Global review of the engineering response to COVID-19: lessons learned for preparedness and resilience

EngineeringX

Royal Academy of Engineering

The devastating impact of the COVID-19 pandemic tested the resilience of societies around the world.

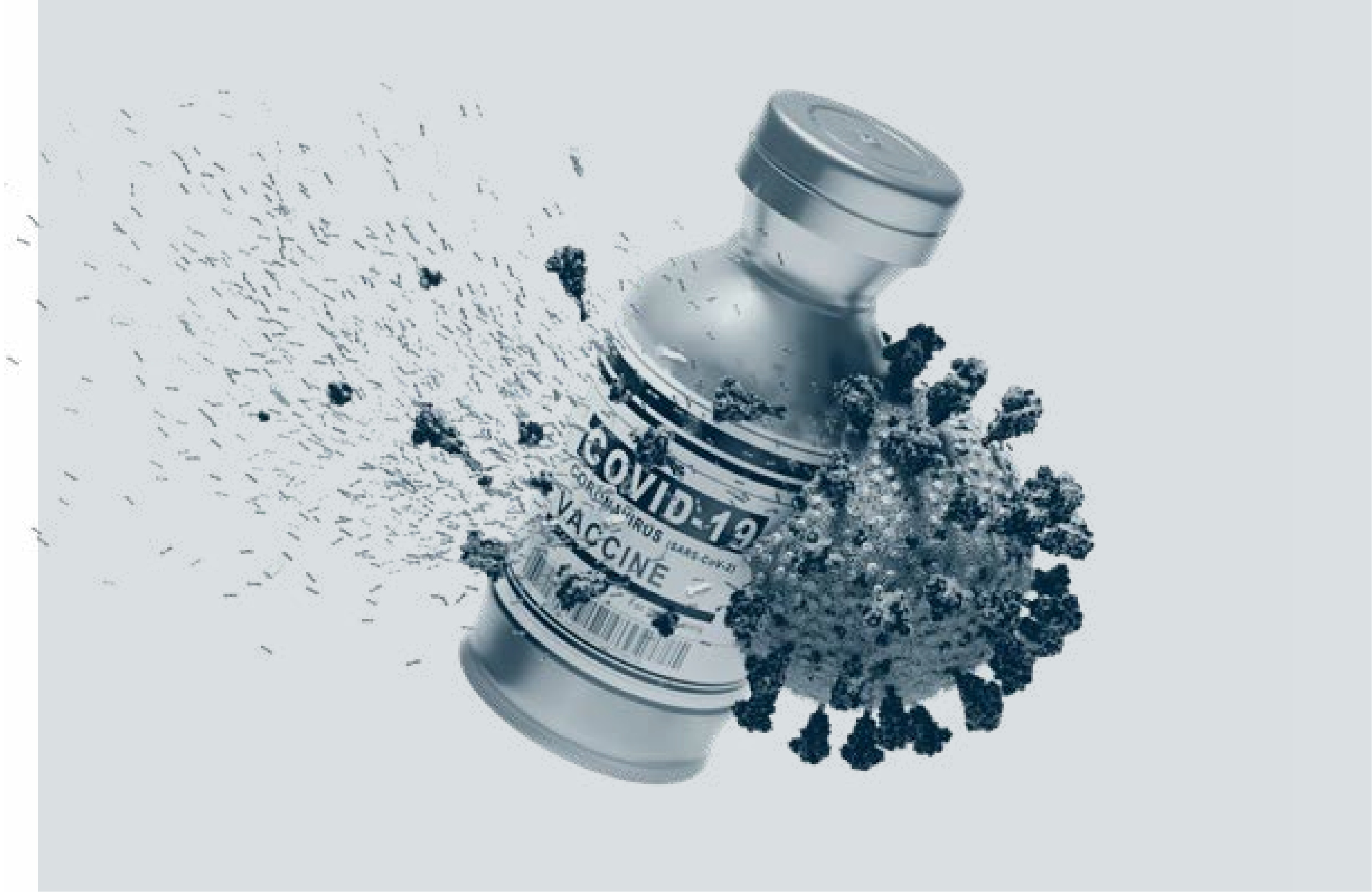
Now more than two and half years since the start of the COVID-19 pandemic, we have witnessed **major illness and loss of life, overburdened health systems and infrastructure, and deep disruptions to our socioeconomic systems – increasing inequalities and weakening the social fabric of communities globally.**[1,2] As the pandemic continues to evolve and spread across the globe, there is a need to **reflect on the efficacy of our response so far and on how to take on pragmatic problem-solving for the future.**

Engineers, supporting the building blocks of systems and societies, were integral to addressing the pandemic's most pressing challenges.

Since the onset of the pandemic, **engineers, often in collaboration with scientists, policymakers or business leaders, have brought a wide range of skills and problem-solving approaches to tackling challenges created by the pandemic.** They have designed and distributed lifesaving medical tools, pioneered new research and technological innovation, and kept strained, foundational systems and infrastructure running behind the scenes.

This report aims to bring engineers to centre stage through a global review of engineering contributions to pandemic prevention, preparedness, and response.

Looking ahead, **engineers will continue to play a vital role in the COVID-19 response, contributing to a strong recovery, and supporting prevention and preparedness for future pandemics.** This review takes stock of global engineering contributions in the pandemic so far, and distils lessons learned for how to further unlock the full potential of the engineering community.



Sources: [1] COVID-19 situation update worldwide, European Centre for Disease Prevention and Control, 2022 [2] Impact of COVID-19 on people's livelihoods, their health and our food systems, WHO, 2020

This report anchors on six major challenges faced during COVID-19 where engineers made key contributions:

Driving value from data:

High-quality and timely data was critical to orchestrating the pandemic response.[3] Engineers worked to ensure this was available and consolidated for public and private decision-makers in near real-time, and could be applied through digital, data-based tools – such as dashboards, models, or contact tracing apps.

Racing the virus:

The rapid spread of the virus required designing novel health tools at unprecedented speeds and in conditions of uncertainty. Together with scientists and clinicians, engineers were at the forefront of this innovation, supporting the design and production of both medical tools – such as vaccines, breathing aids and tests – as well as digital healthcare tools to support overburdened health workers.

Designing for equal access:

The pandemic affected people from all walks of life, all over the globe – yet people were not affected equally. Applying human-centred and context-sensitive design, engineers tailored products and services to meet the needs of diverse users and reduce inequality of access – such as portable labs for testing in areas with weak testing infrastructure, protective masks to fit a range of face shapes, or video calling devices for nursing home residents.

Ramping up production:

As global demand surged for essential health products, limited and concentrated production capacity led to shortages and geographic disparity.[4,5] Engineers pivoted existing industrial capacity – such as shifting automobile manufacturing to build ventilators – and built new capacity – such as expanding vaccine manufacturing facilities in Africa. Engineers also optimised production processes for speed and scale, for example, using 3D printing for rapid prototyping, or designing new processes to fill vaccines.

Streamlining delivery:

COVID-19 strained global supply chains and triggered delays and inequitable access to essential items, medical and non-medical alike.[6,7] Engineers mitigated these disruptions by accelerating the shift to networked, digitised supply chains, using drones and cold-chain innovations to get complex health products to remote areas, and leading emergency construction of critical infrastructure, including hospitals and test centres.

Strengthening society's systems:

To help society function in the chaos caused by the pandemic, engineers bolstered underlying systems and infrastructure. They ensured the resilience of essential utilities, strengthened society's buildings and transportation, and enhanced digital connectivity and its applications in remote education and work.

Sources: [3] Four lessons the pandemic has taught us about health data, Steventon, 2021 [4] Ventilator market set to return to pre-pandemic levels in 2021, Merical Device Network, 2021 [5] Export restrictions do not help fight COVID-19, UNCTAD, 2021 [6] How COVID-19 impacted supply chains and what comes next, EY, 2021. [7] Global shortage of personal protective equipment, Burki T., 2020

The report showcases the breadth of engineering contributions across the world.

This report highlights examples of valuable engineering contributions in responding to some of the most critical challenges during the pandemic. While not aiming to be comprehensive, this report seeks to demonstrate the breadth of contributions in both direct pandemic response and ensuring broader societal resilience. In addition, it aims to draw key lessons and insights to address future waves of COVID-19 or the next pandemic.

Some of the examples of valuable engineering contributions in this report:

- Improving ventilation systems in **Canada**
- Accelerating vaccine rollout using machine learning in the **US**
- Supporting the production of CPAP breathing devices in **Latin America**
- Printing nasal swabs using distributed networks of 3D printers across the **US** for COVID-19 tests
- Using wastewater analysis to monitor community spread of COVID-19 in **Ecuador** and **Brazil**
- Designing IoT devices to track vitals and tailor its use for diverse communities in **Peru**
- Developing rapid, portable lab-free, and cost-effective diagnostics in the **UK**
- Developing an AI-powered, digital recruitment platform in **Tunisia**
- Building new vaccine manufacturing facilities in **Senegal**
- Using drones to deliver tests, treatments and vaccines in **DRC**, **Mozambique,** and **Malawi**
- Enabling procurement of critical supplies through an AI-powered supplier discovery platform designed in **Germany**
- Using AI to improve COVID-19 testing on **Greek** borders
- Designing new edtech platforms for remote schooling in **Jordan**
- Repairing oxygen concentrators in **Malawi**
- Using geospatial and mobile data to close data gaps in **DRC**
- Developing an all-in-one, low-cost breathing device in **South Africa**
- Upgrading vaccination storage to be energy efficient, earthquake resistant, and hold larger capacities in **Mongolia**
- Pivoting high precision manufacturing factories to build ICU ventilators in **Pakistan**
- Designing a 'lab-in-a-suitcase' for COVID-19 testing in **India**
- Designing UV-C light devices to disinfect public escalators in **South Korea**
- Constructing emergency hospitals at speed in **China**
- Preventing zoonotic disease outbreaks through community reporting software solutions in **Cambodia** and **Thailand**
- Expanding digital food delivery platforms in **Fiji** during lockdowns
- Expanding telehealth in **Australia** for remote consultations

By exploring these contributions in addressing six major challenges faced during the pandemic, the report distils drivers of success as well as opportunities to boost further resilience

1 Driving value from data

CHALLENGE

- **Decision-makers needed high-quality and timely data to understand the spread of the virus and its impact** for policymakers to execute responses, businesses to pivot operations, clinicians to run hospitals, and communities to stay safe.
- **However, there were severe challenges across the data value chain** – from data collection and consolidation, to securely storing and sharing data, to rapidly rolling out analysis, digital tools, and dissemination.

ENGINEERING CONTRIBUTIONS

- **Data and software engineers worked to tackle challenges across the data value chain** from gathering missing data – such as using mobile data in the Democratic Republic of Congo (DRC) to estimate population movement[1] – to aggregating and visualising critical data for decision-making – such as an app to display disruptions to essential health services for health workers in Uganda.[2]
- **Engineers then built novel tools that applied this data**, such as contact tracing apps, machine learning to improve and expedite processes – for example, using Artificial Intelligence (AI) at Greek borders to select which travellers to test[3] – and information dissemination – such as the World Health Organisation (WHO) deploying chatbots to interactively share health communications.[4,5]

LESSONS LEARNED

- **The full potential of engineering in this context was often hampered by insufficient investment into underlying data systems (including linking data from different sources) prior to the pandemic.** An important part of improving this moving forward will be investing in dedicated, local engineers who can build and maintain these systems over the long run.
- **Greater communication and collaboration between data experts and policymakers is also needed to ensure decision-makers recognise the limitations of available data and it is not misused.** This includes: working collaboratively to tackle challenges on data interpretation, minimising use of biased or discriminatory data, and safeguarding data privacy.

2 Racing the virus

CHALLENGE

- **Life-saving frontline health solutions were needed urgently.** This included tools to detect, contain, treat, and eradicate the virus, as well as manage increasingly overburdened health systems.
- **The urgency and uncertainty** of the pandemic meant innovators had to fast-track research and development (R&D) and design solutions in tandem with emerging evidence.
- **These new tools and services also needed to be rapidly integrated** into existing health systems, all while maintaining adherence to quality and safety.

ENGINEERING CONTRIBUTIONS

- **Engineers were instrumental in bringing new research findings to real-world application in record time,** such as translating a vaccine from viral sample to approval and manufacture at unprecedented speeds, and University of Oxford engineers developing the first rapid COVID-19 test just three months after the start of the pandemic.[6]
- **These innovations have brought disruptive impact that will be here to stay,** such as the acceleration of trends in digital health, new vaccine platforms, or an increased use of robotics in hospitals. For example, telehealth has boomed in Australia, and studies have shown significant reductions in mortality rates and economic savings as a result.[7,8]

LESSONS LEARNED

- **Innovations built on years of existing R&D, and the context of crisis enhanced appetites to take risks and think outside the box.** This highlights the importance of sustained and mission-driven funding for innovation.
- **Greater coordination and collaboration between researchers could have further enhanced progress.** Research that was duplicative, fragmented, or too small-scale to provide evidence led to wasted resources.
- **Systems thinking and integration is needed to rapidly adopt new tools.** Innovations were most effective when they could be rapidly absorbed by healthcare systems. Addressing fragmentation of the global regulatory environment will be an important barrier to tackle.

Sources: **[1] Using mobile big data to help inform the fight against COVID-19 in the Democratic Republic of Congo, GSMA, 2020 [2] UNICEF, Using Data Innovation to Improve Health Outcomes in Uganda, 2021 [3] Efficient and targeted COVID-19 border testing via reinforcement learning, Hamsa et al, Nature, 2021 [4] WHO Chatbot available at: https://www.whatsapp.com/coronavirus/who [5] WHO launches a chatbot on Facebook Messenger to combat COVID-19 misinformation, WHO, 2020 [6]** Oxford scientists develop rapid testing technology for COVID-19, University of Oxford, 2020 **[7]** How Telehealth company Coviu used the pandemic to boost their business, Australian Institute of Company Directors, 2020 **[8] Health technology report, ATSE, 2020**

3

Designing for equal access

CHALLENGE

- **Tools and services were often insufficiently tailored to meet the diversity of users and contexts affected by the global pandemic.** For example, even though, globally, women were more likely to be frontline health workers, personal protective equipment (PPE) was typically designed for men and so was ill-fitting for many women health workers.[1]
- **The pandemic also exacerbated existing inequalities and disproportionately affected certain groups**. For example, the move to remote education and work left those on the 'invisible' side of the digital divide behind.[2]

ENGINEERING CONTRIBUTIONS

- **Applying human-centred design principles, engineers met the needs of diverse users**. For example, engineers in China used blue light scanners and 3D printing to make customised face seals that would fit any individual's face shape,[3] and UK engineers designed a CallGenie video device specifically for nursing home residents to bridge digital literacy divides.[4]
- **Engineers also optimised designs for low-resource settings,** considering budget constraints of health systems or end users, the available infrastructure, or geographical constraints. For instance, South African engineers designed a less-oxygen intensive, all-in-one breathing device that would be suitable for a range of oxygen infrastructures,[5] and engineers at Learning Equality built a remote education platform for children without at-home internet access.[6]

LESSONS LEARNED

- **A concerted effort is needed to ensure engineers consistently apply a user-centric approach to design.** Cases of designs which were not fit for purpose, such as racial bias in pulse oximetry measurement,[7] or AI applications based on non-inclusive datasets,[8] have shown the importance of adopting human-centred design principles more frequently.
- **More is needed to support home-grown solutions and bring them to scale.** Although innovators closest to the local context are often best placed to design tailored solutions, researchers and innovators in low- and middle-income countries (L/MICs) have received less funding in comparison to their high-income country (HIC) counterparts, limiting the potential of their contribution.[9,10] Funding is needed not only for ad-hoc crisis response, but also sustained investment to create an enabling environment.

4

Ramping up production

CHALLENGE

- **Demand for essential health products surged in the context of COVID-19.** At the same time, over 80 countries enforced export restrictions,[11] leaving non-producing countries vulnerable to shortages, and causing prices to sky-rocket.
- **Countries had to look inward to build up local production capacity.** At the same time, producers and manufacturers had to adapt to new health and safety challenges, as well as critical shortages in the supply of inputs and materials.[12]

ENGINEERING CONTRIBUTIONS

- **Engineers rapidly pivoted industrial capacity to meet the demand for essential products,** such as garment manufacturers in India pivoting to make PPE,[13] or Mercedes AMG repurposing their factory to manufacture breathing aids.[14]
- **Engineers also pioneered new production techniques to facilitate rapid scale-up.** 3D printing, for instance, was used for rapid prototyping and manufacturing – such as Formlabs 3D printing 100,000 nasal swabs for COVID-19 tests to meet shortages in the US.[15]
- **Engineers are already playing a critical role in strengthening local capacity for the future,** such as setting up new oxygen plants closer to points of need or increasing in-country vaccine manufacturing capacity.

LESSONS LEARNED

- **Sustained investment and diversification will be needed** to maintain production capacity for future resilience. For example, although COVID-19 test manufacturing capacity grew over 200% globally, keeping this capacity 'warm' when the pandemic subsides will not be possible without financial support or planned diversification for other uses.[16]
- **Redistributing global manufacturing to increase local resilience will require targeted effort and tackling several issues,** including investing in skilled labour, reaching the right balance in intellectual property (IP) protection and knowledge sharing, and improving working conditions.

Sources: **[1] Medical PPE unfit for women on COVID-19 frontlines, Owings L, 2021. [2] Digital Poverty and its Impact on Education Inequality, Learning Hive.2022 [3] Customized design and 3D printing of face seal for an N95 filtering facepiece respirator, Cai et al, 2018 [4] CallGenie - Video Calls Direct to Their TV, Age Space [5] OxERA® DEVICE, Umoya, 2021 [6] Learning Equality, Kolibri, Date Accessed: July 2022 [[7] Covid: Pulse oxygen monitors work less well on darker skin, experts say, BBC, 2021 [8] Hundreds of AI tools have been built to catch covid. None of them helped., MIT Technology Review, 2021 [9] COVID-19 Research Project Tracker by UKCDR & GloPID-R, Date Accessed: June 2022** [10] Expert interviews **[11]** Export restrictions do not help fight COVID-19, UNCTAD, 2021 [12] Expert interviews **[13]** From clothing production to PPE manufacturing: factories pivot during the pandemic, Better Work, 2020 **[14]** Coronavirus: inside story of how Mercedes F1 and academics fast-tracked life saving breathing aid, The Conversation, 2020 **[15]** Formlabs' 3D Printed Naspharyngeal Test Swabs Honoured as a World Changing Idea by Fast Company, Formlabs, 2021 **[16]** COVID-19 diagnostics: preserving manufacturing capacity for future pandemics, Hannay et al, 2022

5 Streamlining delivery

CHALLENGE

- **Restrictions on trade, travel, and work disrupted critical flows of food, medical supplies, and manufacturing inputs.** This was exacerbated by volatile demand and overburdened staff and infrastructure.
- **Globally, these disruptions had a negative impact at the level of the individual, businesses, and the economy.** Shortages of essential goods left individuals vulnerable, as did cross-sector layoffs. Production bottlenecks, worker shortages, and export bans hurt businesses. Price increases and stunted trade growth impacted overall economic growth.[1]

ENGINEERING CONTRIBUTIONS

- **Engineers intervened to address supply chain disruptions and ensure critical pandemic response efforts.** This included interventions to increase visibility on shocks and disruptions, such as the 'C3.AI COVID-19 Data Lake,'[2] an AI-enabled tool that accelerated the analysis of critical supply chain disruptions. It also involved improving physical infrastructure, such as upgrading vaccination storage in Mongolia to be energy efficient, earthquake resistant, and with four times the capacity of previous facilities.[3]
- **These contributions have helped set the foundation for supply chains to be more resilient, responsive, collaborative, and networked.** For example, in the agricultural sector, Internet of Things (IoT) devices are being used for automatic and remote inventory management, proactively alerting actors of low supply.[4,5]

LESSONS LEARNED

- **The pandemic showed the fragility of complex global supply chains, renewing interest in shortening supply chains.**[6] Engineers will be central to 'nearshoring' efforts to increase local resilience, both in managing the logistics of shorter supply chains and in expanding local production.
- **Accelerating supply chain digitisation requires greater uniformity of digitisation across networks and value chains.** In many sectors, the full potential of digitisation was not reached because parts of the value chain used incompatible systems or did not digitise at the same pace. Equipping the workforce with digital skills will be a key component of improving this.

6 Strengthening society's systems

CHALLENGE

- **Society's underlying systems and infrastructure had to be resilient to pandemic disruptions.** These included systems linking energy and water utilities, as well as physical and digital infrastructure. Their structural resilience was also a prerequisite to positive health outcomes. For instance, hospitals could not function without access to clean water or stable electricity.
- **Resilient, adaptable systems were also needed to facilitate a transition to the new normal;** such as expanded network connectivity to enable remote working and education.

ENGINEERING CONTRIBUTIONS

- **Engineers bolstered society's systems to improve health outcomes and societal resilience.** For example, PowerAfrica funded technicians expanded solar power to rural healthcare centres in sub-Saharan Africa;[7] and in Iran, network engineers worked to increase internet speeds — the backbone needed to facilitate the shift to remote work and education globally.
- **Though typically not recognised as such, these engineers were essential workers,** and in some cases faced a direct risk of infection; such as sanitation engineers working to bolster systems for safe disposal of contaminated products.[8]
- **Many of these strengthened systems will have lasting impact beyond the pandemic**. Disruptive innovations in mobile and internet systems will fundamentally change how we work, study, and socialise. Similarly, increased application of IoT and automation will herald a new era of infrastructure responsiveness and management.

LESSONS LEARNED

- **Engineers need to be brought in earlier to inform decision-making.** Being slow to consult engineering experts, such as in ventilation or sanitation, led to critical delays in improving guidelines and upgrading infrastructure.[9] In addition, these engineering inputs need to be better communicated to the public.
- **A systems approach is needed**. Building back stronger will see further interconnectedness of systems, such as greater links between the digital and physical, and engineers will need to ensure these increasingly complex systems are robust.[10]
- **Engineers must also manage new risks associated with increased digitisation,** including working to ensure inclusivity in access and addressing cybersecurity challenges.

Sources: **[1] Supply chain disruptions and the effects on the global economy, ECB, 2021** [2] C3.AI Data Lake, **website** **[3] Responding To The Covid-19 Crisis In Mongolia With A Climate-friendly Central Vaccine Store, World Bank, 2022.** **[4] IoT and the Supply Chain: How Machine Learning Eases Bottlenecks, DIGI, 2021** **[5] See, for example: IoT and the Coffee Supply Chain, DIGI, 2021** **[6] Building back better: A sustainable, resilient recovery after COVID-19, OECD, 20** **[7]** Solar energy ensures reliable power to India's rural health clinics, Energizing rural India, 2021 **[8]** Telecom security during a pandemic, Enisa, 2020 [9] Expert interviews. [10] A systems approach to infrastructure delivery, Institution of Civil Engineers, 2020

From among the contributions, this review also spotlights six specific case studies

1 Driving value from data

Non-profit 'Ending Pandemics' co-created community surveillance tools to prevent zoonotic disease outbreaks in Thailand and Cambodia

Using 'EpiHacks' — a collaborative process to bring local software engineers and technologists together with public and animal health officials to problem-solve — Ending Pandemics supported communities to design and use digital apps and hotlines to report cases of animal and human disease outbreaks.

Impact at a glance

- Widespread adoption of community-based reporting, leading to the successful reporting and containment of hundreds of human and animal disease outbreaks.
- Rapid adaption of existing surveillance tools for COVID-19 reporting — representing 90% of detected cases in Cambodia.

2 Racing the virus

UCL and Mercedes AMG teamed up to develop and rapidly produce CPAP breathing aids and support global technology transfer

Responding to critical shortages, engineers from UCL designed a breathing aid prototype in under 100 hours and partnered with Mercedes AMG, who repurposed their Formula 1 factories to produce 1,000 devices a day. The open-source design has been made available to local manufacturers globally.

Impact at a glance

- 10,000 breathing aids supplied in the UK.
- Over 2,000 blueprint design downloads.
- Over 25 consortia globally have designed and manufactured devices from scratch, which are now in use in hospitals to treat patients.

3 Designing for equal access

Innovations in wastewater testing addressed gaps in testing access and uptake for underserved communities in the Americas

Engineers deployed wastewater testing technology to detect the amount of COVID-19 in sewage systems. Not only did wastewater testing help detect variants and provide an early indicator of a rise in infections, it also included underserved populations in COVID-19 surveillance.

Impact at a glance

- Facilitated the inclusion of underserved populations in COVID-19 community-level data.
- More easily able to track the presence of COVID-19 variants than traditional PCR testing.
- Successfully implemented in 50+ countries worldwide.

4 Ramping up production

Multi-stakeholder initiatives have started to build vaccine manufacturing capacity on the African continent

COVID-19 underscored Africa's reliance on imported vaccines. Since the pandemic, public and private initiatives have started to build end-to-end vaccine development and manufacturing capability across the continent.

Impact at a glance

- Since the onset of the pandemic, stakeholders in Algeria, Egypt, Morocco, Rwanda, Nigeria, Senegal, and South Africa have committed to plans to expand vaccine manufacturing or have begun production.

5 Streamlining delivery

VillageReach, a tech-for-health NGO, partnered with drone developers to transport medical supplies to hard to access areas in DRC, Malawi, and Mozambique

During the pandemic, VillageReach adapted its drone-enabled transport networks to bridge gaps in the delivery of COVID-19 medical tools for remote communities — such as those with poor road access or those that are inaccessible because of floods.

Impact at a glance

- Rapid response by adapting existing systems to meet new contexts and need.
- Increased speed in diagnosis and treatment for COVID-19 and other diseases.
- Provided access to medicines and vaccines for thousands of patients in remote locations.

6 Strengthening society's systems

Edtech venture, Educational Initiatives, adapted its e-learning software for community access and mitigating learning loss in India

In the context of prolonged school closures in India, Educational Initiatives pivoted its edtech solution for schools to be accessible in homes and communities. The software has a powerful impact on learning outcomes by using adaptive learning technology to tailor content by learning the users' level.

Impact at a glance

- Reached ~125,000 students, many in low-connectivity households.
- Mitigated learning loss: as per one study, students achieved learning outcomes five times higher than targets set and compared to peers without access to Educational Initiatives' solution.

In closing, the review distils key drivers that enabled engineers' impact in the COVID-19 response

DRIVERS OF IMPACT

Rallying around a shared sense of purpose. This empowered engineers to take risks or innovate in unprecedented timeframes – for instance, taking a vaccine from viral sample to approval and manufacture in under a year.

Using existing systems flexibly. Systems and business models that could withstand shocks or pivot were critical to resilience; such as car factories pivoting to building ventilators or adapting existing health apps for remote consultations.

Optimising for low-resource settings in the short term; and in the long term, strengthening health systems and industrial capacity. Engineers optimised solutions for low-resource contexts, such as portable labs for areas with limited health infrastructure. In the long run, however, this will require resolving systemic gaps in these settings – such as building manufacturing capacity or expanding connectivity.

Applying systems thinking and a sensitivity to the wider context of an intervention. This included making a drone innovation work within existing health delivery systems or working with community members to drive the uptake of new

Reflecting on these drivers, this report calls on the engineering community, policymakers, public health actors, academia and funders to act to amplify the value of engineering in future pandemic resilience

CALLS TO ACTION

Systematically identify gaps in pandemic resilience and strategically channel funding to address them.

Accounting for lessons learned, there is a need for more systematic reviews, better planning, and coordinated funding to improve societal resilience. **Potential interventions include:**

- undertaking resilience audits (using systems thinking) to identify areas for strengthening institutions or response mechanisms;
- updating datasets and data systems used for decision-making and removing bias;
- reorienting emergency response task forces with more engineering capability;
- Providing funding along pre-defined priorities and common objectives.

DRIVERS OF IMPACT

edtech solutions.

Employing specialised skills and capacity. The application of technical skills, from data analysis to emergency construction, was critical. Moreover, where engineers were close to the communities they were serving, they adapted their skills to deliver fit for purpose solutions.

Learning across countries. Engineers collaborated across countries and facilitated international technology transfers, including learning from innovators in resource-constrained settings.

Coordinating across disciplines and sectors. This was needed to tackle complex problems from multiple angles, such as engineers working closely with public policymakers or health practitioners to understand their needs and design solutions together.

Cultivating effective communication between technical experts, decision-makers and the general public. In an uncertain context, engineers and technical experts had to build the trust and understanding of policymakers and the general public around complex and rapidly changing topics.

CALLS TO ACTION

Bolster training and capacity of local engineers, accounting for skillsets needed for response and resilience during pandemics.

The experience from COVID-19 revealed the diversity of technical and non-technical skills needed for a strong response, as well as where this is lacking. Potential interventions include:

- undertaking workforce planning to identify and address skills gaps for future responses;
- in the short term, bridging capacity gaps via exchange programmes or one-off trainings;
- in the longer term, supporting local universities and skills providers to design curricula, teacher training and academic–industry linkages that fill gaps in pandemic-specific skills.

Create and support mechanisms for collaboration across disciplines and countries, that persevere in the context of crisis.

Pandemic resilience requires coordinated action across countries and disciplines. Systems to facilitate this need to be set up or bolstered during 'peacetime'. Potential interventions include:

- designing and funding innovation teams or programmes (such as incubators) that link engineering with other disciplines;
- creating, strengthening, and actively maintaining digital collaboration platforms or forums, capturing momentum started during COVID-19;
- supporting initiatives to increase the adoption of open science and data sharing standards;
- running programmes focused on developing effective communication between technical experts, policymakers, and the general public.