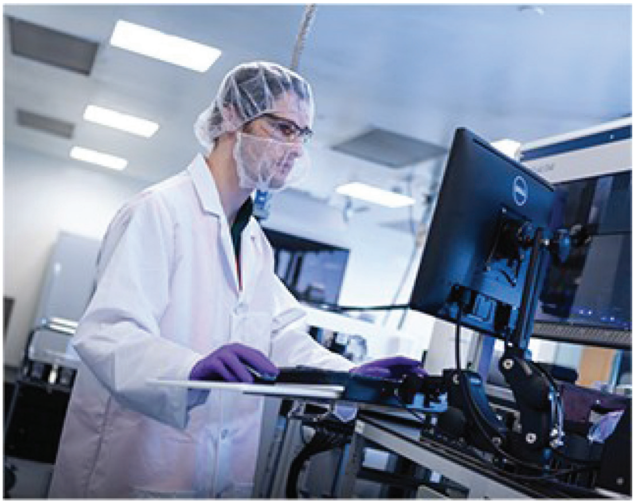


Fig 1: Moderna, a biotechnology company, has developed a vaccine based on m-RNA technology [18]

Importantly, the Moderna vaccines can be manufactured in miniature factories creating capacity in shorter time frames and lower cost. A conventional factory would cost hundreds of millions of dollars and 12-18 months to build. However, the innovative "factory in a box" developed by engineers at Kings College, University of London, can produce m-RNA vaccines at scale at lower cost and in a shorter time [19]. This will dramatically increase current global manufacturing capacity of 5 billion vaccines per annum and will also provide agility to manufacture new vaccines to respond to mutations of the coronavirus **(Figure 2)**.

Fig 2: Factory in a Box to manufacture m-RNA vaccines, Kings College, University of London [19]

RAPID DIAGNOSTICS

Engineers have a key role in the development of rapid diagnostics using new approaches that are cheaper and faster than conventional ones. For example, engineers from Columbia Engineering have established Rover Diagnostics to commercialise their invention of a rapid diagnostic tool [20]. The affordable, portable, and ultrafast point-of-care Rover platform provides reverse transcription polymerase chain reaction (RT-PCR) results in eight minutes, faster than any other test of its kind, with targeted accuracy to match laboratory-based tests. The system uses a new approach to thermal cycling, bypassing the standard approach of Peltier device—a semiconductor that heats and cools the sample from outside the vial with radiant heat. Instead, Rover's system uses a photo thermal process that relies on nanoparticles to generate heat from inside. It can be used to test a wide range of infectious diseases.

Professor Chris Toumazou, Regius Professor of Engineering at Imperial College London, is an electronic engineer, who has developed Covid Nudge,an innovative, lab-free, cartridge-based COVID-19 PCR test that combines advances in microfluidics, biochemistry, and electronic engineering to deliver test results in just over an hour, dramatically accelerating testing workflows. The same cartridge can simultaneously test for other viruses such as various influenza strains [21].

DETECTING AND MITIGATING TRANSMISSION OF THE VIRUS

The droplet transmission of the corona virus was identified in March 2020 and medical teams were alerted worldwide [22]. An engineering analysis of the fluid dynamics in air-conditioned room resulted in guidelines to reduce transmission, including by aerosol transmission, which included, the need for good ventilation and/or short exposure times. Recommendations were made for air recirculation in HVAC systems and for high quality filters to be installed to avoid transmission through the air. Additional personal protective equipment (PPE) was recommended for tasks which required close proximity [23]. The application of fluid dynamics analysis tools has thus been important to fight the COVID-19 pandemic and to enable health authorities to prescribe measures to reduce virus spread. With the evidence from engineers that corona virus could be spread by tiny particles suspended in the air, the World Health Organisation began to advise widespread use of face coverings in July 2020 [24].

ADVANCED MANUFACTURING TECHNOLOGIES FOR DETECTION, PREVENTION, TREATMENT AND VACCINE MANUFACTURING

Engineers have had a key role in the detection of the corona virus, the design of preventative measures and equipment, equipment to support clinical treatment and technologies for vaccine manufacturing.

Engineers in India also made significant contributions, designing, prototyping and testing new hospital equipment in a few weeks, meeting regulatory requirements, including PPE gels and UV sanitisers and inexpensive throwaway bag respirators, through to supportive breathing devices with additional features, to full-scale ICU invasive ventilators. For example, Dr Pawan Goenka, Mechanical Engineer and Managing Director of automotive firm Mahindra and Mahindra, fast-tracked a major project to manufacture affordable respirators. The Tata Group and engineers in Tata Motors worked to build robots to sanitise hospitals. Other innovations developed at the Indian Institute of Science (IISc) and India Institute of Technology (IIT) Bombay include low-cost ventilators as well as sanitising equipment and processes using gels and UV light, the design and manufacture of ‘tunnels’, through which materials can be sanitised, and smaller mobile sanitisation units and portable room sanitiser for hospitals **(Figure 3)** [25].

Other innovations developed by Indian engineers include a drive through booth for COVID-19 testing, low cost PPE and masks and no-touch advanced washbasins [26].

Figure 3: The Dwaar Pro, a sanitising facility to allow students to enter the Indian Institute of Science [25]

Engineers around the world have also used 3D printing, consisting of direct manufacture of physical objects from digital models, to fabricate medical devices using low-cost materials and from complex geometries. This has enabled the supply of low cost masks, face shields, medical ventilator valves, clinical test kits and other personal protective equipment (PPE). For example, the start-up founder of Issinova, Christian Fracassi, developed a digital model of the Venturi valve that was required urgently in hospitals in Brescia, Italy, to supply oxygen and used 3D printing to fabricate these in two days, Fracassi and his team designed, tested and manufactured 100 valves for the hospital and saved many people's lives. The 3D printed valves were donated to the hospital **(Figure 4)** [27].

Figure 4: Original Venturi valve (left) and 3D printed Venturi valves. Source: [27]

3D printing has also been used to manufacture nasal swabs for COVID-19 testing kits, essential for the collection of biological samples to detect the corona virus and to manufacture several components of biosensors, including electrodes, substrates, parts for liquid handling and of devices [28]. Some of these innovations have been recognised with awards from the Royal Academy of Engineering, including a high-performance ventilator, a personal respirator for healthcare workers and an environment friendly face shield [29].

ARTIFICIAL INTELLIGENCE (AI) TO DETECT AND MANAGE THE CORONA VIRUS

AI applications to deal with the coronavirus pandemic include the early detection and diagnosis of infection; monitoring of treatments performed; tracking personal contacts of infected individuals; projection of cases and mortality; development of medicines and vaccines; and prediction of survival in severe cases of the disease. For example, AI is being used to detect COVID-19 from chest X-rays **(Figure 5)** [30, 31].

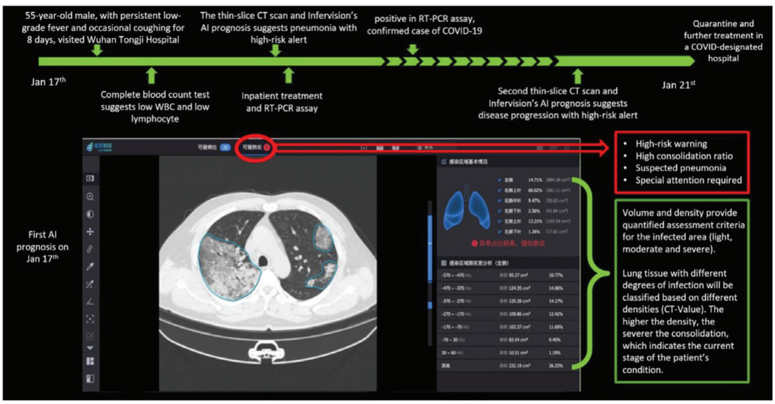


Figure 5: AI being used to detect Coronavirus from Chest X-rays. Photo: Ming-Ming Chen, China [31]

AI has also been used to identify molecular structures than can become effective vaccines [32], to optimise inpatient care [33] and for COVID-19 management including contact tracing [34].

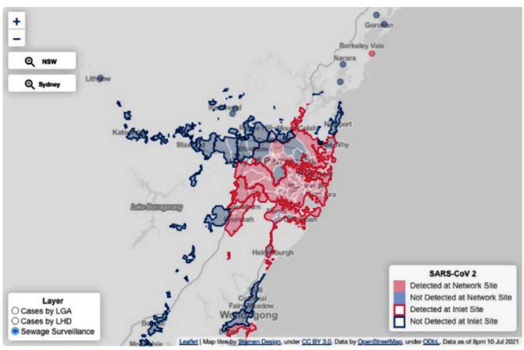
My company iOmniscient, has developed iQ-FeverCheck, an AI-based multi-sensory capability instrument for crowded spaces such as airports, sports stadiums, railway stations and other public spaces as well as in hospitals, nursing and aged care homes and other health care facilities, where it is necessary to detect when individuals are suffering from a fever. The system can also be used to monitor and manage mask wearing, social distancing and limiting numbers of people in particular areas in an unobtrusive manner while maintaining privacy **(Figure 6)** [35].

Figure 6: AI used for tracking and tracing people with fever in crowded public spaces [35]

An AI international vaccination certificate to authenticate if a person has been vaccinated has also been developed [36].

WASTEWATER SAMPLING TO MONITOR THE SPREAD OF CORONA VIRUS

Civil engineers at Stanford University have developed a process to test wastewater — a robust source of COVID-19 as those infected shed the virus in their stool-to track and supplement information on the spread of the virus. This is important for public health officials as they develop measures to combat the virus. The test works by identifying and measuring genetic material in the form of RNA from SARS-CoV-2, the virus that causes COVID-19. The trends in concentrations of SARS-CoV-2 RNA in wastewater aligns with trends of new COVID-19 infections in the community and is used by public health officials to manage outbreaks[37].For example, testing of wastewater to detect the virus is being used effectively in the state of New South Wales Australia and in public health messages and warnings. The map below is at 25 June 2021 **(Figure 7)** [38].



A map shows areas highlighted in red where Covid-19 has been detected in NSW. Source: NSW Health

Figure 7: Map showing spread of coronavirus in wastewater in New South Wales Australia by Local Government Authority (LGA), June 2021 [38]

Engineers in IIT Bombay and the University of Strathclyde have developed a low-cost sensor to detect the SARS-CoV-2 virus in wastewater. This low-cost technology can help several middle-to-low-income countries, who are struggling to control the prevalence of COVID-19. The project commenced in May 2021, led by Prof. Siddharth Tallur and Prof. Kiran Kondabagil at IIT Bombay. The sensor was tested with wastewater collected from a sewage treatment plant in Mumbai and can detect the genetic material at concentrations as low as ten pictograms per microlitre [39].

SOFTWARE AND COMMUNICATIONS ENGINEERING TO DEAL WITH COVID-19

The role of communications and software engineers were at the forefront of the battle against the coronavirus as billions were forced to work and study from home. The internet and communications technologies became essential to everyday life and engineers rapidly created new approaches to the accelerated digitisation of work and study [40].

Software engineers are also developing systems to manage the logistics of distribution and delivery of vaccines and websites and apps to manage registration, eligibility, and scheduling and integrate these into reminder and multipronged communication programs. Public health messaging is increasingly being provided through new technologies using social media, videos, and podcasts about COVID-related issues, including testing, recovery, and vaccination. All these require technical expertise and engineering. Clinicians from different health organizations require real-time access to its patients' vaccine information — helping to ensure that people receive their second dose of the right vaccine at the right time, while maintaining privacy and confidentiality [41].

The Indian Institute of Science and IIT Bombay are among leading engineering institutions that are developing software applications including for collecting anonymised data related to pandemic spread and virus tracing [42].

Technologies such as geospatial mapping has also been used to effectively trace the spread of the virus **(Figure 8)** [43].

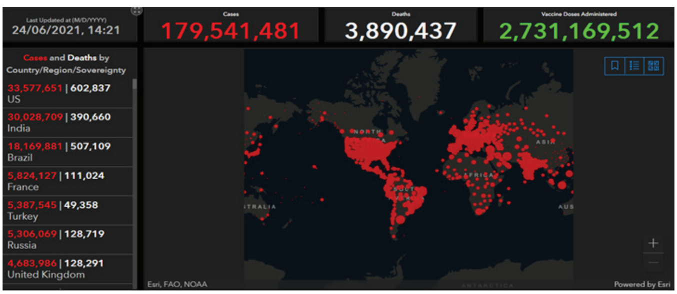


Figure 8: Johns Hopkins University, Center for Systems Science and Engineering, Coronavirus Global Map, 24 June 2021, [43]

SUPPLY CHAIN LOGISTICS, DISTRIBUTION AND VACCINE DELIVERY

Needless to say, engineers are essential not only for the design of manufacturing facilities for the vaccine, but also for the logistics systems and cold storage required for the distribution of vaccines around the world.

The supply chain challenges for the delivery of the vaccine are the largest the world has seen[44]. In short, it is the biggest logistical challenge the world has ever seen with up to 100 million deliveries or more per month. Key elements for this supply chain are increased cold chain capacity, storage requirements at low temperatures and 'Last-Mile Delivery' logistics.

Cold chain capacity is one of the most important factors in distribution of any vaccine, but in the case of the Pfizer vaccine, which needs to be stored at below -70°C, this capability is lacking in many countries. Typically, cold supply chain carriers used to transport medical supplies operate roughly between two and eight degrees Celsius. This is fine for most vaccines, which are stored at around 4°C. However, requirements for the Pfizer vaccine are significantly different. This has implications for distribution in parts of South America, Asia, and Africa. Not only is the climate hotter in these areas, but the infrastructure to support such low temperature storage is lacking. For example, if a power outage causes refrigeration to fail, the vaccines would likely be rendered useless. Storage capabilities will be hampered further by the volumes required, given that these areas are home to over six billion people combined. Engineers will be needed to ensure access to reliable power supplies and for the construction of large scale refrigerated storage warehouses. Engineers are innovating in this area, for example the development of the reusable Credo Cube, available for minus 80°C, storage [45].

Last-mile delivery is a challenge due to the need for trained truck drivers and staff to deliver from port to end destination and the need to maintain cold temperatures. This situation becomes more acute in rural and regional centres. Once the vaccine arrives, there is the added complexity of different interval periods for a second dose and the process of prioritizing and tracking those who will be offered the vaccine.

RESILIENCE AND RESPONSE BY ENGINEERS FOR THE FUTURE

This paper has shown the work of engineers around the world in responding to the coronavirus pandemic. It is also important to develop engineering capacity to respond to future challenges. For example, the Royal Academy of Engineering [46] has recommended measures for national infrastructure resilience, strengthening cyber security to mitigate risks arising from large-scale remote working, ensuring entrepreneurial ecosystems survive and thrive and supply chain agility, to minimise disruptions and reduce vulnerabilities.

Engineers have impacted not only the responses to the health aspects of the pandemic but have generated innovations, for example in India, for facilitating technologies for telehealth, making medical care accessible in regional locations [47, 48] and accelerated the implementation of contactless mobile payment systems [49]. These innovations have social, economic as well as health benefits.

Reflections on the year that changed the world include considerations of inequalities in terms of access to education [50], healthcare and vaccines. India is well placed to develop low cost innovations in healthcare [51, 52]. Engineers are also needed for infrastructure especially electricity, clean water and sanitation. For the future, it is essential to build resilience, including through accelerated digitalisation, rapid innovation and scale-up and importantly to address the need for more engineering skills and a diverse engineering workforce to take advantage of the opportunities created by the engineering responses to the pandemic [53].

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Dr Marlene Kanga is the Immediate Past President of World Federation of Engineering Organisations (WFEO), the peak body for engineering institutions internationally representing some 100 engineering institutions and approximately 30 million engineers. A Chemical Engineer, she was the 2013 National President of Engineers Australia. She is a Fellow of the Academy of Technology Science and Engineering Australia and a Fellow of The Institution of Engineers (India). She is a Member of the Order of Australia, a national honour, in recognition of her leadership of the engineering profession. During her term as WFEO President, Dr Kanga led the initiative for the member states at UNESCO to declare 4th March, the founding Day of WFEO as World Engineering Day. The inaugural World Engineering Day was held on 4th March 2020. Dr Kanga has been listed among the 100 engineers making a contribution to Australia in the last 100 years as part of Engineers Australia Centenary celebrations in 2019, among the Top 100 Women of Influence and one of the Top 10 women engineers in Australia. Dr Kanga is a Board Member and non-executive Director of some of the largest organizations in Australia in the utilities, transport and innovation sectors. She is an Honorary Fellow of the Institution of Engineers Australia, an Honorary Fellow of the Institution of Chemical Engineers (UK) and a Foreign Fellow of the ASEAN Academy of Engineering and Technology