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

EngineeringX

Royal Academy of Engineering

Engineering X Pandemic Preparedness

This Global Review was commissioned as part of the Engineering X Pandemic Preparedness programme, which was launched in May 2020. The programme aims to support engineering to play a key role in global efforts to prevent, respond to, prepare and build resilience to pandemics through global sharing of lessons and best practice approaches.

The report has been produced in partnership with Dalberg Advisors, a strategic advisory firm that works collaboratively across the public, private and philanthropic sectors to drive inclusive and sustainable growth. The Dalberg team behind this report was led by Daphnée Benayoun and James Eustace, and included team members Dia Banerjee, Anna Schnupp, and Kiara Soobrayan. The views and opinions expressed in this report are those of the authors and do not necessarily reflect the views of Engineering X.

Dalberg Advisors (2022). *Global review of the engineering response to COVID-19: lessons learned for preparedness and resilience*. Engineering X (founded by the Royal Academy of Engineering and Lloyd's Register Foundation).

ISBN: 978-1-909327-56-6
engineeringx.raeng.org.uk
#EngineeringX
@RAEngGlobal
Photo credits: Pexels.com & Unsplash.com

EngineeringX Royal Academy of Engineering In partnership with Dalberg

Contents

Foreword

Since the COVID-19 pandemic started over two and a half years ago, the engineering profession has played a leading role in global efforts to manage and mitigate its impacts.

Engineers have underpinned many elements of our society's response to the virus, ranging from PPE and new vaccine manufacture to securing supply networks, from improved indoor ventilation to enabling remote work and education. However, systemic barriers - including lack of collaboration mechanisms, insufficient data and skills, and a lack of understanding and consideration for engineering's role – often limited engineers' ability to deliver timely and effective responses.

This review was conceived by the Engineering X Pandemic Preparedness programme at the height of the COVID-19 pandemic in November 2020 to learn lessons and set recommendations to overcome these barriers and ensure more systemic engineering response and preparedness for future pandemics.

The review highlights the breadth of contributions made by engineers and engineering globally in responding to key challenges, across sectors, disciplines, geographies, and across pandemic prevention, preparedness, response and recovery. It celebrates transformational innovations in low resource contexts as well as world-changing advances in medical and communication technologies, the pivotal role of data collection, distribution and management, and the importance of applying a systems lens to complex multifaceted challenges. The review identifies enabling factors that contributed to success as well as the barriers that prevented engineers and engineering solutions from making their full contribution.

It finally calls on governments, policy makers, public health actors, funders and the engineering community to identify and close structural gaps in resilience against future pandemics, to invest in skills, training and capacity of engineers all around the world, and to develop robust platforms for collaboration within engineering and between engineering and other disciplines.

COVID-19 has claimed over six million lives so far, and will have long term impacts on public health, education, social and economic development. Our hope is that we can use the insights provided by this truly global overview of the engineering response to COVID-19 to better integrate engineering skills and habits of mind into resilience policies and structures all around the world, to improve our recovery from the virus, and to help us on the path to a safer, more prepared and resilient future.

Professor Peter Guthrie OBE FREng
Chair of the Pandemic Preparedness board

Foreword

"The COVID-19 pandemic has acted as a reminder that a global emergency requires a global response, and that no single country or discipline can tackle a crisis alone. This report reinforces this message, and focuses on the role of engineering in this fight. It calls on the global community to learn lessons and act to improve our future pandemic response - creating better mechanisms for global collaboration and coordination, engaging with stakeholders from across disciplines, and developing the skills needed to prevent, prepare for and respond to pandemics."

→ *Sir Richard Feachem KBE FREng – Professor Emeritus of Global Health, Institute for Global Health Sciences, University of California San Francisco*

"COVID-19 has demonstrated once again the critical role of engineers in society. Engineers have been crucial in rapidly developing infrastructure and technologies to support healthcare systems, scaling up vaccine supply chains, harnessing data systems, and advising on transmission routes and risks. This report highlights the continued need for engineering skills and multi-disciplinary approaches to maximise our resilience to any future pandemic."

→ *Sir Patrick Vallance FRS FMedSci – UK Government Chief Scientific Adviser*

"The COVID-19 pandemic has highlighted the pivotal role that engineers play in responding to public health emergencies and resilience planning. There are important lessons that we must learn around understanding the needs of providing healthcare in diverse, global settings and working collaboratively across sectors, listening and building trust. Now is the time for governments and international organisations to act on these lessons, and I commend the Royal Academy of Engineering for highlighting the successes and learnings of our community"

→ *Professor Rebecca Shipley OBE – Director, UCL Institute of Healthcare Engineering, Co-Lead, UCL-Ventura CPAP programme and Pandemic Preparedness board member*

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.**

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.

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.

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** (pg 85)
- Accelerating vaccine rollout using machine learning in the **US** (pg 30)
- Supporting the production of CPAP breathing devices in **Latin America** (pg 45)
- Printing nasal swabs using distributed networks of 3D printers across the **US** for COVID-19 tests (pg 62)
- Using wastewater analysis to monitor community spread of COVID-19 in **Ecuador** and **Brazil** (pg 55)
- Designing IoT devices to track vitals and tailor its use for diverse communities in **Peru** (pg 49)
- Developing rapid, portable lab-free, and cost-effective diagnostics in the **UK** (pg 51)
- Developing an AI-powered, digital recruitment platform in **Tunisia** (pg 86)
- Building new vaccine manufacturing facilities in **Senegal**
- Using drones to deliver tests, treatments and vaccines in **DRC**, **Mozambique,** and **Malawi** (pg 78)
- 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 (pg 30)
- Designing new edtech platforms for remote schooling in **Jordan** (pg 86)
- Repairing oxygen concentrators in **Malawi** (pg 52)
- Using geospatial and mobile data to close data gaps in **DRC** (pg 31)
- Developing an all-in-one, low-cost breathing device in **South Africa** (pg 52)
- Upgrading vaccination storage to be energy efficient, earthquake resistant, and hold larger capacities in **Mongolia** (pg 73)
- Pivoting high precision manufacturing factories to build ICU ventilators in **Pakistan** (pg 45)
- Designing a 'lab-in-a-suitcase' for COVID-19 testing in **India** (pg 51)
- Designing UV-C light devices to disinfect public escalators in **South Korea** (pg 40)
- Constructing emergency hospitals at speed in **China** (pg 74)
- Preventing zoonotic disease outbreaks through community reporting software solutions in **Cambodia** and **Thailand** (pg 34)
- Expanding digital food delivery platforms in **Fiji** during lockdowns (pg 74)
- Expanding telehealth in **Australia** for remote consultations (pg 41)

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 achieved scratch design to manufacture and 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 run, 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 the context of uncertainty, 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.

Chapter 1

Context and overview

The COVID-19 pandemic has had a devastating impact on communities across the globe

The impact on human health and life has been catastrophic.
By mid-2022, more than 11 million COVID-19 cases have been reported in Africa, 159 million in the Americas, 134 million in Asia, 217 million in Europe and 9 million in Oceania[1] – infecting people from all walks of life, and in every corner of the globe. Over 6.3 million people have died from COVID-19,[2] and one-fifth of those infected are estimated to experience lasting 'long COVID' symptoms.[3,4] In addition, many more have suffered because of disruptions to other essential health services.

This impact was not confined to health but has had ricocheting effects throughout society.
Beyond the dramatic impact on human health, the pandemic has triggered widespread disruptions to our socioeconomic systems. The shock of COVID-19 tested and strained many of our foundational structures – such as our global supply chains, education systems, and digital networks. Core functions had to continue during the pandemic despite lockdowns and disruptions, requiring societal systems to have the resilience to adapt to a 'new normal'.

Understanding societies' resilience to a pandemic[5]

Shock

Health resilience
Systems capacity to promote, restore, and maintain health when confronted with a shock.

Societal resilience
Societies' ability to maintain core functions while minimising the impact of the pandemic and other societal effects.

Sources: [1] COVID-19 situation update worldwide, European Centre for Disease Prevention and Control, 2022 [2] Weekly epidemiological update on COVID-19 - 15 June 2022, WHO, 2022 [3] Estimates of long COVID are startingly high. Here's how to understand them, STAT, 2022 [4] Long COVID is a condition characterised by long-term consequences persisting or appearing after the typical convalescence period of COVID-19. [5] Definitions from Building a multisystemic understanding of societal resilience to the COVID-19 pandemic, British Medical Journal, reliefweb, 2021

> **"There's a tremendous tendency to look at things in silos – such as 'this is a health crisis to be solved by health people'; but we need to look at the implications across wider society: one thing impacts another, and you have multiple crises at once. This is why whole society resilience is important. "**

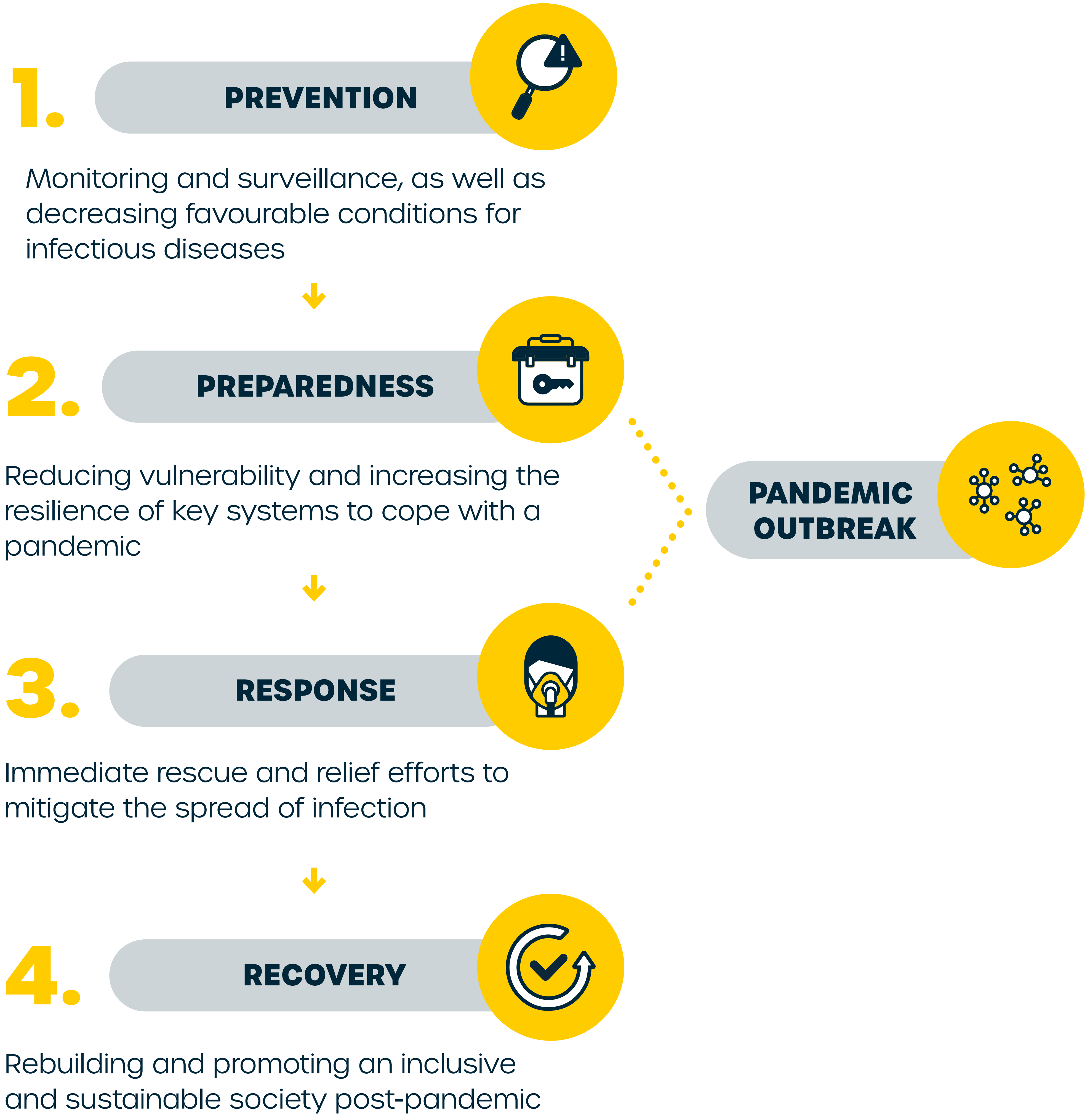
Policymaker working on crisis resilience

The pandemic called for rapid, pragmatic problem-solving across dynamic circumstances and a wide range of contexts

Successfully reacting to a pandemic threat is a function of prevention, preparedness, response, and recovery.
COVID-19 has tested the international community's ability to detect and contain outbreaks, bolster systems to cope with the shock of the pandemic, quickly respond to the crisis, and create foundations for a strong recovery.

The urgency of the pandemic required solutions at speed and scale, under conditions of great uncertainty.
At the onset of the pandemic, the nature of the virus and the way the pandemic would impact systems, economies, and communities was unknown. However, the urgency to find solutions meant rapid problem-solving had to start immediately, iterating and adapting efforts to changing circumstances. This included needing to find solutions which worked for diverse users and contexts, in high-income and low-resource settings alike.

Model for pandemic risk management :



Engineers brought unique skillsets and approaches to problem-solving that were crucial during the pandemic

At their core – engineers are problem solvers.
Engineers work to bring the latest innovations into real-world application. Optimising for constraints such as functionality, cost, speed, or durability, engineers design the devices, structures, and processes which allow societies to run. Applying a practical approach to problem solving, as well as a broad range of specialisms and expertise, engineers brought a unique set of skills to approaching the challenges created by the pandemic.

Though often working behind the scenes, engineers were central to enabling pandemic resilience.
Although often not seen as essential workers, engineers were instrumental in the pandemic response. This included workers on the frontlines – such as those that repaired oxygen machinery in strained hospitals or retrofitted ventilation systems to reduce airborne transmission. Overall, the range of engineering skills needed and used was vast: from data and software engineers designing systems to track the spread of COVID-19, to civil engineers building emergency facilities in a matter of days, to biomedical and mechanical engineers designing and manufacturing breathing aids at scale. Engineers were vital in ensuring that society's foundational systems continued to function – such as water, energy, telecommunications, the built environment, and transport.

Engineers undertook this work under challenging circumstances.
The rapid evolution and uncertainty of the pandemic meant engineers needed to quickly react, adapt their solutions, and tackle new problems. At the same time, engineers had to adapt their ways of working to increasingly challenging conditions – such as reduced workforces, social distancing, and shortages in materials and supplies.

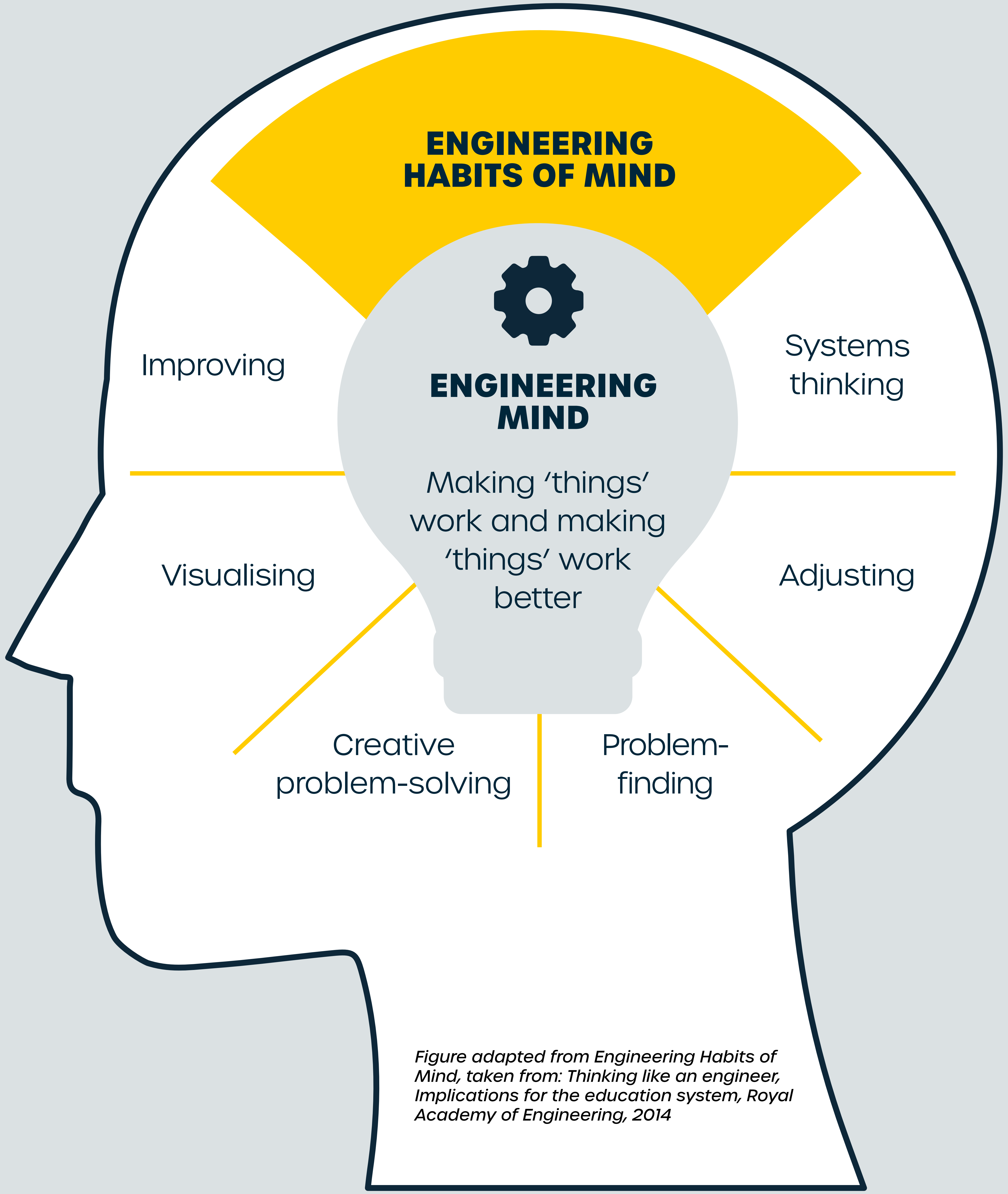


Figure adapted from Engineering Habits of Mind, taken from: Thinking like an engineer, Implications for the education system, Royal Academy of Engineering, 2014

"Engineers are at the heart and soul of making things happen – but they are often unrecognised, working in the background. Many engineered elements are out of sight, out of mind: the roads we drive on, the hospital we are in, the wires in the wall."

Senior director at an international health organisation

Moving forward, it is important to take stock of lessons learned on the role engineering can play in a pandemic, and better prepare for the future

This requires identifying where and why the full potential of engineers was not reached.
Globally, efforts have begun to distil learnings from the pandemic and look towards how to improve future preparedness. Given engineering's important role in pandemic resilience, it is vital that the engineering community be part of these efforts – reflecting on where engineers can contribute to both the on-going response to COVID-19, and in prevention and preparation for future pandemics. By looking at the challenges faced in the last two years of the COVID-19 response, this review will consider where engineering potential could have been further unlocked.

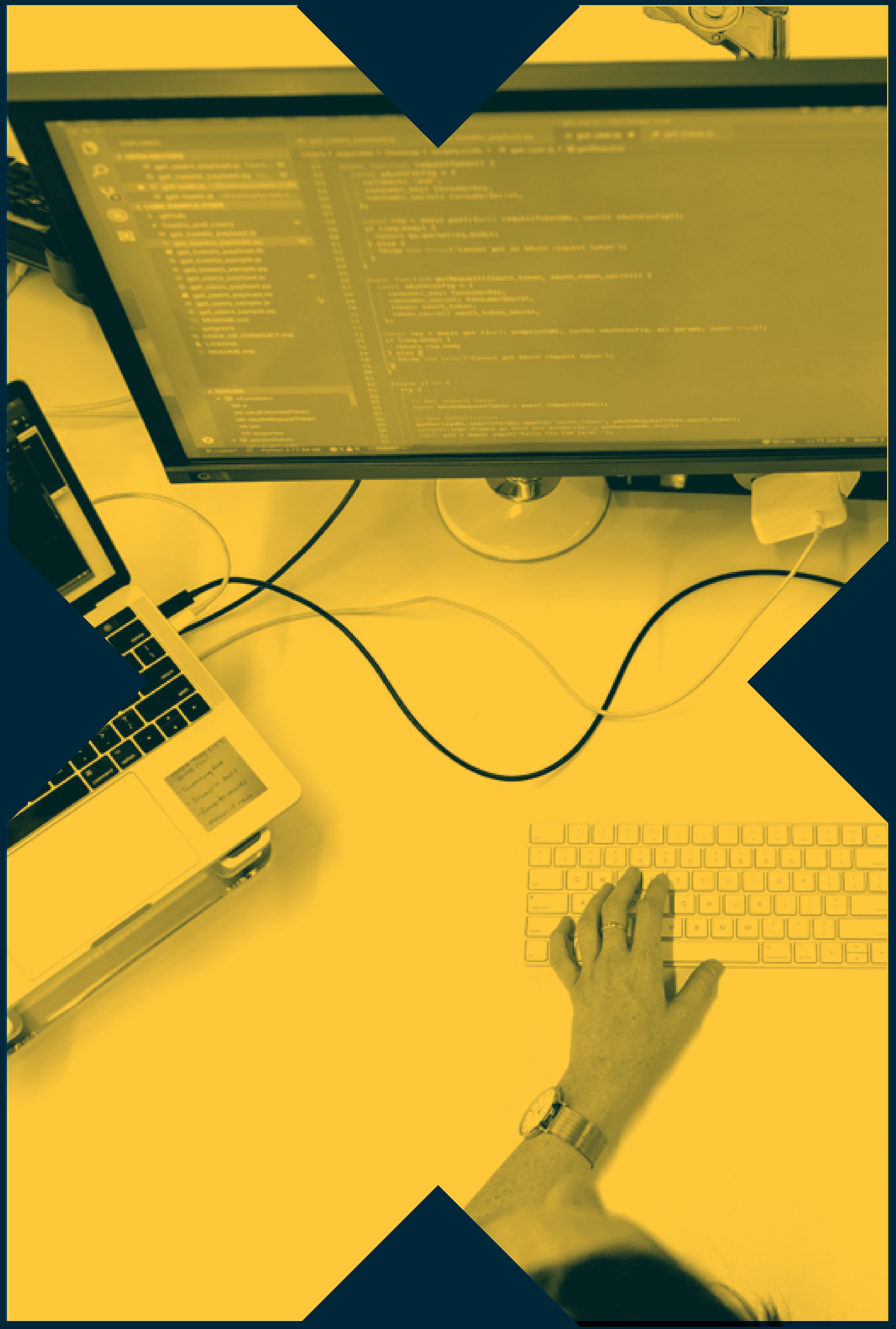
Action needs to be taken across stakeholders to unlock the full potential of engineering in the future.
Engineered solutions do not exist in a silo, and unlocking the full potential of engineering will require collaborations beyond the engineering community. Acknowledging this, the review culminates with calls to action for the engineering community, local and national governments, public health decision-makers, funders, and academia and research institutions to better leverage engineering skills and approaches into pandemic prevention, preparedness, and response.

"From the start of the pandemic, a large responsibility fell to engineers. Facilities were not designed to handle COVID-19 and, around the globe, engineers had to come together to tackle challenges. Everything had to be done in trying conditions: deliveries stopped, personpower was low, movement was restricted – but we had to get it done."

Lead of a vaccine manufacturing network

Chapter 2

Global review of engineering contributions to COVID-19 response and resilience



This review uncovered six critical challenges to combating COVID-19 in which engineering has made major contributions

1. Critical **data** to support pandemic prevention and response was often **unavailable or of poor quality**

2. The **rapid spread** of the virus required designing **novel health solutions** at **unprecedented speeds** and in **conditions of uncertainty**

3. Products and services needed to be **designed for different contexts and needs** – including disproportionately affected groups

4. Limited **production and manufacturing capabilities** challenged intervention scale-up, and geographic disparity led to inequitable access

5. **Supply chain and delivery** issues resulted in delays and inequitable access to essential items

6. **Society's underlying systems had to be stabilised** to support health and societal resilience

This review covers examples of engineering value in addressing these critical challenges, but also drivers of unrealised potential

PLAN

1

Critical data for prevention and response was **unavailable or of poor quality**

Leveraging big data and mobile data; conducting epidemiological and population monitoring, modelling, and contact tracing; and developing dashboards and data analysis

DESIGN AND DEVELOP

2

The rapid spread of the virus left limited time to **design novel health solutions**

Developing health innovations including in the design of PPE, diagnostics, vaccines, therapeutics, breathing aids, and digital health

3

Products and services needed to be designed for **different contexts and needs**

Designing custom products and services for diverse environments and user bases, such as customised PPE, or wastewater testing for low-resource settings

MANUFACTURE AND SCALE

4

Limited **production and manufacturing** constrained the scale-up of interventions

Developing, redirecting, and repurposing the capacity of production and manufacturing, as well as optimising production techniques

DELIVER

5

Supply chain and delivery issues resulted in delays and inequitable access

Optimising supply chains; innovations that facilitated the delivery of health products (like drones for last mile delivery or cold-chains); and building emergency construction

ENABLE

6

Society's underlying systems had to be stabilised to support societal resilience

Maintaining society's essential services (such as energy or water); adapting the built environment; and expanding connectivity and digital solutions for remote education or working

2.1

Driving value from data

THE CHALLENGE

Critical data to support pandemic prevention and response was often unavailable or of poor quality

COVID-19 created great uncertainty, and stakeholders at all levels needed reliable data points to make decisions.

Decision-makers needed to be able to gather data and incorporate it into dynamic learning to make robust decisions within a quickly changing environment. This ranged from data to understand the nature of the virus, its transmission, and potential waves of infection, to data needed to assess the trade-offs of different policy options. **These decisions had implications for both direct pandemic response, and broader societal resilience.**

However, significant challenges across the data 'value chain' meant decision-makers at all levels had limited access to quality data.

> **"During the pandemic, data became a part of our daily life: from the food industry, to civil engineering consortia, to driving medical innovations."**
>
> *Chair of a major international biomedical engineering association*

THE CHALLENGE

Challenges across the data value chain

COLLECTING

→ **Data availability** was low in many **core areas.** Many countries lacked up to date censuses, patient health records, or economic data. For example, WHO estimates two-thirds of deaths go unrecorded, with many L/MICs not recording deaths at all.[1] Along with a lack of testing data from many countries, this led to an inability to detect where the highest COVID-19 case burdens were.

→ **Data quality** was poor for many **key indicators.** For example, death statistics became controversial during COVID-19, but had long had reliability issues: in the US, pre-pandemic, it was estimated one in three death certificates had major errors, including cause of death.[2] Inconsistencies in COVID-19 death statistics were then exacerbated by varying definitions of who is counted as a COVID-19 fatality.[3]

MANAGING

→ **Secure storage and sharing** became a **pressing issue** as governments collected larger volumes of sensitive data on their populations (like health and location data), and as businesses and communities moved their operations online – increasing cyber security risks.[4] For example, a major data leak in Russia in 2020 released personal data of COVID-19 patients – including names, addresses, phone numbers, and their medical records – highlighting the risks of large scale collection of private data.[5]

→ **High volumes of data challenged weak data systems**. Many countries' data systems crashed as a result of not being designed for volume. For example, the UK lost 16,000 test results because they were operating in Excel – meaning that 50,000 potentially infectious people were missed by contact tracers.[6]

→ **Aggregation and integration was needed across diverse datasets**. Globally, there were challenges to pull together multiple disparate electronic health records from different institutional systems. This was exacerbated by inconsistent data governance and confidentiality policies.[7,8]

APPLYING

→ **Analysis and modelling** was **needed at speed.** The uncertainty called for greater application of predictive modelling to forecast pandemic trends and the impact of policies. In addition, the demand for real-time analysis grew – an ask that had never been made before of public health systems.[9]

→ **Data-enabled digital tools and processes were needed to tackle new problems**, such as how to track the contacts of those with COVID-19, or how to allocate scarce human and medical resources.

→ **Data communication, visualisation, and dissemination were needed at scale, and to ensure valid interpretation.** As data emerged, and the picture on COVID-19 changed, there was a need to keep people up to date and to tackle misinformation.

DECISION-MAKING

For example:

Policymakers in planning and executing international and national level responses

Clinicians in making hospital and individual-level decisions for their patients

Businesses and organisations in pivoting their ways of working

Communities and the general public in changing their behaviour to stay safe and adapt, based on latest developments

Sources: [1] In Low-Income Countries Fundamental Data Issues Remain for COVID-19 Response, Thematic Research Network on Data and Statistics, 2020 [2] One in 3 death certificates were wrong before coronavirus. It's about to get even worse., USA Today, 2020 [3] The World Health Organization advises that the deaths of victims with probable or confirmed cases be listed as due to COVID-19 "unless there is a clear alternative cause of death that cannot be related" to the disease. However, not all countries have agreed with this method, leading to a discrepancy in who is counted as a COVID-19 related fatality. For more information see: By How Much Are Countries Underreporting COVID-19 Cases and Deaths?, Council on Foreign Relations, 2021 [4] Solutions to COVID-19 data sharing, The Lancet Digital Health, 2020 [5] Personal data of thousands of COVID-19 patients leaked in Moscow, Human Rights Watch, 2020 [6] Covid: how Excel may have caused loss of 16,000 test results in England, The Guardian, 2020 [7] Privacy, security, and public health in a pandemic year, McKinsey & Co, 2020 [8] Why AI Failed to Live Up to Its Potential During the Pandemic, Harvard Business Review, 2022 [9] Expert stakeholder interviews

ENGINEERING'S CONTRIBUTION

Engineers played a critical role in collating, harmonizing, and analyzing critical data inputs for decision-making

Engineers tackled challenges across the data value chain.
Engineers played a crucial role in building the core datasets that reflected the state of society. This included planning data collection, stitching together disparate datasets, and building secure means to store and share large volumes of data. Data was aggregated to cover almost every angle of society during the pandemic, ranging from trade and business indicators, to travel and testing data, to procurement and supply chain volumes, and to social media metrics.

This allowed us to see, in near real-time, the effect the pandemic was having on the world.
One of the biggest comparisons made with the 1918 flu pandemic is that, in contrast, during the COVID-19 pandemic technology has allowed us to map the virus's spread, its mutation, and the effect it has had on communities and economies across the world.

Engineers built novel tools that translated this data into use.
Building on the datasets collected, engineers were able to use this data to build digital tools that tackled new issues raised by the pandemic. For example, software engineers built smartphone applications that linked testing, Bluetooth, and mobile data to alert users that they had been in contact with someone with COVID-19, and AI engineers built machine learning tools that could speed up vital processes and even be used to predict outcomes.

The importance of data has brought new attention from policymakers, and fast-tracked thinking and developments in this space.
The uncertainty created by COVID-19 showed the importance of having analytic capabilities. At the same time, it revealed severe existing challenges in our global data systems. This increased public and policy awareness of the importance of using data and investing in its improvement. In turn, the space has seen advancements. For example, modelling experts have ventured that epidemiological modelling progressed as much in the first 10 months of the pandemic as it had the previous six years.[1] For many countries, COVID-19 has been the first time policymakers built a feedback loop between their decisions and the data —and this approach is likely to stay.[2]

Sources: **[1] The Hard Lessons of Modeling the Coronavirus Pandemic, Quant Magazine, 2021 [2] The role of data in a world reshaped by COVID-19, Penn Today, 2020**

EXAMPLES OF ENGINEERING EXCELLENCE

Building secure data sharing

Working with data during a pandemic meant dealing with sensitive patient information and national datasets. This called for engineers to devise secure data sharing solutions.

- A new statistical analytics platform called **OpenSAFELY**[1] provides researchers with secure access to over 58 million UK patient records by separating the development of the analysis code from the actual data – meaning the data never leaves the National Health Service servers. This novel innovation was a collaboration between the University of Oxford's DataLab, the London School of Hygiene & Tropical Medicine, and several healthcare technology companies.[2]

Designing data aggregations, visualisations, and dashboards

As the pandemic spread, there was a rush to collate **available data into datasets, dashboards, and visualisations that were easy to use and as near real-time as possible –** not only for policymakers, but also to keep businesses and the public informed. For example, by January 2020 the John Hopkins University Centre for Systems Science and Engineering had already set up the **JHU interactive COVID dashboard**[3] which has since racked up a billion views.[4]

- Engineers not only built these tools from scratch, but also created **ready-to-use templates and modules** for others to set up dashboards without the need for coding. For example, cartography software company **Esri**[5] gave 5,000 organisations free licenses[6] to set up easily customisable dashboards for decision-making on COVID-19 response, maintaining business continuity, and reopening communities.

SPOTLIGHT

The Ugandan Ministry of Health leveraged data to ensure continuity of essential health services during pandemic disruptions.

In the summer of 2020, Ugandan health officials knew that maintaining essential health services would be a challenge. Strict pandemic restrictions, including curfews and restricted vehicle movement, created disruptions and health practitioners needed to be able to monitor these to see where support was most needed.

The Health Insights and Visualisations for Essential Services (HIVES) App was designed to support this.

With the support of the Rockefeller Foundation, UNICEF, and Dalberg Data Insights, the Ministry of Health (MoH) launched the HIVES App, which:

- pulls data from the District Health Information System to provide **over 150 health indicators as data insights and visualisations,**
- **tracks the quality of data** from the national health management information system, and
- sends **automated data emails and monthly reports** to district level officials and key health workers.

The app allows health workers to see trends and disruptions for many key programmes. This included HIV, tuberculosis, family planning, malaria, immunisation, and neonatal and maternal health.

Based on the trends, health workers can decide where to send scarce human resources, like midwives, or where to restock medical supplies. This was a particular need in rural areas where human and pharmaceutical resources were scarcer and spread over larger distances.[7]

The integration of the app into MoH's existing structures ensures its functionality and sustainability. Following a highly successful pilot, the app is currently being scaled to cover 40 districts.[8]

Sources: [1] OpenSAFELY, website. [2] Data science and AI in the age of COVID-19, The Alan Turing Institute, 2021 [3]] Johns Hopkins, Coronavirus Research Center, Global Map, website [4] Johns Hopkins Coronavirus Resource Center passes 1 billion views, John Hopkins, 2021 [5] Esri, COVID-19 overview, Accessed 2022 [6] The Rise of the Pandemic Dashboard, Bloomberg, 2021 [7] UNICEF, Using Data Innovation to Improve Health Outcomes in Uganda, 2021 . [8] Internal Dalberg Data Insights Resources

EXAMPLES OF ENGINEERING EXCELLENCE

Using predictive modelling

Models and data-driven computer simulations were used to predict trends and the impact of interventions, drawing on a range of 'Big Data' inputs. Although imperfect and subject to change, such forecasts have been invaluable to businesses, hospitals, cities, states, and nations in making decisions.

- **Early warning systems and detection:** Rockefeller Foundation set up the Pandemic Prevention Institute to provide early warnings from Big Data analysis to identify future pandemic threats.[1]
- **Estimating the true spread:** a predictive model by Imai et al used travel and imported case data to forecast the size of Wuhan's epidemic, suggesting cases were higher than official statistics and giving a crucial early warning to the international community.[2]
- **Predicting business impact:** a Sisense survey found small US businesses significantly increased their use of data analytics during the pandemic, including 45% using analytics to predict business outcomes in changing markets.[3]

Using AI techniques

In select cases, AI and machine learning techniques were successfully used to automate and improve processes and to make predictions based on the available data.

- **Accelerating vaccine rollout:** Pfizer accelerated its vaccine rollout via a machine learning Smart Data Query tool which reduced clinical trial data cleaning from 30 days to just 22 hours. The tool's creation was enabled by Pfizer's Breakthrough Change Accelerator – a novel 'incubation sandbox'[4] that invites collaborators to solve complex research challenges.[5] In the context of a global pandemic, accelerating the kick-off of vaccination by even a single day could have saved hundreds of lives.
- **Testing at border controls:** Greece deployed a reinforcement learning system nicknamed 'Eva' across all Greek borders to determine how to allocate limited testing resources. Based on information provided by travellers and testing results from previous travellers, Eva recommended who should be tested. Eva detected 1.85 times as many asymptomatic travellers as a random testing policy would have.[6]

Sources: [1] Rockefeller Foundation Pandemic Prevention Institute online re12sources and interviews with stakeholders. [2] Applications of predictive modelling early in the COVID-19 epidemic, The Lancet Digital Health, 2020 [3] State of BI & Analytics Report 2020, Sisense, 2020 **[4] How a Novel 'Incubation Sandbox' Helped Speed Up Data Analysis in Pfizer's COVID-19 Vaccine Trial, Pfizer, Accessed 2022 [5] Breakthrough Change Accelerator, Pfizer, Accessed 2022 [6] Efficient and targeted COVID-19 border testing via reinforcement learning, Hamsa et al, Nature, 2021**

EXAMPLES OF ENGINEERING EXCELLENCE

Pioneering contact tracing

Contact tracing tools were needed to inform those at risk and to allow policymakers to monitor spread and the effectiveness of interventions. Data and software engineers designed digital tools to enhance tracing and used triangulation from a range of data sources.

- At least 46 countries used Bluetooth apps to detect COVID-19 contacts.[1]
- Public transport tracing apps, such as those designed by FabLab mSafari, were used to track passengers.[2]
- South Korea used multiple data sources to triangulate movements, including cellular GPS data, credit card transactions, drug purchase records, and CCTV footage to make up its centralised contact tracing data constellation.[3]
- In addition, **smart data management lightened the workload for contact tracers.** Apps which allowed COVID-19 contacts to track their symptoms, such as those used in Vietnam, were used to limit the number of calls that contact tracers had to make.[3]

SPOTLIGHT

DRC used a range of sources to mitigate missing data and drive evidence-based policy

Data to inform policy in DRC was scarce. Not having had a census since 1984, DRC lacked baseline population data. However, there was still a need to drive evidence-based decision-making during the pandemic.

Local technology companies worked closely with the government to find innovative work arounds using geospatial and mobile data. A consortium led by Grid3 – a company providing georeferenced infrastructure and demographic data – have been working with the government to close this information gap by mapping settlements.[4] Since the onset of the pandemic, several technology partners[5] have collaborated with government and major mobile operators (including Africell, Orange and Vodacom) to use mobile data to map mobility patterns. These were used to see patterns in response to changes in confinement measures.[6]

Disseminating risk communication

Keeping the population abreast of new information became a key hurdle in the pandemic. Engineers supported by designing tools that could quickly disseminate new information.

- **The WHO Health Alert Chatbot**[7] operates through governments to provide updated COVID-19 information in an interactive way through WhatsApp and Facebook Messenger, in over 10 languages. By April 2020 the Chatbot had already reached 12 million people.[8]

> **"In the field of data, communication and translation are critical. There needs to be an intermediary layer between the engineers and the policy makers to understand the limitations, nuance, and uncertainty in the data."**
>
> *Director of data strategy at a major global health institution*

Sources: **[1] Why many countries failed at COVID contact-tracing – but some got it right, Nature, 2020 [2] Africa's digital solutions to tackle COVID-19, European Investment Bank. 2020 [3] Why many countries failed at COVID contact-tracing – but some got it right, Nature, 2020 [4] New dataset released for one of the most populous provinces in the Democratic Republic of the Congo, Grid3, 2020** [5] Other key partners included PATH, Flowminer, GSMA, ANICiis, Kinshasa Digital, Texaf Digital Campus, Fluxvision and DRC's telecommunications regulator l'Autorité de Régulation de la Poste et des Télécommunications du Congo. **[6] Using mobile big data to help inform the fight against COVID-19 in the Democratic Republic of Congo, GSMA, 2020 [7] WHO Chatbot avaible at:** https://www.whatsapp.com/coronavirus/who **[8] WHO launches a chatbot on Facebook Messenger to combat COVID-19 misinformation, WHO, 2020**

UNLOCKING ENGINEERING POTENTIAL FURTHER

However, despite progress, the full potential of engineers was hampered by insufficient investment into underlying systems, capacity, and preparedness

Getting the most from data requires a strong foundation.
Although engineers are often able to find workarounds to poor data systems, such as using an estimate from a model to make up for insufficient data, these cannot replace the investment needed to strengthen underlying data systems. For example, countries without digital identification systems, such as Liberia and Ethiopia, were unable to take advantage of digital, data-enabled technologies used elsewhere.[1] Even in HICs, weak and inefficient data systems meant there were delays in bringing the full value of engineering. For example, antiquated health database systems in Australia, and certain US states, like Hawaii and Washington, meant health departments had to conduct manual entries to record cases.[2] Time taken to bolster these systems in the middle of a crisis was time that engineers could have used elsewhere to create value.

For sustainability, data systems and tools need to be maintained by dedicated, local engineers.
Although the pandemic saw a great deal of 'volunteerism' of data professionals — such as Amazon and Apple employees working on flu and COVID-19 tracking sites[3] — relying on volunteers does not lead to sustainable solutions nor future preparedness. In addition, volunteer engineers lack the experience to work on certain issues, such as optimising for data-scarce environments or lower resourced systems.[4] A lack of data professionals in L/MICs is a significant part of this puzzle, with brain-drain and skills gaps in newer disciplines — such as data engineering — leading to a lack of in-country engineering talent to build and maintain resilient systems.[5]

"Almost every data system I've seen created has been done by an international partner or NGO — it is not sustainable to build these systems and leave. We need to invest in in-country data engineers."

Acting Chief of Staff of a COVID-19 medical products delivery partnership

Sources: [1] Africa's digital solutions to tackle COVID-19, European Investment Bank, 2020 [2] Why many countries failed at COVID contact-tracing — but some got it right, Nature, 2020 [3] TECH How volunteers from tech companies like Amazon, Apple and Google built a coronavirus-tracking site in six days, CNBC, 2020 [4] Expert interviews [5] Workforce Wanted: Data Talent for Social Impact, Data.org, 2022

UNLOCKING ENGINEERING POTENTIAL FURTHER

Better communication was needed between engineers and other decision makers to ensure data was not misused

Data does not always tell a clear story or point to a single recommendation. Engineers need to take on a role in educating policymakers on how to interpret data and understand its limitations.[1] This is clearest in areas such as predictive modelling, where assumptions, imperfect data inputs, and errors mean care is needed in interpretation and application. Unlike predictive models like weather forecasts, there are a great deal more unpredictable variables at play in pandemic models – notably human behaviour. For example, the University of Illinois deployed a sophisticated model considering population movement and aerosol spread to determine when it would be safe to reopen. However, the model did not account for the fact that students might break social distancing rules – a factor which led to many more students getting infected than predicted.[2] This brings lessons not only for how to improve epidemiological modelling to consider broader interactions in the external environment, understanding of behaviour, and rule following, but also to ensure that decision-makers understand the limitations of the data tools they use.

Poor data can lead to discriminatory decisions. Exclusion of certain groups (sampling bias) in datasets can lead to skewed decision-making. For example, a lack of data on gender and ethnicity hampered socioeconomic research at the start of the pandemic. Similarly, where there was a reliance on mobile data, digital divides meant some users remained 'invisible'.[3] In AI applications, algorithms trained on biased data can disadvantage certain subpopulations. If left unchecked, these biases can lead to a further reinforcement of inequalities – such as underreported groups not being targeted for care. To combat this in the future, University Hospitals Birmingham NHS Foundation Trust will lead STANDING Together – an international consensus process working to ensure AI datasets and systems account for diversity and inclusion across demographic groups.[4]

Data privacy has also been a concern. For example, in South Korea, although contact tracing methods were highly effective, there were significant concerns raised about the level of personal data being shared about peoples' movements.[5] Not only does this raise ethical considerations, but it can also lead to lower user uptake, as studies have found that privacy concerns, mistrust, and fear of stigmatisation have been barriers to uptake. This then limits the potential that contact tracing can have.[6]

Sources: **[1]** Applications of predictive modelling early in the COVID-19 epidemic, Lancet Digital Health, 2020 **[2]** The Hard Lessons of Modeling the Coronavirus Pandemic, Quant Magazine, 2021 **[3] Data science and AI in the age of COVID-19 – report, Alan Turing Institute, 2020 [4] New Artificial Intelligence projects funded to tackle health inequalities, NHS, 2021 [5] South Korea is reporting intimate details of COVID-19 cases: has it helped?, Nature, 2020 [6] Facilitators and barriers to engagement with contact tracing during infectious disease: A rapid review of the evidence, Megnin-Viggars et al, 2020**

CASE STUDY

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

THE INNOVATION

- Empowering communities to report on animal and human disease outbreaks via the design and use of apps and digital hotlines.

IMPACT AT A GLANCE

- Widespread adoption of community-based reporting.
- Hundreds of human and animal disease outbreaks successfully reported and contained.
- Rapid adaption for COVID-19 reporting – representing 90% of detected cases in Cambodia.

ENABLING FACTORS

- Built collaborative models for innovation and partnership.
- Leveraged local engineering talent.
- Ensured buy-in and sustainability through a community-based approach.
- Applied user-centric design.

CHALLENGES

- Lack of integration of 'One health' approach in broader pandemic prevention
- Limited existing interface between public health, animal health and local technologists for problem solving.

CONTEXT AND NEED

Zoonotic disease outbreaks are not new.

Recognising that up to 75% of infectious diseases have arisen from animals (zoonotic),[1] a 'One Health' approach that considers the health of people, animals and ecosystems is essential for pandemic prevention. Countries with longer histories of zoonotic epidemics (such as the avian flu outbreak in Thailand in 2004) and closer contact between animals and humans had been investing into prevention prior to the current pandemic.

ENGINEERING CONTRIBUTION AND IMPACT

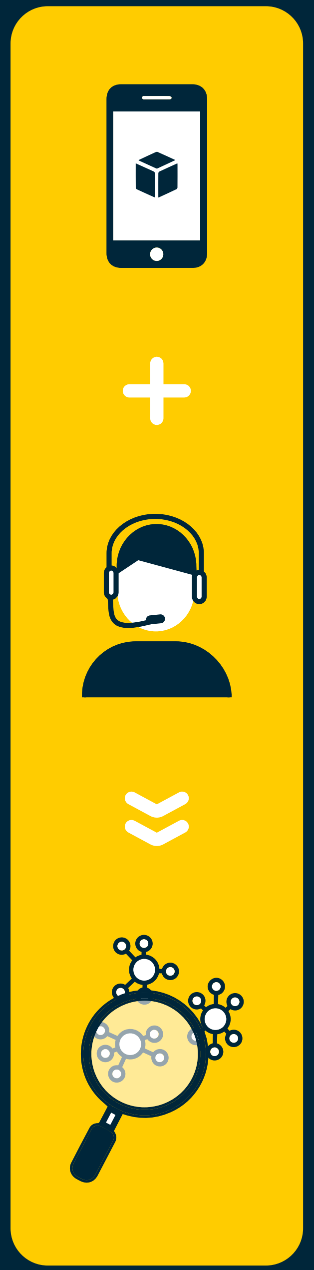
To empower communities to design preventative solutions, Ending Pandemics created unique spaces for intensive collaboration.

The pandemic prevention focused non-profit Ending Pandemics run 'EpiHacks' – multi-day epidemiology 'hackathons' bringing together local technologists and public health and animal health practitioners to create, improve, or adapt disease monitoring systems. EpiHacks are often the first time these stakeholders have come together, giving them the opportunity to collectively engage in understanding and solving the problem, drawing on their different skills and viewpoints.

Sources: [1] Preventing the next pandemic - Zoonotic diseases and how to break the chain of transmission, UNEP, 2020 p

CASE STUDY

These sessions have led to surveillance tools that have been widely adopted with high impact:



In a 2015 EpiHack in **Thailand** the **PODD App** was set up. **This mobile application** can be used by volunteers to report animal disease outbreaks. The app has been taken up by 400 local governments and 20,000 volunteers. The impact from the reporting has been significant: **73% of confirmed poultry outbreaks have been contained in their village of origin,** and the remaining 27% to neighbouring villages. The reporting enabled by the PODD App is also estimated to have **saved the local economy $4 million USD** in facilitating a swift response to foot-and-mouth disease outbreaks.

In **Cambodia** a 2016 EpiHack resulted in **the 115 Digital Hotline** – an **automated interactive voice response system** where community members can dial in and report outbreaks. The 115 Hotline also serves a dual role by **disseminating public health advice** to its callers. From the outset, the hotline was quick to identify outbreaks of concern, receiving **~500 reports** a day, of which ~20 needed follow-up by a case manager. As a result of this intervention, **hundreds of disease outbreaks were contained,** and there was a marked increase in the timeliness of reporting – which is vital to ensuring successful containment.

Engaging local technologists and experts ensured relevance and sustainability.

Leveraging local talent and expertise from idea inception to prototype development ensured solutions met the communities' needs, and that cultural and social considerations were accounted for. In addition, the tools were designed to work within the existing infrastructures, systems, and environmental constraints.

Designing for useability was key.

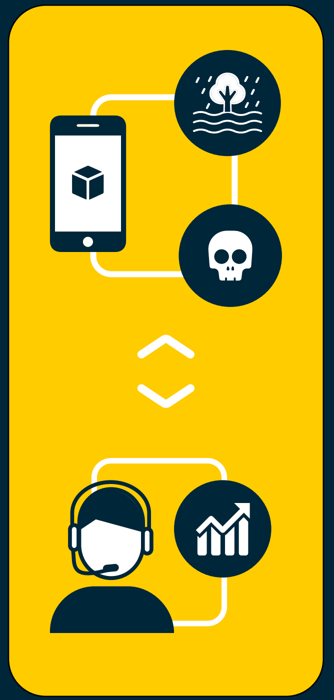
In Cambodia neither digital literacy nor phone credit are needed to call the hotline and report an observation. In Thailand 89% of volunteer users can navigate the app effectively after a basic training, even though 50% had never owned a mobile phone.

Empowering communities was a key aim, and a foundation of the programmes' successes.

Community based surveillance depends on local ownership and buy-in, and local engagement and awareness raising is integral to the EpiHack process.

Communities quickly pivoted these tools to respond to other crises – including the COVID-19 pandemic.

Leveraging the established link between public health authorities and communities, the surveillance technology teams were able to quickly adapt the tools to serve other purposes. For example:



PODD in **Thailand** has been adapted to also capture community reporting on environmental health threats, counterfeit drug sales, and other hazards. For example, in 2017 PODD was used to alert at-risk communities of flooding.

The **Cambodia 115 Hotline** was adapted to be a contact tracing tool for COVID-19**,** scaling up from ~500 to **~18,000 reports a day** during the pandemic. The automated interactive system saved contact tracers' time in identifying cases and facilitated widespread dissemination of health advice and risk communications. The hotline ended up being Cambodia's primary contact tracing tool and recorded **90% of Cambodia's** confirmed cases.

The programmes' success shows the importance of having community surveillance systems in place, and that lessons can be learned from countries with longer histories of successfully managing zoonotic disease outbreaks. In addition, it illustrates the power of establishing flexible systems that can be quickly pivoted to respond to new crises.

2.2

Racing the virus

THE CHALLENGE

The rapid spread of COVID-19 required designing novel health solutions at unprecedented speeds and in conditions of uncertainty

Steps to fight a communicable disease:

1. PREVENT
2. DETECT
3. CONTAIN
4. TREAT
5. PREVENT

As COVID-19 spread rapidly around the globe, innovators worldwide raced to develop health tools to fight it.
Just three months from the first confirmed death in China in 2020, there were already over one million confirmed cases worldwide and over 75,000 recorded deaths.[1] The virus was spreading rapidly, and frontline health solutions were urgently needed to save lives. These included solutions to detect the virus, to stop its spread, treat its symptoms, and eradicate the disease. Health workers also needed tools to manage essential health systems, which were increasingly overburdened as the pandemic progressed.

There was no time to waste, meaning health innovators had to work as the crisis unfolded and under conditions of great uncertainty.
At the outset, little was known about how the virus was transmitted, its risk factors, fatality rate, or the speed of its mutation. However, there was no time to wait for research to be concluded. The urgency for health tools and services called for scientists, health practitioners, entrepreneurs, and engineers to fast-track R&D and design solutions in tandem with emerging evidence – iterating designs and guidelines as evidence was being updated.

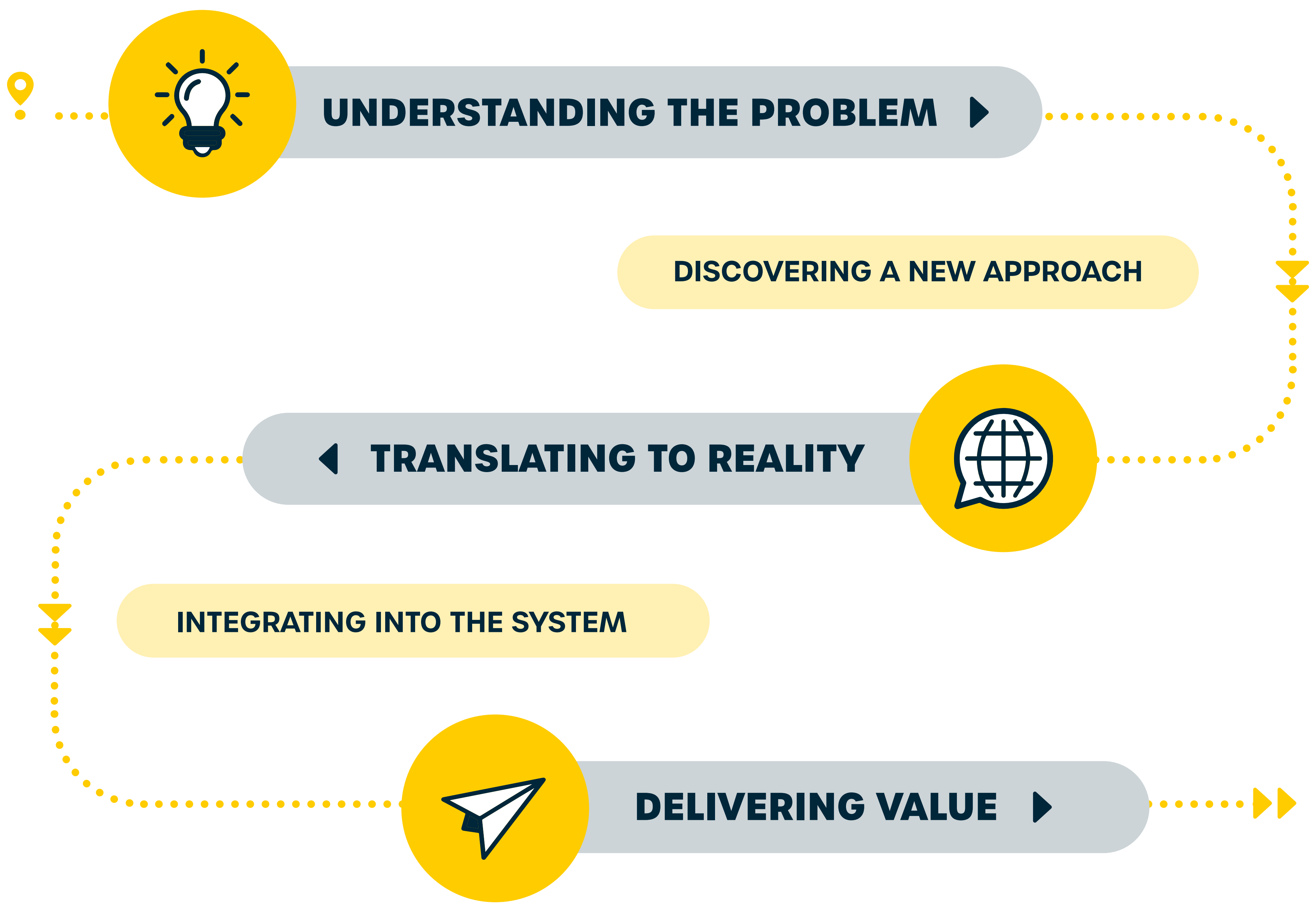
At the same time, these new tools and services needed to be rapidly integrated.
Innovation in this space was needed not only for new products and services, but also in facilitating their integration into health systems. In other words, mechanisms had to be built for new products to be rapidly approved, produced at scale, and integrated efficiently into already overburdened health systems – all while maintaining the quality needed for patient and health worker safety. This meant needing to carefully balance speed and risk, often requiring new ways of working and evidence building.[2]

Sources: [1] How coronavirus spread across the globe - visualised, The Guardian, 2020] [2] Innovation in a Crisis - Online Event Series, Royal Academy of Engineering, 2021

ENGINEERING'S CONTRIBUTION

Engineers swiftly turned new discoveries into life-saving tools and services; many of which will bring lasting impact

A conceptualization of the process of innovation



In this urgent context, engineers moved ideas towards real-world application – collaborating with clinicians and scientists to do so.
As scientists and medical professionals learned more about the nature of the virus, engineers brought practical, collaborative, and iterative approaches to designing life-saving medical products and services that could quickly be put into production and brought to market. Multi-functional teams that integrated engineers early expedited these processes further, as did working with regulators to ensure products could be quickly and safely brought to patients.

Several health innovations created in that time were disruptive and changed the status quo.
From lab in a box technologies that allow testing for a range of diseases in remote locations,[1] to transformations made in digitising healthcare, to new vaccine platforms — health innovations created during the pandemic have now changed our perception of what is possible and how fast we can do it.

These innovations built on years of previous R&D.
Record speeds reached during the pandemic were enabled by years of previous research on related viruses and on faster ways to manufacture vaccines.[2] Similarly, decades of honing techniques for rapid prototyping allowed engineers to quickly reverse-engineer breathing aids.[3] These successes highlighted the importance of continued investment into R&D before a pandemic hits.

Working in the context of a crisis enhanced the appetite to take risks and embrace new ideas.
Funders were willing to fund experimentation and embrace the risk of failure, giving engineers the room to think outside the box. This included 'moonshot' and challenge funds, which encouraged disruptive innovations. Local entrepreneurs were often at the forefront of driving innovation, with many startups forming to address new challenges and fill gaps in their local markets.[4] In addition, actors across engineering, health, industry, and policymaking were willing to trial new ways of doing things. For example, a network of robotics engineers across Colombia, Chile, Brazil, and Argentina have observed a growing willingness from healthcare workers to incorporate robotics into their work.[5] Similarly, accelerations towards digital health have been widely accepted and quickly integrated. These disruptive innovations are here to stay.

Sources: [1] For example, the Abbot ID device: **Detect COVID-19 in as Little as 5 Minutes, Abbot, 2020** **[2] The lightening fast quest for COVID vaccines, and what it means for other diseases, Nature, 2020** [3] For example, see UCL-Ventura CPAP case study at the end of the section. **[4] Entrepreneurship during a pandemic, Storr et al, 2021** [5] Interview with project manager of COVIBOT project. Find out more here: **https://sites.google.com/view/biomtlab/robots/covibot**

“We cannot fully design against a pandemic, but we can find ways to respond very quickly.”

Director of data strategy at a major global health institution

EXAMPLES OF ENGINEERING EXCELLENCE

Developing vaccines

During the pandemic, a record time was set for vaccine development: moving from viral sampling to approval went from four years to just under a year. Integrated teams of scientists and bioprocess engineers enabled this speed.

- In the multifunctional and multidisciplinary teams used in the development of the AstraZeneca vaccine, engineers played a pivotal role in the process of moving rapidly from a new vaccine technology to the development of a practical, robust, and scalable product.[1] *(See more on vaccine manufacturing in Section 2.4)*

Building breathing aids

As the global shortage of breathing aids and ventilators became a concern, engineers pivoted from their day jobs to design breathing aids that could be locally produced at scale, often in repurposed factories. Although most worked from existing designs, engineers also added functionality based on clinical needs.

- In India, a team of robotics engineers adapted an open-source ventilator design from MIT for the Indian market, collaborating closely with expert clinicians and entrepreneurs.[2,3]

Improving diagnostics

The pandemic called for rapid innovation in diagnostics. While maintaining test accuracy, engineers spearheaded optimisations in speed, usability, and cost.

- **Speed:** just 3 months into the pandemic, Oxford University's Engineering Science Department developed the first antigen rapid tests.[4] These brought result times down to just minutes, removed the need for a lab to process results, and opened up the possibility of self-testing.
- **Usability:** several teams of engineers innovated to make tests less invasive – including saliva tests,[5] breath tests,[6] and even wearable tests.[7]
- **Lowering cost:** engineers designed electrochemical tests that used graphite to lower material costs.[8]

Automating sanitisation

Mechanical and electrical engineers designed automated antiviral cleaning devices using UV-C or hydrogen peroxide vapour, offering thorough disinfection, reducing exposure of staff, and freeing up valuable time of health workers.

- UVD robots designed in Denmark can autonomously disinfect hospital rooms in 10 minutes and kill 99.9% of bacteria.[9]
- UV-C light devices to disinfect public escalators were designed by South Korean innovators and have since been adopted by over 50 countries, including the UK, US, China, Japan, and Saudi Arabia.[10]

Delivering digital health management

As waiting times soared in many countries, efficiency became paramount to managing scarce resources and time. Software and data engineers brought many automated management solutions to support health workers in this task.

- In the UK, the NHS has been exploring ways to use **AI software to dynamically schedule hospital appointments.** The aim is to improve efficiency and minimise the strain on the staff who have been manually managing overburdened systems since the pandemic.[11,12]
- In the US, Definitive Healthcare and Esri used a GSI type system to **track the quantity and location** of ICU beds to flag where critical patients could be placed.[13]

Sources: **[1]** Interviews with stakeholders involved in the Oxford- Astrazeneca design **[2]** **COVID-19: Collaboration is the engine of global science – especially for developing countries, World Economic Forum, 2020** **[3]** **Coronavirus: India's race to build a low-cost ventilator to save Covid-19 patients, BBC, 2020** **[4]** **Oxford scientists develop rapid testing technology for COVID-19, University of Oxford, 2020** **[5]** Technologies include the saliva based tests designed by **TestEd** **[6]** On-going efforts to design breath-based tests include those by **Ghent university** **[7]** Wearable test technologies include those by the **Wyss Institute for Biologically Inspired Engineering**, who have used CRISPR-Based SHERLOCK technologies in standard facemasks, and **John Hopkins** development of COVID-19 sensors using label-free optical detection, machine learning and nanomanufacturing which could enable wearable tests in the future. **[8]** **Penn Engineers Create Faster and Cheaper COVID-19 Testing With Pencil Lead, Penn Engineering Today, 2021** **[9]** **UVD Robots Autonomous Disinfection, UVD Robots, 2022** **[10]** **The inventor inspired by wanting to keep his daughter safe, BBC, 2020** **[11]** **Using AI to improve back office efficiency in the NHS, NHSX, 2022** **[12]** **AI for healthcare, Imperial College, 2020** **[13]** **Data Platform Tracks Hospital Bed Capacity During COVID-19 Outbreak, Health Analytics, 2020**

EXAMPLES OF ENGINEERING EXCELLENCE

Designing digital health tools

Digital tools designed for those working on the frontline have been used to provide the latest information and support on diagnosis and case management.

- In Nigeria, a free **community health worker app** was launched by the health technology company Instrat. By March 2020 it already had 20,000 users. Accessibility was key to its design: the app was made available in local languages, and Instrat partnered with internet satellite providers to enable connectivity in remote locations.[1]

Expanding telemedicine

Telemedicine brought enormous impact in reducing the risk of health workers becoming points of infection and in improving efficiency during surges in demand for appointments.

- In Australia, a telemedicine app called Coviu allowed doctors to give remote consultations to quarantined people. By mid-April 2020, it was already supporting 25,000 consultations a day.[2,3]

- Increased adoption of telemedicine has sped up pre-pandemic trends, bringing impact beyond the pandemic.

- In another case in Australia, the use of telemedicine was found to be associated with a 40% reduction in mortalities in elderly care facilities and 25% economic savings during a CSIRO telemedicine trial.[4]

SPOTLIGHT

In Burkina Faso, health centres rapidly adapted digital healthcare systems to arm community health workers with the tools needed to fight COVID-19

In Burkina Faso, community health workers were equipped with digital health tools before the pandemic...

Prior to COVID-19, ~65% of Burkina Faso's Primary Health Centres (PHCs) were using CommCare-based[5] apps to support their work in managing childhood illness. CommCare is a no-code, open-source app by digital health company Dimagi which supports 10% of frontline community health workers globally.

... which were quickly updated with COVID-19 modules to keep health workers up to date and in control of their case management.

With the support of Terre des Hommes, the Ministry of Health was able to adapt its existing app to include modules on COVID-19 and automatically roll them out to 1,200 PHCs.

The new COVID-19 modules allowed community health workers to:

- conduct screening and triage of symptoms,
- send automated SMS to health authorities to follow up on testing and case management,
- distribute tools for counselling and community sensitisation,
- disseminate e-learning content and the latest guidance, and
- integrate data collection and aggregated dashboards into the National Health system.

The speed and effectiveness with which Burkina Faso was able to adapt their digital health system highlights **the importance of having well-distributed, foundational systems that can be quickly adapted to absorb new innovations in a time of crisis.**[6]

Sources: **[1] Instrat Website, Accessed 2022 [2] Coviu 2 years on, Coviu, 2022** [3] How Telehealth company Coviu used the pandemic to boost their business, Australian Institute of Company Directors, 2020 [4] Health technology report, ATSE, 2020 [5] https://www.dimagi.com/commcare/ [6] Commcare In Burkina Faso: How An Existing App At Scale Was Adapted For COVID-19, Exemplars in Global Health, 2021

UNLOCKING ENGINEERING POTENTIAL FURTHER

Despite delivering this value, medical engineering contributions could have been even stronger with greater platforms for collaboration...

The pandemic saw an explosion of R&D, but a lack of platforms to share, collaborate with, and learn from others meant the full potential of that undertaking was not always reached.
The complex and global nature of the pandemic meant no single organisation, discipline, or country alone could have the full answer. Engineers, clinicians, and policymakers recognised this, but often lacked the tools to coordinate and enable collaborative, international efforts. For example, funders noted that finding funding avenues and creating partnerships were easier in regions where collaborative bodies already existed at the regional level, such as with the Africa Centre for Disease Control and Prevention (Africa CDC), which coordinated responses across African Union member states. On the contrary, where collaborative networks and relationships were less formalised or operated at the country rather than regional level, these were more challenging.[1]

The impact of open science initiatives was not fully realised.
COVID-19 accelerated the push toward open science. By January 2020, 117 organisations had pledged to share their findings, and by April many large institutions had signed the 'Open COVID pledge' to make their IP freely available.[2] However, in many instances, either the infrastructure and standards were not in place to facilitate such a shift, or stakeholders were insufficiently familiar with open science principles and practices to apply them. Funders noted, for example, that a lack of experience in data sharing policies led to data sharing hesitancy – limiting the potential for research collaboration.[1] It was also noted that greater emphasis on facilitating uptake was needed to accompany open science initiatives. This included working to ensure published data, findings, and designs were usable by third parties,[1,2] as well as that knowledge transfer was accompanied by active collaboration and support.[1,3] Finally, the explosion of open science also came with a need to improve science communication and mitigate risks in preprints (non-peer reviewed research) being misused.[4]

Many research efforts were duplicative, fragmented or too small-scale to provide evidence.
This was driven by a lack of coordination between researchers and funders, as well as many small-scale studies and prototypes lacking sufficient funding and scale to be properly assessed. This included clinical studies with insufficient statistical power to be conclusive,[5] and led to what has been called 'research waste at unprecedented scale'.[6] For example, in one database, 40% of trials were enlisting under 100 patients – a sample size generally considered too small to be useful in evidence generation.[6]

Dispersed data did not always translate into consolidated learning.
Until organisations stepped in to collate 'living reviews' and research trackers,[7,8] the explosion of projects meant many findings went unnoticed and unused. Lack of oversight limited the full potential engineers could have had because of missed opportunities to consolidate, collaborate, and build on each other's learnings.

Sources: [1] Funding and undertaking research during the first year of the COVID-19 pandemic: Lessons for Funders, UKCDR and GLOPID-R, 2021 [2] Why open science is critical to combatting COVID-19, OECD, 2020 [3] Expert interviews [4] Preprints in times of COVID19: the time is ripe for agreeing on terminology and good practices, BMC Medical Ethics, 2021 [5] A Power Boost for COVID-19 Clinical Trials, Hopkins Bloomberg Public Health, 2020 [6] How COVID broke the evidence pipeline, Nature, 2021 [7] COVID research tracker, UKCDR [8] Living Mapping Review, UKCDR

UNLOCKING ENGINEERING POTENTIAL FURTHER

...and with better processes to rapidly integrate innovations into health systems

The speed at which new health tools and services had to be adopted shone a light onto challenges in global health systems.

A systems approach was needed.
Medical innovations are only valuable if effectively adopted by the systems they aim to serve. This calls for engineers to take a 'true systems approach' considering not only the technical solutions, but also their alignment with processes, people, policy, and capacity[1]— and how these interact during a crisis. The innovations with the greatest impact at speed were those that were able to plug into existing, flexible systems — such as adapting CommCare apps to have COVID-19 modules. However, this was not universally applied. For example, despite wide-spread digital health tools in many countries, several countries attempted to design new tools from scratch rather than use what could be adapted within existing systems.[2]

Fragmentation of the global regulatory environment caused delays.[3]
Regulatory processes and technical specifications vary significantly between countries, creating barriers for innovations to be rapidly dispersed internationally. For example, delays in passing Emergency Use Authorisations for testing in the US at the outset of the pandemic have been attributed to higher caseloads — at a time where, by comparison, China was already running 20,000 tests a day.[4] There were also delays for comparably less novel health products. In the EU, complex regulatory processes[5] for hydro-alcoholic solutions slowed the increase in production of sanitisers.[6] During a pandemic, delays like these can cost lives.

Sources: **[1] Engineering better care, Royal Academy of Engineering, 2017** [2] Expert interviews **[3] Lessons and risks of medical device deployment in a global pandemic, The Lancet, Shipley et al, 2021 [4] The 4 Key Reasons the U.S. Is So Beind on Coronavirus Testing, The Atlantic, 2020 [5] Removing administrative barriers, improving regulatory delivery, OECD, 2020** [6] Despite hydro-alcoholic solutions (HAS) being simple to produce and based on commonly available ingredients, there were challenges in regulations. In certain countries in Europe, this resulted from a combination of application of the EU regulation on biocides, and a gap in some countries' pharmacopeia (not having an official formula for hydro-alcoholic solution). At the EU level, a general approval for ethanol as a biocide is in preparation (under the biocide directive) but has not been completed yet. This meant preparing 'generic' (not specifically approved) HAS fell under national regulations.

> **"What does not work is the Global North saying, 'here's our tech and some money'. What we need to do is actually work with engineers in other countries."**
>
> *Sustainable manufacturing lead at a major global health institution*

CASE STUDY

University College London and Mercedes AMG teamed up to develop and rapidly produce CPAP breathing aids and support global tech transfer

THE INNOVATION

- Designing and locally producing a continuous positive airway pressure (CPAP) device to support patients' breathing.

IMPACT AT A GLANCE

- Breathing aid prototype developed in under 100 hours.
- Regulatory approval in just 10 days.
- 10,000 breathing aids supplied in the UK.
- Over 2,000 design downloads.
- 25 consortia globally rolling out local production.

ENABLING FACTORS

- Strong partnership model across engineering and health practitioners.
- Applying agile engineering and manufacturing approaches to facilitate speed.
- Global collaboration and knowledge sharing.

CHALLENGES

- Lack of existing platforms to support technology transfer, collaboration, or capacity building.
- Delays caused by fragmented global regulation.
- Supply chain disruptions and raw material shortages.

CONTEXT AND NEED

As cases rose, so did the global concern over the supply of breathing aids.

As the **UK** moved towards its first peak, public health officials raised the alarm on the critical demand for breathing aids. The UK, like many countries around the world, had limited local production of breathing aids and because of surges in global demand was at risk of a national shortage.

ENGINEERING CONTRIBUTION AND IMPACT

Engineers across the country teamed up to tackle this issue.

One such team was the UCL Institute of Healthcare Engineering, who brought their established academic and clinical collaborations and joined forces with the rapid prototyping and mechanical manufacturing expertise of Mercedes AMG HPP.

Speed was at the core of the project.

Reverse engineering from an off-patent device (the Respironics WhisperFlow), the UCL and Mercedes teams were able to design a prototype in just 100 hours. Mercedes set about repurposing their factory and applied their mentality of speed from Formula 1 by setting a target of 24 hours to have a commercial production line – a target they missed, but only by two hours. Repurposing was made challenging due to the need for safe distancing of staff – a problem they solved in part with the use of increased robotics for automation.

CASE STUDY

Working closely with the UK Medicines and Healthcare products Regulatory Agency (MHRA), regulatory approval was also expedited to just 10 days. Ramping production to 1,000 devices a day, UCL-Ventura were able to provide 10,000 CPAP devices in the UK.

These devices quickly created impact.

CPAP devices prevent some patients needing invasive medical ventilation – contributing to patient recovery and reducing strain on ventilator capacity. 83 observational studies worldwide indicated two-thirds of COVID-19 patients receiving CPAP did not subsequently require invasive ventilation.[1]

The team did not stop at a national response.

Seeking to share the innovation globally, the team made its designs open-source. At first, the team sought an existing platform to facilitate technology transfer. However, after not finding one, they created a hub themselves to share the designs, comprehensive instructions, and give on going technical and regulatory support to institutions interested in locally producing. Overall, the blueprints were downloaded over 2,000 times across 105 countries, and 25 consortia are now manufacturing devices locally or assembling locally from UK components made available at cost.

This technology transfer process fostered international collaboration and spurred further innovation.

For example, the SmartCityTech team in **Paraguay** went on to support other countries in the region with the technology transfer and local production process. In **Pakistan** Alsons Group not only switched from manufacturing high precision parts to creating the CPAP devices, but went on to innovate further. Based on its learnings, they have since created their own design for an ICU ventilator which is currently undergoing clinical trials. Not only is this the first full medical device that the company will have designed, but it will also be one of the first ICU ventilators to be designed and manufactured in Pakistan.

However, fragmentation in global regulations slowed international uptake.

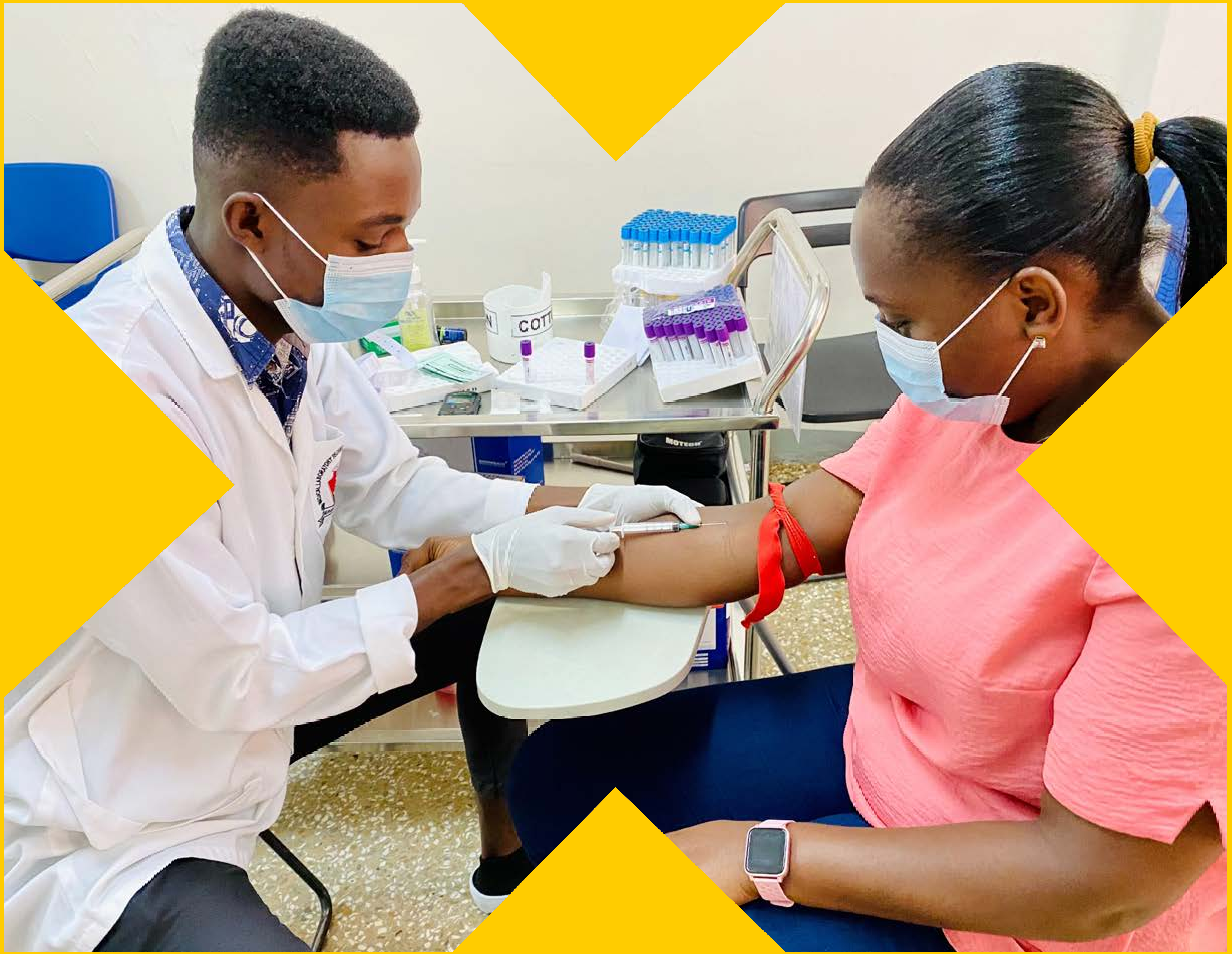
Although regulatory approval was successfully expedited in the UK, other countries faced challenges in pushing through the same speed for approvals for emergency use. For example, in Paraguay, there were no existing in-country regulations for the construction of medical devices, and so the SmartCityTech team, UCL and UK MHRA supported the government to write these. MHRA has also provided guidance to other in-country regulators in an effort to streamline these processes.

International deployment of the UCL-Ventura CPAPs (both local manufacture and direct supply)

Numbered sources: [1] UCL-Ventura CPAP breathing aid: interdisciplinary working to solve a COVID-19 challenge at pace, UCL, April 2022. General case study sources: Coronavirus: inside story of how Mercedes F1 and academics fast-tracked life saving breathing aid, The Conversation, 2020; The Lancet Global Health, Supplementary Appendix, 2021; Stakeholder interviews with key team members from UCL, Mercedes, Smart City Tech (Paraguay), and Alsons (Pakistan).

2.3

Designing for equal access



THE CHALLENGE

Given COVID-19's widespread impact, there was a need to design products and services for a broad range of users and contexts, including groups disproportionately affected by the pandemic

By definition, pandemics affect a broad swathe of people.
COVID-19's expansive reach around the globe meant the needs of diverse communities – spanning ethnic and racial groups, rural and urban communities, and across ages, genders, abilities, and sexual orientations –had to be considered when designing and executing a pandemic response.

COVID-19 did not affect everyone equally – and it was critical for designers to consider the diversity of their userbase and aim to bridge gaps in social inequality.
COVID-19 disproportionately affected certain groups of society – often because of structural inequities.

Some examples included:

Women: globally, women make up the majority of frontline public health workers, meaning they faced increased exposure to COVID-19. In the Americas, for example, women made up 72% of COVID-19 cases among healthcare workers.[1] Women also perform 75% of unpaid care work, a burden which increased as a result of COVID-19 lockdowns.[2] Finally, women were also overrepresented in the hardest hit sectors of the economy (such as food services and the informal economy) leading to disproportionate losses in employment.[1]

People from minority groups: in the US[3] and UK[4], people from Black, Asian and minority ethnic groups experienced higher death rates as a result of COVID-19. For example, a Public Health England report showed that people of Chinese, Indian, Pakistani, Other Asian, Caribbean and Other Black ethnicity in the UK had between 10–50% higher risk of death compared with those of white ethnicity after controlling for other factors (such as age, or region).[3] This has been driven largely by social inequalities, such as being more likely to live in low-income areas, live in overcrowded housing, have fewer opportunities to work remotely, or larger barriers to access healthcare.[3,5]

Informal workers: lack of social security led to significant income loss,[6] with the International Labour Organization estimating a ~55% increase in informal worker's poverty levels globally, relative to in-country averages.[7] In countries like India, where the informal labour market represents over 90% of the total workforce, this had a devastating effect.[8]

Rural and lower-resourced communities: in Argentina, low-resource, urban communities on the outskirts of Buenos Aires faced infection rates that were 30% higher than the cities' average.[9] Similarly, in the US, members of rural communities were over twice as likely to die of COVID-19 than members of metropolitan communities,[10] and ~10% less likely to be vaccinated.[11]

Sources: [1] COVID-19 Pandemic Disproportionately Affected Women in the Americas, PAHO, 2022 [2] 5 ways women and girls have been the hardest hit by Covid-19, OXFAM, 2020 [3] COVID-19 infections by race: What's behind the health disparities?, Mayo Clinic, 2022 [4] Impact of COVID-19 on different ethnic minority groups, UK Parliament, 2020 [5] Drivers of the higher COVID-19 incidence, morbidity and mortality among minority ethnic groups, GOV.UK, 2020 [6] This is how COVID-19 is affecting informal workers, World Economic Forum, 2020

[7] Relief for Informal Workers: Falling through the Cracks in COVID-19, CGAP, 2020 [8] India's Informal Workers Under Lockdown, Shubhangi Gokhroo, 2021 [9] Latin America's Coronavirus Crisis: Why it Disproportionally Affects the Poor, Australian Institute of International Affairs, 2020 [10] Pandemic Precarity: COVID-19 is exacerbating and exposing inequalities in the American Heartland, Brea L. Perry, et al, 2021 [11] New vaccine campaigns target rural Americans to address disparities, The Guardian, 2021

THE CHALLENGE

Moreover, designs needed to be appropriate for the context in which they would be applied.

For example, while investing heavily in telehealth[1] was a popular response in many countries, this was not appropriate for areas where healthcare facilities had no internet connection.[2] Similarly, uptake and use of ventilators depended on the existing oxygen infrastructure and trained staff capacity. Central African Republic, Liberia, Nigeria, and South Sudan, for example, faced a shortage of doctors and anaesthesiologists with the required training to operate ventilators and intubate patients.[3]

Improving patient and community experiences was also paramount given increasing distrust in the healthcare system.

During the pandemic, an increase in distrust of both medical experts and healthcare systems was observed in communities around the world. A global study in 2022 found that more than one in two people felt less confident in their healthcare system since the start of the pandemic, and that a majority were worried medical science was becoming politicised. The study also found a steep decline in people's confidence in their ability to make informed health decisions.[4]

"Technologies are never neutral – the contexts they are being put in need to be carefully thought about so as not to cause unintentional harm."

Executive Director of an international engineering non-profit

Sources: **[1]** Telehealth is the provision of healthcare remotely by means of telecommunications technology, such as by phone or videocall. **[2] Healthcare worker capacity, McKinsey [3] Africa's most vulnerable countries have few ventilators – or none at all, The Washington Post, 2020 [4] People have lost trust in healthcare systems because of COVID. How can the damage be healed?, World Economic Forum, 2022**

ENGINEERING'S CONTRIBUTION

Engineers used human-centred and context specific designs to help close gaps in access

Engineers applied human-centred design principles.
Human-centred design involves taking the human perspective in all steps of the problem-solving process – an approach which some engineers took in designing and adapting elements of the pandemic response. This entailed understanding the needs of the user, the social context in which the tools and services would be used, and working to build trust in new healthcare systems and products.

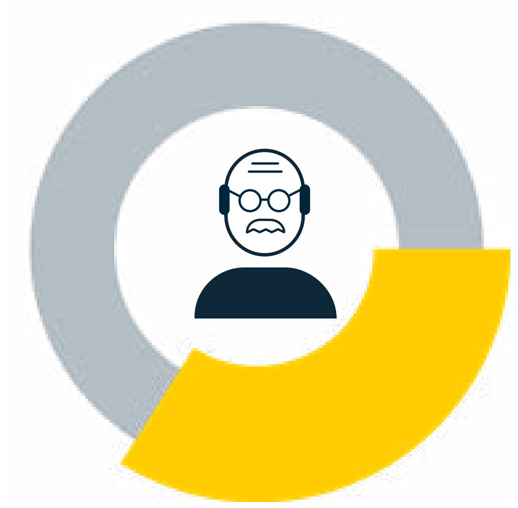
Engineers brought a nuanced understanding of the access and uptake barriers in low-resource settings.
Engineers brought optimisation approaches to finding pandemic solutions – a decision-making process where many options are considered against the needs and context. This included considering the budget constraints of the public health system or end user, the available infrastructure, or geographical limitations. Working to understand these constraints, engineers designed solutions to mitigate them. For example, a team of engineers in Peru working on 'Resp-IoT' (a device which monitors respiratory rates and other vital signs) are currently undergoing a human-centred design process to adapt their prototype to be suitable for the immense diversity within the country. This includes ensuring the sensors can give appropriate readings at high altitudes (to serve communities living above 4,000 metres), will work equally for those with darker skin colours, and will be easy to use with minimal training.[1]

Engineers' contributions did not have to be high-tech or complex to bring value.
In many instances, engineering approaches in low-resource settings leveraged existing materials and technology in a new way to improve access (versus importing or acquiring more expensive alternatives). For example, engineers engaged in Project CARE (COVID-19 African Rapid Entrepreneurs), produced protective mask designs that used everyday materials, such as vacuum cleaner bags.[2] In India, non-profits repurposed existing call centre technology for pre-recorded messages to provide school materials to students without internet access. Students were able to call into this system and receive pre-recorded audio lessons every other day. These simple yet innovative solutions provided rapid impact.[3]

Sources : [1] Expert interviews [2] Project CARE, Impact Report March 2020 to November 2021, Royal Academy of Engineering
[3] The Pandemic Has Snapped Communication Lines Between Schools And Students In India, UN Foundation, 2021

EXAMPLES OF ENGINEERING EXCELLENCE

Two-thirds of the world's school-age children have no internet access at home.[1]



20 - 34% of older adults in China, Europe, Latin America, and the US are lonely.[3]

Only **14%** of women working in healthcare reported they had PPE that fit them.[5]

Adapting education technology for low connectivity and low-tech environments

Many pandemic response products and services, particularly those in the education space, relied on sustained network connectivity and access to technology. To bridge the connectivity divide, engineers sought to create low-tech or offline versions of pandemic response products and services.

- The **Kolibri Learning Platform is designed for children without in-home internet connectivity, providing offline access to popular education channels like Khan Academy and tools for self-paced learning.** Through peer-to-peer distribution, users can share the content with each other using a local network. In addition, to ensure low-cost adoption, Kolibri software can be run on low-cost devices with older hardware, and can be customised by teachers according to the local curriculum. Kolibri became highly valued during the pandemic and is currently being used in more than 200 countries and territories around the world.[2]

Designing telecommunication for older adults during quarantine

Older adults were arguably the most vulnerable group during the COVID-19 pandemic. As a result, nursing homes across the world implemented isolation procedures, limiting contact between residents and their families. Unfortunately, enabling digital communication with nursing home residents was difficult because of lower levels of digital literacy.

- **The CallGenie video calling device** was designed specifically for nursing home residents. The CallGenie automatically answers calls from trusted numbers, and projects the video call onto the TV screen. After the call, it then returns to the original programming.[4]

Ensuring PPE is well-fitting and safe for all users

Historically, PPE has been designed using a reference for face shape and body type based on the average proportions of a white man. This has led to ill-fit and safety issues for many health workers – especially women.

- Fix the Mask in the US made a **brace to fit over a standard surgical mask** to improve fit and seal.[6]
- Engineers in China used **blue light scanners and 3D printing** to make customised face seals that would perfectly fit an individual's face shape.[7]
- African engineering entrepreneurs engaged in Project CARE developed a series of face masks, including an injection-moulded mask with a removable filter, and **tested fit to ensure it was appropriate for users in the local market.**[8]

Masks also created issues for people who are **deaf or hearing impaired.**

- **EchoTextura**[9] and **The Hello Face**[10] designed **transparent masks and face shields** that facilitate lip reading and greater ease of communication.

Sources: **[1] Two thirds of the world's school-age children have no internet access at home, new UNICEF-ITU report says, UNICEF, 2020 [2] Learning Equality, Kolibri, Accessed: July 2022 [3] Social isolation and loneliness among older people: advocacy brief, WHO, 2021 [4] CallGenie - Video Calls Direct to Their TV, Age Space** Date Accessed: July 202 [5] FIT for Women: Safe and Decent PPE, Women in Global Health, 2022 **[6] Fix the Mask, Website Accessed: July 2022 [7] Customized design and 3D printing of face seal for an N95 filtering facepiece respirator, Cai et al, 2018 [8] COVID-19 African Rapid Entrepreneurs Impact report: March 2020 to November 2021, Royal Academy of Engineering [9] Eco Textura, Website Accessed July 2022 [10] Hello Face, Website Accessed July 2022**

EXAMPLES OF ENGINEERING EXCELLENCE

In many countries, **people from minority groups** experienced higher COVID-19 infections and mortalities.[1]

47% of the world's population had no access to diagnostics.[4]

Removing bias from medical technology

Monitoring low levels of blood oxygen has been important to detect deterioration in COVID-19 patients. Unfortunately, it was discovered that Pulse Oximeters overestimate arterial oxygen saturation in individuals with darkly pigmented skin, resulting in higher rates of low oxygen saturation levels going unrecognised.[2] Current efforts are looking at how to improve such devices.

- An engineer and a physicist from Brown University have teamed up to develop a **Pulse Oximeter that uses an LED light source that emits radially polarised light.**[3] According to the developers, this alternative light source should not be absorbed by pigmented skin and, therefore, should provide more accurate blood saturation levels. Further testing is required before the product is ready for implementation and scale-up.

Building portable labs for areas with limited lab infrastructure

Lack of laboratory infrastructure to process COVID-19 tests was a key barrier to testing in many areas of the world. Engineers developed cost-effective and portable options.

- In the UK, Queen Mary University developed a **'Lab in a back-pack'** providing a cost-effective, portable, lab-free diagnostics option for remote areas.[5]
- In India, engineers converted Indigenous Truelab workstations originally for tuberculosis diagnosis into **'lab in a suitcase'** portable diagnostic stations for COVID-19. These included a real-time quantitative PCR system, were fully automated, and only weighed around 3 kilograms. Equipped with network data transfer capacity, Truelab workstations also automatically reported results to a centralised system.[6]

Sources: [1] COVID-19 oxygen emergency impacting more than half a million people in low- and middle-income countries every day, as demand surges, WHO, 2021 [2] Covid: Pulse oxygen monitors work less well on darker skin, experts say, BBC, 2021 [3] Brown Ph.D. student working to correct skin color [4] The Lancet Commission on diagnostics: transforming access to diagnostics, Lancet, 2021 [5] Scientists develop Covid-19 testing lab in a backpack, Queen Mary University of Lonodn, 2022 [6] Innovative point-of-care molecular diagnostic test for COVID-19 in India, The Lancet, 2022

EXAMPLES OF ENGINEERING EXCELLENCE

Almost half
of hospitals in L/MICs have inconsistent or no supply of medical oxygen.[1]

Designing devices for strained oxygen infrastructure

Oxygen provision was a cornerstone of the COVID-19 response, but many areas faced challenges because of the high cost of medical-grade oxygen, poor oxygen infrastructure, and shortages in trained staff.[2,3] Engineers sought low-cost, high-impact solutions to this.

- South African engineers developed a less oxygen-intensive all-in-one breathing device, the **OxERA device,** which is compatible with a range of oxygen infrastructures (both bottled oxygen and small oxygen concentrators) and requires minimal staff training to use.[4] (Further examples of overcoming low oxygen supply in section 2.4)

SPOTLIGHT

Engineers in Malawi repaired oxygen concentrators to increase oxygen supply under rising demand, and saved money for the public health system

During the COVID-19 pandemic, Malawi suffered from a critical shortage of medical-grade oxygen.

This was a result of disruptions in global oxygen supply chains, much of the in-country oxygen infrastructure having fallen into a state of disrepair,[5,6] and constrained public health budgets.[7]

To bring a cost-effective solution to tackle the oxygen shortage, engineers (including biomedical and electrical engineers) from **OpenO2** – an initiative created by a technology, innovation and informatics hub based in Malawi – **set out to repair oxygen concentrators across the country.**[8] Oxygen concentrators pull oxygen from the air and concentrate it to 85 to 95% pure oxygen for patient use, relieving the need to purchase oxygen cylinders.[9] The OpenO2 initiative was launched with crowd-funded support, and focused on **sustainability, cost-efficiency, and context-specific innovation.**[10]

OpenO2 converted two minibuses into **mobile workshops** and travelled across the country conducting concentrator repairs using their own equipment. **They were able to repair 649** of the 850 broken **oxygen concentrators** in 58 hospitals around the country. This made an **additional 657,860 cubic metres of oxygen available** – enough to provide continuous oxygen flow to 4,607 adults for a week.

The average price for OpenO2 to repair a single concentrator was less than it would have cost to refill three oxygen cylinders. Overall, **these repairs saved Malawi more than ~$7.5 million** in oxygen costs.[11]

Sources: [1] Global oxygen suppliers commit to closing oxygen gaps in low- and middle-income countries, Access to Medicine Foundation, 2021 [2] Global oxygen suppliers commit to closing oxygen gaps in low- and middle-income countries, Access to Medicine Foundation, 2021 [3] COVID-19 oxygen emergency impacting more than half a million people in low- and middle-income countries every day, as demand surges, WHO, 2021 [4] OxERA® DEVICE, Umoya, 2021 [5] The OpenO2 Mobile Workshops, Website [6] 'If it comes, it will overwhelm us': Malawi braces for coronavirus, Vidal J, 2020. [7] The World Bank in Malawi , The World Bank, Date Accessed: July 2022 [8] The OpenO2 Mobile Workshops, Website [9] An overview of Covid-19 in Malawi: Scotland-Malawi Oxygen Supply Coordination Group, ScotlandMalawi, 2021 [10] Expert interviews. [11] The OpenO2 Mobile Workshops, Website, Date Accessed: July 2022

UNLOCKING ENGINEERING POTENTIAL FURTHER

Despite areas of excellence in context-specific design, this principle was not applied universally

In some cases, engineers failed to take a sufficiently user-focused approach, resulting in designs which were not fit for purpose.
For example, the rush to make ventilators for low-resource settings resulted in many non-automated designs, which were not suitable for contexts with low numbers of trained staff.[1] In other instances, technologies were deployed that were not yet ready for use. For example, although hundreds of AI tools were built to detect COVID-19 in patients from hospital scans, reviews have found many did not work, and some were not properly tested before being used in clinical settings.[2] Concerns were also raised in the US when participants selected for clinical trials for COVID-19 drugs did not include sufficient diversity.[3]

Inappropriate, low quality, or poorly tested products risk eroding trust in the healthcare system. This is particularly salient given the decline of trust in experts and in healthcare systems observed since the start of the pandemic.[4] To prevent unintentional harm, extreme care is needed when bringing new tools and services to patients. This requires close collaboration between engineers, clinicians, patients, wider stakeholders, and funders, to ensure community consultation and ethical considerations are at the heart of bringing new products to market.[5]

More is needed to support innovators to create 'home-grown' solutions and support them to reach scale

The engineers that are closest to the context they are serving are the best placed to create appropriate innovations.
Developing context-specific engineering contributions requires the designer to absorb the user context and understand the nuances and barriers that exist. For example, studies have shown that when more women are involved in medical research, a greater level of sex and gender analysis is applied during the design.[6] Similarly, local entrepreneurs have shown the ability to innovate for their local markets. For example, engineering entrepreneurs in Africa engaged with Project CARE were able to develop, manufacture and distribute almost 90,000 items of PPE which had been tailored for their local markets.

However, funding to innovators and entrepreneurs in L/MICs was far less than in HICs.
Less innovation and research was conducted in L/MICs during the COVID-19 pandemic. For example, the UKCDR Covid Tracker, which maps COVID-19 research projects, shows less than 18% of COVID-19 research projects came from L/MICs.[7] Funding to L/MICs for research and innovation was also frequently official development assistance (ODA), which was cut during COVID-19 as countries turned inwards to focus on domestic burdens. In addition, ODA frequently does not provide the long-term sustainability of funding needed. Furthermore, in the rush to fund solutions, large health funders preferred to fund via existing relationships or partners and to fund already well-established actors in the engineering and global health space.[8]

Persistent skills gaps in engineering and technical expertise remain in many L/MICs.
Engineers interviewed across disciplines noted a gap in skills capacity in many regions, often short of what was needed during the pandemic response. A combination of a lack of specialised engineering education and brain-drain have contributed to this problem, and have limited the potential for both home-grown innovation, and cross-country collaborations.[9,10,11,12]

Of the innovations that were designed, many were not sufficiently funded to reach scale.
Despite many engineers focusing on designing products to meet the needs of women or underserved communities during the COVID-19 pandemic, many products were not brought to scale. For example, no efforts to improve the fit of PPE were ever widely scaled in a way that made a significant difference to the number of healthcare workers with well-fitting PPE. Further investment into innovation for underserved groups should also seek to ensure paths to scale up, aiming to reach a critical mass of users.

Sources: [1] Expert interviews **[2] Hundreds of AI tools have been built to catch covid. None of them helped., MIT Technology Review, 2021 [3] Why AI Failed to Live Up to Its Potential During the Pandemic, Harvard Business Review, 2022 [4] Researchers call out lack of diversity in COVID-19 clinical trials, Medical News Today, 2020 [5] People have lost trust in healthcare systems because of COVID. How can the damage be healed?, World Economic Forum, 2022** **[6]** Why AI Failed to Live Up to Its Potential During the Pandemic, Harvard Business Review, 2022 **[7]** COVID-19 Research Project Tracker by UKCDR & GloPID-R, Accessed June 2022 [8] Expert interviews **[9]** Women and minorities are lost in engineering 'brain drain', The Times, 2021 **[10]** Brain Drain – The loss of engineers and doctors in India, University Times, 2021 **[11]** Variants, Misinformation, and 'Brain Drain' — The COVID-19 Vaccine Experience in Brazil, India, and Africa, National Academies, 2021 [12] Expert stakeholder interviews

“ In Ethiopia we lack specialist engineers in several areas (…) but when students go abroad to learn these specialities, most of them don’t come back.”

Africa Engagement Lead for a major upstream vaccine partnership

CASE STUDY

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

THE INNOVATION

- Testing technology to detect the amount of COVID-19 in sewage systems for community level surveillance.

IMPACT AT A GLANCE

- Acted as an early warning indicator of upcoming rise in infections.
- Ensured systematic inclusion of underserved populations in diagnostics data that had previously been absent in testing data.
- Tracked and determined the relative percentages of different COVID-19 variants.
- Successfully implemented in over 50 countries worldwide, both HICs and L/MICs.

ENABLING FACTORS

- Used existing wastewater plants and collection systems.
- Built on already existing wastewater testing technology.
- Fostered local collaboration and skills sharing.

CHALLENGES

- Reaching those not connected to a sewer network: in HICs only 80% are connected, while only 24% are in low-income countries (LICs).[1]
- Requiring partnership with local governments for implementation.
- Should be done alongside individual diagnostic testing to preserve granularity of data of who needs to isolate.[2]

CONTEXT AND NEED

In the wake of the pandemic, access to and use of COVID-19 tests was highly unequal.

Both between and within countries, there was disparity in the availability of testing sites, driven by large differences in access to health systems. Moreover, already disadvantaged groups, such as underrepresented communities, undocumented persons, people living in poverty, or those living in 'medical deserts' (areas that are underserved by healthcare facilities) were often those with the lowest access to tests. Uptake barriers were also prevalent: mistrust in the health system, high costs of testing, inability to take time off work, or stigma associated with being infected with COVID-19 prevented many people from getting tested. This often resulted in underrepresented groups and rural communities not being included in COVID-19 infection data and trend analysis, and therefore limited appropriate response efforts to cater to their needs.

ENGINEERING CONTRIBUTION AND IMPACT

Wastewater testing is a high impact, complementary tool to traditional testing – and can serve as an early predictor of an upcoming wave of infections or new variants.

Before becoming symptomatic, people infected with SARS-CoV-2 shed the virus in their faeces. Using PCR testing on wastewater samples, it is therefore possible to detect the presence and level of virus in a community's wastewater, serving as an early predictor of an upcoming rise in infections.[3] Compared to individual testing – which experienced delays during peaks of infection – wastewater testing has a fast turn-around time for results, and is also effective at detecting variants. For example, in a town in California wastewater testing found Omicron BA.2 in sewage samples before it had been found in a clinical specimen.[4]

Sources: [1] Opportunities and limits of wastewater-based epidemiology for tracking global health and attainment of UN sustainable development goals, Sangeet Adhikari, Rolf U. Halden, 2022 [2] Wastewater network infrastructure in public health: Applications and learnings from the COVID-19 pandemic, Sharara et al, 2021 [3] National Wastewater Surveillance System (NWSS), CDC, 2022 [4] Using Genomic Sequencing to Monitor Covid Variants and Subvariants in Wastewater, Biobot, 2022

CASE STUDY

In the US, wastewater testing enabled greater inclusivity in COVID-19 analytics data.

Wastewater analysis does not rely on users having to visit a test centre, meaning it is better at capturing infection rates among underrepresented groups.[1,2] Biobot Analytics (the first wastewater testing company in the US to adapt PCR testing and wastewater testing technology to monitor COVID-19) first implemented their technology in Massachusetts. Biobot Analytics was able to show that their wastewater testing resulted in a more equitable and inclusive dataset than individual testing programmes across age, vaccination status, race, and ethnicity.[3]

After the success in reaching communities in the US, Biobot expanded its reach to Latin America.

Throughout the pandemic, Ecuador reported relatively low confirmed cases, which experts indicated was in part due to low laboratory capacity for population testing.[4] In an attempt to mitigate these challenges, the World Bank partnered with Biobot Analytics to implement a pilot programme in Guayaquil, Ecuador, in collaboration with the government and the city's private water authorities. The pilot was successful in enhancing wastewater-based epidemiology and has since evolved into a one year programme for tracking COVID-19 at the community level for the city's 2.7 million inhabitants.[5]

Wastewater testing has been applied elsewhere, with simplicity being a key to its success.

In Brazil, communities living in densely populated slum areas were poorly represented in traditional COVID-19 data.[6] A group of researchers implemented a wastewater testing programme in low-income neighbourhoods in São Paulo. They found that COVID-19 trends collected through wastewater correlated to traditional test data – proving the testing system's efficiency – while also displaying trends almost two weeks earlier than traditional testing methods. Wastewater collection relied on already existing systems for collection and did not require users to change their behaviours in any way. This simplicity enabled the inclusion of communities who were previously excluded from COVID-19 diagnostics data.[7]

Wastewater testing facilitates improved health equity.

Since the onset of the pandemic, the inclusion of Native American communities in US COVID-19 data has been poor. To facilitate greater health equity, the Wastewater Action Group successfully partnered with tribal communities in Arizona to equip the population with the tools to be able to collect wastewater samples for COVID-19 testing. This allowed them to bypass the affordability issues associated with traditional COVID-19 diagnostics and facilitated the inclusion of Native American communities in US COVID-19 data.[8,9]

Looking to the future, wastewater analysis can serve as a cornerstone of recovery and prevention.

Wastewater surveillance has been shown to be a relatively inexpensive, flexible, and accessible tool to support long-term recovery and resilience. It can serve as a background monitoring tool during recovery and thereby support the return to normal as rates of individual COVID-19 testing fall. In addition, wastewater-based epidemiology can be adapted to monitor for a range of different diseases, and so can act as an early warning system for other outbreaks.

Sources: [1] National Wastewater Surveillance System (NWSS), CDC, 2022 [2] Metrics to relate COVID-19 wastewater data to clinical testing dynamics, Science Direct, 2022 [3] Wastewater for equitable Covid-19 monitoring, Biobot, 2021 [4] Assessing critical gaps in COVID-19 testing capacity: the case of delayed results in Ecuador, BMC Public Health, 2021 [5] How innovation in wastewater monitoring helps track down deadly diseases in Latin America, World Bank, 2021 [6] COVID-19 Infection Rate In Rio's Favelas Far Exceeds Official Count - a new study says, NPR, 2020 [7] COVID-19 data on Native Americans is 'a national disgrace.' This scientist is fighting to be counted, Science.org, 2020 [8] Ensuring Equity as Wastewater Testing Matures in the United States, Mathematica, 2022 [9] Wastewater surveillance as a long-term tool for resilience, Arcadis, 2021

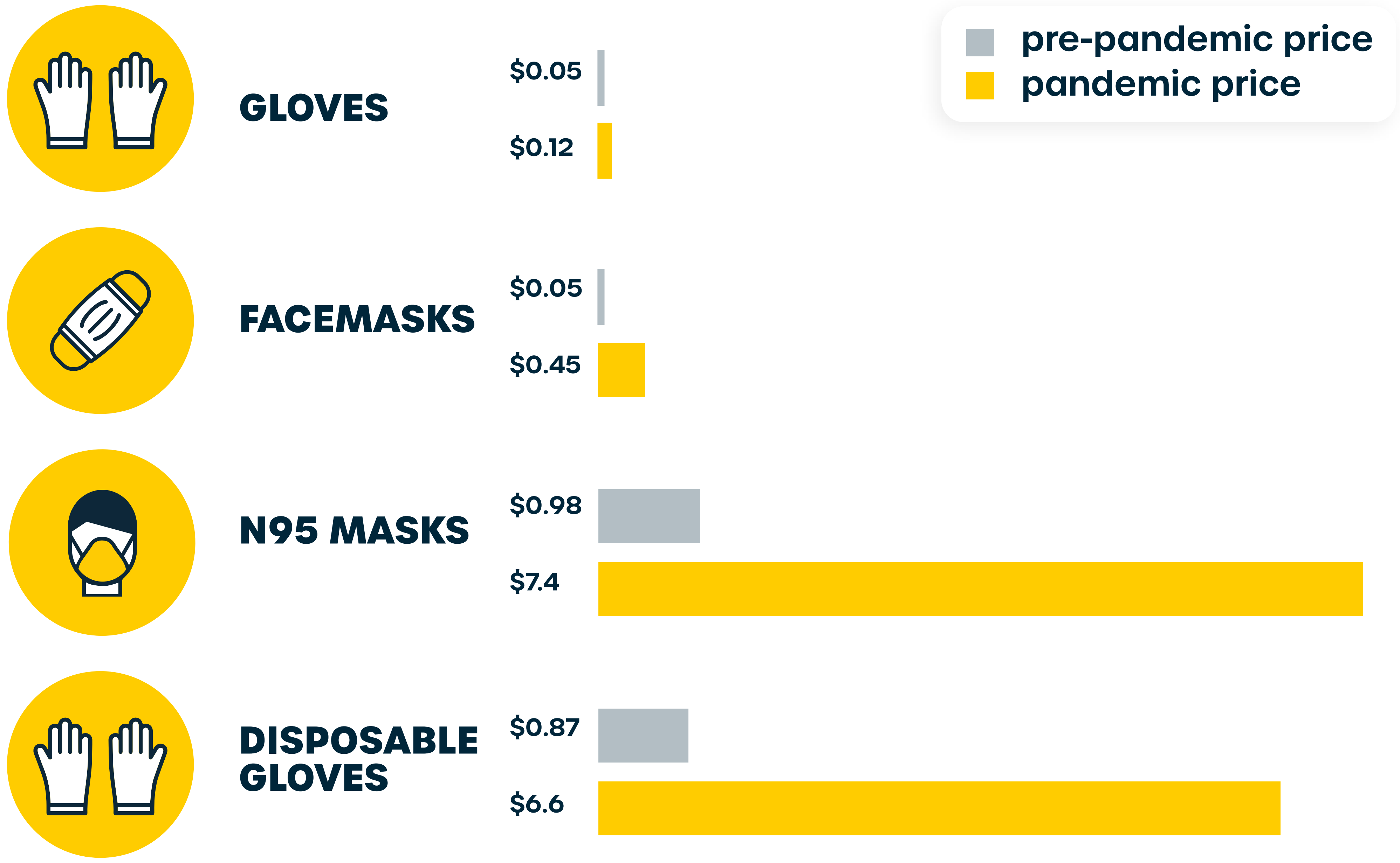
2.4

Ramping up production

THE CHALLENGE

Limited production and manufacturing capabilities challenged the scale-up of essential health products, and geographic disparity led to inequitable access

Sky-rocketing prices: Changes for PPE prices in Chicago during the first wave of COVID-19 cases[1]



Sources: [1] Cost of Personal Protective Equipment During the First Wave of COVID-19, Cambridge University Press, 2021

Unprecedented volumes of essential health products were needed as global demand surged.
To avoid shortages during COVID-19, manufacturers and producers had to keep up with rapidly rising demand. For example:

- In 2020, the global market for both critical care and transport ventilators increased by over 300%[2]
- Since the start of the pandemic, the top 25 highest burden countries have used over 5 billion COVID-19 tests –creating heightened demand for tests, reagents, pipettes, swabs, and lab equipment[3]
- Already by March 2020, WHO was calling for PPE manufacturers to increase their production by 40%[4]

As global demand grew for essential health products, over 80 countries enforced export restrictions, leaving many countries vulnerable to undersupply.
Countries with restricted production and manufacturing capabilities rely heavily on imports for essential healthcare products. However, with the surge of demand in 2020 for medical supplies, many exporting countries imposed restrictions to keep these supplies at home. Nearly 80 countries enforced restrictions.[5] This left many countries highly vulnerable to shortages in essential products, such as PPE and ventilators. Where production capacity was highly concentrated to a few regions, this led to significant geographic disparity. For example, many countries in Africa, which as a continent imports 99% of its vaccines, were left behind in the race to acquire COVID-19 vaccines as other countries stockpiled. Globally, prices soared for products, parts, and materials –compounded by severe supply chain disruptions *(see section 2.5)*.

Countries had to look inwards to build up their local manufacturing and production capabilities, all while adapting to new social distancing and health and safety requirements.
This included pivoting existing industrial capacity towards essential healthcare products and building new capacity. Engineers were needed to rapidly assess production capacity, reconfigure facilities towards new products, and optimise production techniques for speed, scale, and distribution. These challenges were made more complex by the need to incorporate new health and safety standards and social distancing measures on the production floor to protect workers from infection.

Sources: [2] Ventilator market set to return to pre-pandemic levels in 2021, Merical Device Network, 2021. [3] Statistics as of June 2022 reported at: Number of coronavirus (COVID-19) tests performed in the most impact countries worldwide as of June 27, 2022 [4] Shortage of personal protective equipment endangering helath workers worldwide, WHO, 2020 [5] Export restrictions do not help fight COVID-19, UNCTAD, 2021

“As we saw the urgency of the pandemic and that our traditional [trading] partners were struggling themselves, we knew we had to solve our own problems ... this was the driver of the push for localisation.”

Africa engagement lead for a major upstream vaccine partnership

“We had to balance moving quickly with not putting our workers at risk – in April 2020 there weren’t many guidelines yet. We had to expand and convert the production floor so employees were far apart, put in shielding screens, and even use automated robotics to move parts to limit interactions.”

Head of facilities at a manufacturing business that pivoted to make ventilators

ENGINEERING'S CONTRIBUTION

Engineers bolstered and optimised localised and scaled production

Engineers quickly pivoted industrial capacity to meet gaps in critical resources, and also save jobs.
Across industries, engineers quickly reapplied their expertise to meet new problems – such as manufacturers learning how to build ventilators, or distilleries how to prepare hand sanitiser. Quickly pivoting these skills and workspaces not only led to the development of life-saving products, but also allowed companies to save jobs at a time when industry was hit hard by lockdowns and falling consumer demand. For example, in Bangladesh, the garment sector faced order cancellations and delays equivalent to $3.18 billion between March and April 2020. Pivoting to PPE was a way for some companies to survive.[1]

Engineers also optimised production techniques to bring the speed and flexibility needed during dynamic circumstances.
For example, the 3D printing and additive manufacturing industries were quick to lend expertise and capacity towards rapid prototyping, allowing production to start faster than with other processes such as injection moulding. In drug manufacturing, producers brought in new flexibility. For example, whereas setting up machinery for new drug packaging (which requires highly prescriptive formats) typically has long lead times of eight to twelve months minimum, Pfizer and Biovac were able to cut the lead times for cartoning machines in half by bringing in machinery that could be customised later on.[2]

Moving from product development to manufacturing was run as a dynamic process, needing engineers to be brought in early.
Traditionally, the move to mass manufacturing and transferring technologies to other organisations for production occurs after a product or process has been finalised and trialled extensively. However, the need to get novel products – such as vaccines – out as quickly as possible meant developers were collaborating with their manufacturing partners from the outset. This required manufacturers to be open to changing circumstances, and to adapt their facilities and techniques alongside the product development process.

To reach scale at speed, public-private partnerships were frequently used to encourage local production.
For example, in Morocco, the government forged relationships to support the Moroccan research institute MASCIR, who brought the expertise and networks to develop diagnostics kits that could be locally produced.[3,4] Public-private partnerships are also becoming a part of the vaccine manufacturing landscape which is developing in Africa, such as those in Senegal and Egypt. Forging closer links between industry and the public sector has allowed for faster regulatory approval, and also greater access to funding.

Looking to the future, engineers will need to take a central role in building long-term capacity.
The experience of the pandemic may well bring lasting changes in how health products are developed, produced and distributed. For example, experts have called for hospitals to invest in 3D printers as emergency back-ups for production in the case of supply chain breakdowns.[5] Many countries have also realised the importance of increasing national resilience through expanding local industrial capacity, and so have launched long-term investments into developing this as part of 'build back better' plans.[6] For some countries this has entailed building new capacity for the first time, and in others has included 'reshoring' (reversing the offshoring of production) for key goods. For example, EU member states, the UK, and Japan have all pursued policies to increase local production as part of 'reshoring' initiatives for key products. *(For more on supply chain implications of 'reshoring', see section 2.5.)*[7]

Sources: [1] From clothing production to PPE manufacturing: factories pivot during the pandemic, Better Work, 2020 [2] Expert interviews. [3] MASCIR develops a 100% Moroccan Diagnostic Kit for COVID-19 Testing, MASCIR, 2020 [4] Innovation ecosystems and start-ups in the Mediterranean as a means of recovering from the COVID-19 crisis, European Committee of the Regions, 2021 [5] The global rise of 3D printing during the COVID-19 pandemic, Nature reviews materials, 2020 [6] Building back better: A sustainable, resilient recovery after COVID-19, OECD, 2020 [7] Post Covid-19 value chains: options for reshoring production back to Europe in a globalised economy, European Parliament, 2020

EXAMPLES OF ENGINEERING EXCELLENCE

Textile manufacturers pivoting to make PPE

Garment and textile manufacturers were hard hit by global declines in demand and lockdown measures closing factories. However, many managed to successfully pivot to producing PPE.

- In just two months, India went from no PPE production to being the largest PPE producer after China – making 450,000 PPE suits a day. Half of this supply came from Bangalore's garment centres pivoting towards PPE manufacturing, leading to over 600 Indian textile companies becoming lab-certified to produce PPE. This success capitalised on the expertise of major textile players (such as Alok Industries and Gokaldas Exports) and cutting-edge public research (such as that of the South India Textile Research Association, a government-integrated textile company).[1,2]

- Similarly, in Vietnam, Better Work-affiliated Smart Elegant International Vietnam LTD, a clothing plant with over 450 employees of whom 80% are women, pivoted to making PPE and avoided laying off workers.[3]

Manufacturers pivoting to produce ventilators

As global demand outpaced supply, automobile, aerospace and high-precision manufacturers pivoted to produce ventilators.

- The UK government launched the 'Ventilator Challenge', calling UK manufacturers to produce existing designs or develop new designs for ventilators. Receiving responses from over 5,000 companies, UK manufacturers produced over 14,000 ventilators. The consortium included a mix of medical manufacturers (such as Smiths Medical and Penlon) and businesses pivoting from other sectors (such as GKN Aerospace, Airbus, McLaren, Rolls-Royce, and STI).[4,5]

(See section 2.2 for other examples, including a case study of UCL and Mercedes pivoting to manufacture breathing aids.)

Alcohol manufacturers pivoting to create sanitising solutions

As sanitisers fell into short supply, several beer and spirits manufacturers turned to making alcohol-based disinfectants.

- In just 14 days in March 2020, UK brewery Brewdog went from never having made sanitiser to becoming a fully approved supplier to the National Health Service. Brewdog went on to ship over 10,000 units free of charge.[6]

- Similarly, Bacardi rapidly pivoted distilleries in Puerto Rico to produce hand sanitisers for essential workers.[7]

Expediting vaccine manufacturing at scale

To expedite timelines, manufacturing experts worked closely with clinical developers. By working in tandem with the clinical development process, they were able to ensure a rapid scaling of manufacturing.

- At AstraZeneca, vaccine developers worked in partnership with engineers, manufacturing specialists, and supply chain experts from the outset, and even started manufacturing during clinical trials so that roll-out could start immediately after regulatory approval. AstraZeneca worked with over 20 supply partners in over 15 countries – which required an extensive analytical network to ensure quality control.[8]

Engineers pioneered **new methods to cut lead times of creating new factory capacity.**

- German company BioNTech made vaccine factories in shipping containers which could be quickly exported to Africa, expediting the process of setting up a new factory to just 12 months.[9] *(See case study at end of the section for examples.)*

Engineers optimised **production techniques to increase yield.**

- In drug substance production, deploying bioreactor-based production technologies allowed higher productivity,[10] and innovations in mRNA processes may soon become possible through mobile 'microfactories'– further reducing the footprint and labour requirements needed in vaccine manufacturing.

- In fill and finish,[11] innovations in materials and in blow-fill-seal technologies[12] have removed the need for vials – resulting in more efficient use of materials across products. Such innovations are slowly being tested at scale and may well prove useful in increasing preparedness for future pandemics.[13]

Sources: **[1] India now manufactures 4.5 lakh PPE suits a day in the fight against Covid-19, mint, 2020 [2]From clothing production to PPE manufacturing: factories pivot during the pandemic, Better Work, 2020 [3] How Asia's clothing factories switched to making PPE – but sweatshop problems live on, The Conversation, 2020 [4] Venitlator Challenge UK marks the end of the consortium after delivering 13,437 ventilators to the NHS, Smiths, 2020 [5] Ventilator Challenge hailed a success as UK production finishes, Gov.uk, 2020 [6] Sanitiser: Sharing what we have learned, Brewdog, 2020 [7]Bacardi makes hand sanitisers, Bacardi [8] Innovating production and manufacture to meet the challenge of COVID-19, Astrazeneca, 2021 [9] BioNTech to ship mRNA vaccine factory kits to Africa, Reuters, 2022 [10] 3D printed face shields for medics and professionals, Prusa Research, 2020** [11] Fill and finish refers to the final step of the process where the substance of the vaccine is sent to the plant to be put in vials and distributed. [12] Blow-fill-seal technology is a form of advanced aseptic manufacturing, the container is formed, filled, and sealed in one continuous, automated system. Its advantages include reducing need for human intervention, reducing risk of microbial contamination and foreign particulates, allowing for many different container designs, facilitating high process quality and output, and being inexpensive compared to other packaging processes. **[13] Formalbs' 3D Printed Naspharyngeal Test Swabs Honoured as a World Changing DIea by Fast Cmpany, Formlas, 2021**

EXAMPLES OF ENGINEERING EXCELLENCE

Expanding oxygen production capacity close to sources of need

As the majority of global oxygen production is non-medical, increased demand surpassed available supply in many countries. To overcome this, engineers found ways to quickly increase the production of medical oxygen.

- During the peak of the pandemic in December 2020 in South Africa, The Cintocare private hospital in Pretoria became the first hospital in the country to fully generate its own oxygen on-site using PSA technology.[1]
- Setting up new oxygen plants is typically a complex, highly customised process with a long lead time. To shorten this for the emergency context, UNICEF collaborated with industry partners to create the Oxygen Plant-in-a-Box package. This standardised pack has everything needed to set up a pressure swing adsorption (PSA) plant within days of arriving at a health facility and can produce enough oxygen for 50 COVID-19 patients or 100 children with pneumonia. A hospital in Uganda was the first to use this technology, followed by clinics in over 15 other countries.[2]

Using 3D printing or additive manufacturing for rapid production

Having a short lead time, 3D printing (also known as additive manufacturing) can be used for rapid prototyping, as well as quickly filling supply gaps for some emergency products.

- Prusa Research in Prague printed and donated 200,000 3D-printed face shields to medics and essential workers in the Czech Republic. Having made their designs open source, anyone can download and print the designs themselves.[3,4]
- 10XBeta were the first to get Emergency Use Authorisation in the US for a 3D-printed breathing aid in the form of a low-cost automatic resuscitator. The device works by automating a manual resuscitator and works with standard medical components readily available in most hospitals.[5,6]

SPOTLIGHT

Formlabs 3D printed nasal swabs for COVID-19 tests across the US through its distributed network of printers to combat shortages

As the pandemic hit the US, nasal swabs quickly ran out. Nasal swabs (nasopharyngeal swabs) must be long and flexible enough to reach deep into the nose and upper throat, and are integral to COVID-19 tests. The US supply of these swabs, which mainly came from Maine and Italy, ran low in early 2020.

Over a weekend, Formlabs, a leading 3D printer company, developed a nasal swab prototype. Together with the University of South Florida and Northwell Health, they designed a prototype that was ideal for sample collection and also had a break-off point, making it easy to store in a vial for laboratory testing.

Formlabs was in a unique position to start distributed supply. Across the US, hospitals and medical device manufacturers already had Formlab 3D printers, which they used to make patient-specific parts. Therefore, Formlabs could work with these partners to quickly start decentralised production.

At the peak of the US outbreak, Formlabs was producing 100,000 swabs a day. Formlabs have now produced tens of millions of swabs in 25 countries – making them one of the most manufactured 3D printed objects in history.[7]

Sources: [1] Expert interviews and First of its kind Cintocare Hospital, issuu, 2021 [2] The Oxygen Plant-in-a-Box: Innovation drives a key response to COVID-19, UNICEF Supply Division, 2021 [3] 3D printed face shields for medics and professionals, Prusa Research, 2020 [4] Open science takes on the coronavirus pandemic, Nature, 2020 [5] Open science takes on the coronavirus pandemic, Nature, 2020 [6] Spira Wave, 10x Beta, 2022 [7]Formalbs' 3D Printed Naspharyngeal Test Swabs Honoured as a World Changing DIea by Fast Cmpany, Formlas, 2021

UNLOCKING ENGINEERING POTENTIAL FURTHER

The increases in production capacity seen during the pandemic will need to be maintained if they are to contribute to future preparedness

Many industries expanded capacity during the pandemic, however, they will need to diversify to last through 'peacetime'.
For example, the manufacturing capacity of rapid diagnostic tests (RDTs) for COVID-19 is estimated to have grown 200% globally since the outset of the pandemic. However, suppliers have indicated it will not be financially viable to maintain these plants in anticipation of future pandemics.[1] Diagnostics experts have suggested suppliers diversify into RDTs for other diseases. To support this, governments and health funders can invest in volume guarantees that incentivise suppliers to maintain their capacity.[1] Similarly, ensuring the vaccine manufacturing facilities currently being developed on the African continent are sustainable will require building capacity beyond COVID-19 vaccines to meet the demand for other diseases.

Redistributing manufacturing and production capacity for greater local resilience will require tackling a number of issues

Investments into skilled labour that can set up, maintain, and run local production systems are needed for self-sufficiency.
For example, in Lesotho plans to set up PSA plants for oxygen met the challenge of not having sufficient trained technicians to run them.[2] Similarly, although South Africa has set up its first hospital with an integrated PSA plant, stakeholders noted it would not be possible to replicate this country-wide because of a shortage of skilled technicians and engineers.[3] Having the human resources to ensure local ownership and maintenance is a core pillar to sustainability – without which investments into increasing capacity will fail. A challenge within this has been fighting the perception that products produced in certain geographies will be of low quality. Several stakeholders interviewed highlighted the challenge created by this stigma. This included international donors preferring to import new products rather than use local technicians to repair and maintain existing infrastructure, and local producers having to fight the perception that their medical products would not meet medical standards.

Redistributing global production capacity will require tackling challenges around IP.
Since the outset of the pandemic, IP has been a contentious issue. On the one hand, IP plays an important role in incentivising innovation.[2] However, on the other, it constrains access and pricing. In the context of significant loss of life and an urgent need to stop the virus's spread, many called for open access to COVID-19 related IP.[4] Recognising a global emergency, many designers voluntarily made their designs and processes open source – allowing them to be manufactured anywhere in the world. However, many products, including most vaccines, have remained protected. Since 2020, over 100 countries have backed a movement to temporarily waive IP protection on COVID-19 vaccines, treatments, and tests.[5] However, as per the World Trade Organization (WTO) decision in June 2022, a

Sources: [1] COVID-19 diagnostics: preserving manufacturing capacity for future pandemics, Hannay et al, 2022 [2] BRING O2 To Fill Oxygen Gap in Five Countries, Partners In Health, 2022 [3] Stakeholder interview [4] A patent waiver of COVID vaccines is right and fair, Nature, 2021 [5] The impact the TRIPS waiver would have on Covid-19 and why it's so important, Bond, 2022 and Intellectual Property, innovation, and access, World Intellectual Property Organization, 2020

UNLOCKING ENGINEERING POTENTIAL FURTHER

full waiving of IP protections did not occur[1] – a result which left many activists for equitable access disappointed.[2] As technology transfer plays an important role in facilitating local production and innovation, reaching the right balance of IP protection and knowledge sharing in the context of critical health products and emergencies will be an important cornerstone of equity within pandemic preparedness.[3]

Increasing local production capacity needs to be accompanied by good working conditions.
Increased investment into local production and manufacturing is an opportunity to create sustainable employment opportunities. However, the opportunity must also be taken to improve working conditions, including safety during a pandemic. Unfortunately, not all producers invested sufficiently into upgrading protective infrastructure and safeguarding staff, and dangerous working conditions were exacerbated by mounting pressures to reach demand. For example, in Malaysia – the world's largest exporter of rubber gloves – there were reports of forced labour and abuse of migrant workers.[4,5] In China, there were also reports of forced labour of Uyghur populations producing facemasks, and North Korean populations in making hospital gowns.[6]

"Because we are seen as a low-tech country, even to serve the local market we have had to fight the perception that we couldn't develop and produce these medical devices ourselves."

Manager of a company producing breathing aids in a low-income country

Sources: [1] In June 2022, after 20 months of negotiation, the World Trade Organisation decided on a compromised measure clarifying flexibilities for compulsory licensing, exclusively for L/MICs, and only for vaccines. **[2]** Lack of a real IP waiver on COVID-19 tools is a disappointing failure for people, Medecins Sans Frontieres, 2022 **[3]** Why intellectual property and pandemics don't mix, Brookings, 2021 **[4] Malysia: Concerns over labour abuse to meet rubber globves demand, Aljazeera, 2020** [5] **How Asia's clothing factories swithced to making PPE but sweatshop problems live on, The Conversation, 2020** [6] **Labour rights abuse in global supply chains for PPE through COVID-19 – issues and solutions, British Medical Association, 2021**

CASE STUDY

Multi-stakeholder initiatives to bolster vaccine manufacturing capacity on the African continent

THE INNOVATION

- Public and private initiatives to build end-to-end development and manufacturing capability of vaccines across the African continent.

IMPACT AT A GLANCE

- Public and private partners in Algeria, Egypt, Morocco, and South Africa have begun COVID-19 vaccine manufacturing.
- Nigeria, Rwanda, and Senegal have signed memorandums of understanding (MoUs) towards expanding vaccine manufacturing in the coming years.
- Long-term initiatives will develop capacity beyond COVID-19 vaccines for routine immunisations and future pandemic preparedness.

ENABLING FACTORS

- Growing political and financial commitment since the outset of the pandemic.
- Leveraging existing technical expertise on the African continent by working with industry players.
- Focusing on long-term sustainability.

CHALLENGES

- Meeting the high cost of vaccine manufacturing development and committing to sustained, local investment.
- Developing skilled workforces.
- Building an enabling regulatory environment.
- Resolving IP barriers.

CASE STUDY

CONTEXT AND NEED

A lack of vaccine manufacturing capacity in Africa left the continent vulnerable to COVID-19, as exporting countries elsewhere turned inwards.

Historically, African countries have imported 99% of their vaccines.[1,2] This reality left them vulnerable during the pandemic, when vaccine exporters focused on supplying their own populations or higher-paying customers first. As of June 2022, only 18% of Africa's population had been fully vaccinated.[3]

Moving forward, decentralising the current vaccine supply and building up vaccine manufacturing is critical.

This will require a long-term, Africa-led, and multistakeholder agenda which builds local ownership, not only for COVID-19 vaccination and pandemic preparedness, but also routine immunisations. Vaccine manufacturing capacity can be thought of at three levels of capability:

1. **Contract manufacturing and formulation for fill and finish.**
   Africa currently has around ten vaccine manufacturers[1] which can complete the final manufacturing processes of filling vials and distributing (known as fill and finish).[4]

2. **Drug substance and drug product[5] manufacturing capacity.**
   This will require the transfer of IP, as well as developing the technical capacity and know-how to produce and manufacture the active ingredients in vaccines.

3. **Base product development capability.**
   Developing new vaccine candidates will require both a strong scientific base, as well as the capabilities to bring a product from R&D, to clinical trial, and then to market.

Several initiatives across each level have started since the outset of the pandemic, detailed on the following page.

African leaders are committed to seeing change.

In April 2021, African Union member states set the ambition of building vaccine manufacturing capacity over the subsequent 20 years to produce 60% of all vaccines used on the continent.[6,7] The African Development Bank committed $3 billion towards this goal, including investments into infrastructure, logistics, regulatory support, and pharmaceutical manufacturing.[1] These new commitments build on efforts started in 2007 with the African Union's Pharmaceutical Manufacturing Plan for Africa, establishing the African Medicines Agency, and the development of the Framework For Action of the Partnership for African Vaccine Manufacturing of the Africa CDC.[2]

ENGINEERING CONTRIBUTION AND IMPACT

Since the onset of the pandemic, several initiatives to increase vaccine manufacturing capacity in Africa have sprung out of both public and private enterprise.

These initiatives range from fill and finish deals to longer-term capacity-building efforts, hoping to move the needle towards greater local vaccine manufacturing capacity. In Algeria, Egypt, Morocco, Rwanda, Nigeria, Senegal, and South Africa, partners have either signed MoUs for COVID-19 vaccine manufacturing or begun production. Côte d'Ivoire, Ghana, and Kenya have also expressed interest in, or have future plans to, expand into vaccine manufacturing.[8]

Sources: **[1] Africa is bringing vaccine manufacturing home, Nature, 2022 [2] The future of vaccine manufacturing in Africa, Brookings, 2022 [3] Latest updates for Africa CDC on progress made in COVID-19 vaccinations on the continent, Africa CDC COVID-19 Vaccine Dashboard, Accessed June 2022** [4] Fill and finish refers to the final step of the process where the substance of the vaccine is sent to the plant to be put in vials and distributed [5] The process of drug substance production entails growing host cells in a series of bioreactors of increasing scale and infected by the cirus seed to produve a final vaccine molecule. A series of filtration and chromatography steps are taken to harvest and purify the vaccine. Once the drug substance is produced, it is combined with buffers to achieve a final formulation – known as the drug product. For more information, see: **Innovating Production and Manufacture to meet the Challenge of COVID-19, Astrazeneca, 2021** [6]] Interim goals are 10% by 2025, and 30% by 2030. **[7] Prospects for local manufacturing of COVID-19 vaccines in Africa, Devex, 2022 [8] Prospects for local manufacturing of COVID-19 vaccines in Africa, Devex, 2022**

CASE STUDY

Snapshots of key initiatives to increase vaccine manufacturing capacity in the African continent during the pandemic

Morocco is scaling up its vaccine production. Morocco's Sothema laboratory is producing the Chinese Sinopharm vaccines, manufacturing 3 million vaccines a month. In January 2022, Morocco started constructing a new manufacturing facility (Sensyo Pharmatech) with Swedish firm Recipharm for COVID-19 and other vaccines.[1,2]

Institut Pasteur de Dakar (IPD), is building a new regional vaccine manufacturing hub. With funding from several European institutions,[3] IPD has started construction of a new vaccine manufacturing facility (MADIBA) which could supply 300 million doses of vaccines annually. This will include COVID-19 vaccines (likely starting with fill and finish) as well as other diseases, including a high-volume site for yellow fever, and a training site for next generation vaccines.[4] Furthermore, the facility — which was built from converted shipping containers — is highly customisable, with modules that can be swapped in and out as the technologies and needs evolve.[5,6] Currently, the institute has MoUs with BioNTech *(see box on right)* and with CEPI for strategic and technical support.[7] Leveraging its expertise as an established WHO-prequalified manufacturer of yellow fever vaccines, this upgrade will position IPD as a regional hub and bolster the health security of the region.

Algeria is producing COVID-19 vaccines at state-owned company Saidal following an agreement with China Sinovac laboratories to produce the CoronaVac vaccine.[8]

The first vaccine production facility in Nigeria is being launched in collaboration with Merck and Innovative Biotech as part of the West African Pandemic Readiness Programme.[9]

Egypt is locally producing COVID-19 vaccines through multiple initiatives. The state-owned firm Vacsera has produced 25 million doses of the Sinovac vaccine. Private firm Minapharm Pharmaceuticals has completed a tech-transfer process to produce the Russian Sputnik V vaccine. There are also efforts to develop Egypt's own COVID-19 vaccine (EgyVax) through a public-private venture which started phase one clinical trials in December 2021.[6,10]

BioNtech has signed agreements to produce in Rwanda and Senegal. The agreements with BioNTech (the company producing mRNA vaccines for Pfizer) will go beyond fill and finish to include full production mRNA vaccine manufacturing facilities under license, with construction aiming to start in mid-2022. Initially, BioNTech staff will run the facility as the company trains local partners, who will then take over the vaccine manufacturing process.[6]

Fill and finish deals in South Africa have created greater supply for the continent. Aspen Pharmacare has helped produce over 120 million Johnson & Johnson vaccines, with aims to increase production to 1.3 billion doses a year.[6] Biovac has also struck a deal with Pfizer, and, following a supply chain integration process in 2021, will start supporting production this year.[6]

Sources: [1] Morocco starts construction of COVID vaccine plant, Aljazeera, 2022 [2] Key partners included the Swedish company Recipharm, three Moroccan banks, the Mohammed VI Investment Fund and the Moroccan Samir Machour. [3] Including the European Commission, European Investment Bank, France and Germany. [4] Senegal: EIB provides €75 million to Institut Pasteur de Dakar for new vaccine manufacturing facility, European Investment Bank, 2022 [5] Senegal nears completion of 'bespoke' vaccine manufacturing facility, Devex, 2022 [6] Prospects for local manufacturing of COVID-19 vaccines in Africa, Devex, 2022 [7] CEPI and Institut Pasteur de Dakar partner to advance COVID-19 vaccine manufacturing in Africa, CEPI, 2022 [8] Algeria Begins Producing a Coronavirus Vaccine, Al-Fanar Media, 2021 [9] Merck Collaborates with Innovative Biotech to Support Establishment of First Vaccine Production, Merck, 2021 [10] WHO announces first technology recipients of mRNA vaccine hub with strong support from African and European partners, WHO, 2022

CASE STUDY

WHO has set up an mRNA technology transfer hub aiming to develop drug substance manufacturing capacity for COVID-19 vaccines.

The hub aims to work with local producers by sharing technology and know-how, bringing financial support, building human and technical capacity, and assisting with licensing and IP issues. In February 2022 a major milestone was reached when South African scientists at Afrigen Biologics and Vaccines successfully replicated the Moderna vaccine, using publicly available information.[1,2] The hub aims to start local production and phase one clinical trials, later moving to establish second-generation mRNA technology that can bring advantages over the current vaccine candidates and adapt existing technologies to emerging strains and new vaccination strategies.[3] The hub announced six initial countries (Egypt, Kenya, Nigeria, Senegal, South Africa, and Tunisia) who will be supported to adopt tools for local mRNA production. The hub also envisions expanding its platform to other diseases, including malaria, tuberculosis, and even cancer.[4]

Sources: [1] The mRNA technology transfer hub, WHO, 2021 [1] Missing source [2] South African scientists copy Moderna's COVID vaccine, Nature, 2022 [3] 6 African nations chosen for mRNA vaccine production, Devex, 2022 [4] WHO announces first technology recipients of mRNA vaccine hub with strong support from African and European partners, WHO, 2022

FORWARD LOOKING

→ Tackling issues with patents and IP.

Although African scientists and engineers are making progress based on what is publicly available or granted through technology transfer licensing, many parts of the mRNA and COVID-19 vaccine process are patented. This could pose challenges for the speed and success of initiatives such as the WHO mRNA technology transfer hub.[1] During the pandemic, member states and international organisations failed to reach a consensus on how to treat IP issues during international emergencies, with the WTO failing to adopt the full TRIPS waiver.[2] Looking ahead, ensuring that African producers can access the licenses and knowledge needed to develop their local vaccine industries will be integral to building up local capabilities.

→ Innovating on vaccine production techniques to work towards competitive costs.

A significant concern in the success of African vaccine manufacturing is that production costs will likely be higher than current major producers which have existing economies of scale – such as India, which makes approximately 70% of Africa's vaccines today. Setting up regional hubs will likely be key to reaching necessary economies of scale. In addition, innovations in the vaccine manufacturing value chain may lower costs for newer entrants, such as miniature-modular-manufacturing platforms, high-density bioreactors, and innovation in the steps for fill and finish.[3]

→ Fostering an enabling regulatory environment.

Creating an effective African vaccine market will require political and regulatory support to promote greater integration of vaccine markets across the continent. In 2021, the launch of the African Continental Free Trade Area was an important step towards this, as are the African Medicines Agency's efforts to harmonise regulation across the continent. Such efforts will need to continue, including keeping momentum after the COVID-19 pandemic.[3]

→ Building skilled local labour forces with cross-sectional skills.

Human resources are a vital pillar of vaccine manufacturing and expanding capacity will require a concerted and targeted approach to training. Vaccine manufacturing requires diverse skillsets, ranging from technical, regulatory, quality assessment and control, as well as an understanding of the market. To develop this cross-sectional view, creating links between universities and industry partners will be needed to provide a mix of theoretical and hands-on experience, such as is offered through the IDP Senegal apprenticeship programmes.[4] Some players are beginning to invest in this. For example, as part of a $1.5 billion partnership with Africa CDC, Mastercard Foundation is developing human capital programmes for vaccine manufacturing. This will focus on critical areas including process design, quality assurance, and laboratory testing, with plans to later expand into building the skills needed to drive R&D.[5] In the medium to long term, such investments should also lead to increased employment.

→ Committing to significant and sustained local investment.

For long-term sustainability, these initiatives cannot rely solely on international investment and aid, requiring a shift from 'donorship to ownership'.[4] Several African nations and institutions have made commitments so far, and this will need to continue post-pandemic. In the long term, such investments could reduce strain on trade balances and foster economic growth through employment and export potential.

→ Responding to the diverse demand within the African continent

African vaccine manufacturing must go beyond COVID-19 vaccines. Spurred by population growth, large immunisation coverage gaps, and the possibility of new products such as a malaria vaccine, estimates for the size of the public market for vaccines in Africa are between $2.3 billion and $5.4 billion by 2030.[3] Having local development and production capacity on the continent will hopefully allow African scientists and engineers to better address Africa-specific disease burdens, including responding to future endemic diseases or pandemics.

Sources: **[1] Moderna, WHO Set for Vaccine Clash as Patents Threaten mRNA Use, Bloomberg UK, 2022** [2] The Trade-Related Aspects of Intellectual Property waiver, otherwise known as the TRIPs waiver, would temporarily waive patents and certain other intellectual property protections associated with vaccines, treatments, and tests. For more information see: **The impact the TRIPS waiver would have on Covid-19 and why it's so important, Bond, 2022** [3] Africa Needs Vaccines, What Would It Take to Make them Here?, McKinsey, 2021 **[4] Ambitious vaccine plan requires different training approach, University World News Africa Edition, 2021** [5] Saving Lives and Livelihoods Four Areas of Focus: COVID-19 Vaccines for Africa, Mastercard Foundation, 2022

2.5

Streamlining delivery

THE CHALLENGE

Supply chain and delivery issues during COVID-19 resulted in delays and inequitable access to essential goods and services

The pandemic disrupted supply chains and the delivery of essential items. COVID-19 lockdowns and restrictions on trade, travel, and work disrupted the flows of food, medical supplies, and manufacturing inputs.[1] Some studies estimate a ~315% increase in supply disruptions between 2019 and 2022[2] — interrupting production processes, slowing or temporarily halting access to essential goods, and causing price fluctuations for both medical and non-medical items.

Overburdened staff and infrastructure exacerbated these challenges. Increased demand for testing, vaccinations, and non-medical goods (such as construction inputs), coupled with trade disruptions and increased stockpiling, placed significant strain on existing staff and infrastructure capacity. Ports were overwhelmed with goods that were slow to be cleared because of staff shortages and pandemic restrictions.[3] Health systems and warehouses suffered from similar under capacity of staff and infrastructure, which slowed the delivery of critical goods and services.[4]

The impact was more acute for low-resource communities and L/MICs. Increased demand for items like PPE, tests and vaccines, paired with constrained supply resulting from trade restrictions, created a sellers' market for producing countries. This meant buyers had to provide before-sale financial commitments or stockpile — a requirement not always possible for L/MICs.[4] Countries like Uganda, Malawi, and Nigeria faced critical shortages and a limited ability to purchase to meet their needs.[5] In addition, countries that received donated vaccines from HICs frequently received them close to their expiration date, leading to unnecessary wastage. For example, Malawi had to destroy ~20,000 doses and DRC reported an inability to use much of the 1.7 million doses received.[6] Within countries, supply chain disruptions affected communities in rural or humanitarian settings more, where challenges to last-mile delivery were exacerbated.[7] In refugee camps in Mali, for example, there were severe shortages of medical products and construction materials required to respond to the pandemic.[8] Remote communities with poor road access also experienced greater challenges in delivery. For example, in Peru, hard to access communities in the mountainous Andes struggled to access critical medical goods and services.[9]

Sources: **[1]** How COVID-19 impacted supply chains and what comes next, EY, 2021. **[2]** Number of supply chain disruptions worldwide from 2019 to 2021, Statisa, 2022 **[3]** Impact of COVID-19 on the supply chain industry, PWC, 2021 **[4]** **Health systems resilience in managing the COVID-19 pandemic: lessons from 28 countries, Haldane, V., De Foo, C., Abdalla, S.M. et al., 2021.** and Global shortage of personal protective equipment, Burki T. 2020 **[5]** Insights From Africa's Covid-19 Response: Repurposing Manufacturing, Tony Blair Institute for Global Change, 2020.

Globally, these disruptions had critical implications at the individual, business, and economy level. Some examples of these implications included:

Individuals

- **Critical shortages of essential goods left many vulnerable.** For example, by April 2022, the number of people living in severe food insecurity had doubled from pre-pandemic levels to 276 million, largely as a result of supply chain disruptions.[10]
- **Fluctuations in demand caused cross-sector layoffs.[11]** This experience was particularly acute for vulnerable daily workers who faced layoffs, cuts in working hours, and decreases in income.[12] For example, 13% of garment workers in Ethiopia, Honduras, India, and Myanmar had their contracts terminated during the pandemic, while employed garment workers saw an average 11% drop in their monthly income.[13]

Businesses

- **Production bottlenecks, worker shortages, and export bans stymied business growth:**
  73% of surveyed supply chain executives from around the world indicated that they experienced problems with their supplier base during the pandemic.[14]
  In the manufacturing and services sectors, suppliers' delivery times hit record highs in the US and the EU. The Purchasing Managers' Index (where values below 50 indicate slower delivery times compared to the month prior) dropped from ~50 to ~20 for both regions between early 2020 and 2021.[15]

The economy

- **Price increases and stunted trade growth impacted the overall economy.[16]** Between November 2020 and September 2021, some estimates indicate that world trade would have been ~3% higher without supply chain shocks, and industrial production would have been ~1.5% higher.[17]

Sources: **[6] COVID-19 vaccines: Why some African states can't use their vaccines, BBC, 2021** [7] Humanitarian supply chains during COVID-19: systems failures, recovery and emerging alternatives, Lowe A, Travers C., 2020 [8] Expert interviews. **[9] Wingcopter: Improving Health Logistics Infrastructure In Peru, 2022** Sources: **[10]** COVID-19 Brief: Impact on Food Security, U.S. Global Leadership Coalition, 2022 **[11]** Labour market developments: The unfolding COVID-19 crisis, OECD, 2021. **[12]** COVID-19: The impact on workers in global supply chains, Lewry J, 2020 **[13]** The Unequal Impacts of Covid-19 on Global Garment Supply Chains, LeBaron G et al, 2021. **[14]** Resetting supply chains for the next normal, McKinsey, 2021 **[15]** What longer delivery times say about global supply chains, World Economic Forum, 2021. **[16]** Why the Pandemic Has Disrupted Supply Chains, Helper S, Soltas E, 2021. **[17]** Supply chain disruptions and the effects on the global economy, ECB, 2021

ENGINEERING'S CONTRIBUTION

Engineers undertook critical innovations and optimisations to address delivery disruptions

Engineers intervened to address supply chain disruptions and ensure that critical pandemic response efforts could run.
In response to disruptions, engineers (including systems, supply chain, software, and civil engineers) worked to decrease the susceptibility of supply chain networks to shocks and bolster their ability to recover from or respond to crises. Investments into greater visibility – such as expanding digitisation of demand forecasting, inventory planning, and procurement – allowed supply chain managers to better plan for and mitigate shocks.[1] Digital platforms for procurement also supported supplier diversification, which created greater supply chain flexibility.[1,2] In addition, engineers improved physical infrastructures and pioneered technical innovations for the transportation of essential goods. This included improving cold-chains in L/MICs to transport vaccinations, deploying drones for last-mile delivery, and emergency construction of warehouses, test centres, and medical facilities. These efforts allowed essential goods and services for direct pandemic response and broader societal support to be delivered despite severe disruptions.

These contributions have set the foundation for supply chains to be more resilient, responsive, collaborative, and networked.[1]

Sources: **[1] Role of systems engineering attributes in enhancing supply chain resilience: Healthcare in context of COVID-19 pandemic, Hossain N et al, 2022**. [2] How COVID-19 impacted supply chains and what comes next, EY, 2021.

Resilient. Supply chain engineers conducted risk reviews to reveal potential pandemic-related gaps or vulnerabilities and bolster their resilience to potential shocks. For example, Afrox, a sub-Saharan African gas producer, conducted an oxygen supply chain risk review and developed a range of emergency responses for potential disruptions in the supply chain.[3] Engineers also supported efforts for increased optimisation to ensure supply chain resilience in the face of labour supply disruptions. Engineers in China designed and constructed the first fully automated port in Shandong boasting the fastest loading and unloading efficiency of any terminal in the country and requiring minimal staff capacity to function.[4]

Responsive. The pandemic catalysed the shift towards digitising end-to-end supply chain processes, which increased visibility and the ability to respond to disruptions quickly.[5] Engineers also expanded the use of AI for demand and disruptions forecasting. For example, C3.AI developed the C3 AI COVID-19 Data Lake which used AI to accelerate the analysis of critical supply chain issues and allow for rapid planning and response.[6] Similarly, where engineers propelled e-commerce solutions – a sector that has grown two to five times faster than pre-COVID-19 – there have been gains in tracking and tracing, intervention planning, and visibility.[7]

Collaborative. The pandemic necessitated increased coordination between different nodes of the supply chain to navigate disruptions. Engineers and supply chain managers built relationships with actors across the supply chain to quickly establish collaborative processes for delivery.[8] For example, engineers building quarantine centres in Mali's peacekeeping camps collaborated with suppliers and transport providers (such as passenger airlines pivoting to transporting cargo), to facilitate the procurement of critical goods across borders despite lockdowns.[9]

Networked. The pandemic accelerated the shift from linear supply chains toward digital supply networks. Using web-enabled capabilities, these networks more readily considered external factors, and improved connectivity between customers, suppliers, and other stakeholders. IoT devices[10] were leveraged, for example, in the agricultural sector where they were used in warehouses as a form of automatic and remote inventory management to provide alerts on low supply. These devices were able to provide more information and inventory decision-making capability to actors across the supply chain while minimising the need for in-person monitoring, which was particularly important during lockdowns.[11]

Sources: [3] Afrox medical oxygen supply statement, Afrox, 2021 [4] Qingdao Port: a Chinese model for the construction and operation of the intelligent port of the future, 2021.[5] Supply chain disruption: Repurposed supply chains of the future must have resilience and responsibility at their heart, Accenture, 2022, and Supply chain challenges, lessons learned and opportunities, National Engineering Policy Center & Royal Academy of Engineering, 2020 [6] C3 AI COVID-19 Data Lake, website [7] The rise of e-commerce in the post-pandemic world, Burke J, 2022. [8] Expert interviews. [9] Expert interviews. [10] IoT and the Supply Chain: How Machine Learning Eases Bottlenecks, DIGI, 2021 [11] IoT and the coffee supply chain, DIGI, 2021

EXAMPLES OF ENGINEERING EXCELLENCE

Strengthening oxygen logistics

Software, construction, and biomedical engineers worked to strengthen weak or disrupted supply chains for medical-grade oxygen.

- Engineers at Afrox – sub-Saharan Africa's leading gas producer – used remote telemetry monitoring to gauge oxygen levels available in storage tanks in hospitals across South Africa. Once these tanks reached 40%, Afrox would facilitate the delivery of bulk oxygen to circumvent the impact of any potential supply chain delays on hospital capacity.[1]
- The COVID-19 Respiratory Care Response Coordination partnership[2] worked with software engineers to develop the COVID-19 Oxygen Needs Tracker[3] which estimated the daily oxygen needs of countries based on reported COVID-19 cases. This data was used to plan for sufficient oxygen and to strengthen supply chains.[4]

Improving cold chain infrastructure

Insufficient cold chain infrastructure was already a salient problem pre-pandemic, especially in L/MICs. This worsened during COVID-19 alongside an increased need to deliver temperature-sensitive therapeutics.[5] Engineering innovations worked to bridge this gap.

- At Gricd, a Nigerian IoT company, engineers developed an active cooling box that can be monitored remotely.[6] During the pandemic, they scaled their reach, partnering with Nigeria's Health Care Development Agency to deliver 4.2 million doses of the Moderna COVID-19 vaccine using this technology.[7]
- In Ulaanbaatar, Mongolia, engineers and technical experts from the Energy Sector Management Assistance Programme with support from UNICEF and the World Bank collaborated to upgrade the city's vaccination storage to be energy efficient, earthquake resistant, and hold four times the vaccination capacity as the previous facility.[8]
- During the pandemic, the social enterprise Ideabatic tested their vaccine transport 'Smart last-mile' (SMILE) cooling system in Madagascar. SMILE technology relies on a singular ice pack and can go without power for three to six days, making it ideal for settings with limited access to electricity.[9]

Delivering to remote locations with drones

To tackle challenges in last-mile delivery, engineers integrated drone technology into supply chains. This allowed hard-to-reach communities to access key supplies and reduced the need for cold chain infrastructure or dry storage in remote health facilities.[10]

- UAV LATAM, a Peruvian Robotics Knowledge Centre, partnered with Wingcopter, a German drone company, to provide medical products to remote Andean communities. The team used AI and robotics, along with knowledge of the Peruvian landscape, to build the devices and start delivering critical products.[11]

Sources: [1] Afrox medical oxygen supply statement, Afrox, 2021 [2] COVID-19 Respiratory Care Response Coordination Project, PATH, 2021 [3] COVID-19 Oxygen Needs Tracker, PATH, 2022 [4] Expert interviews. [5] Port to patient: Improving country cold chains for COVID-19 vaccines, McKinsey and Company, 2021. [6] A comprehensive condition monitoring solution for the healthcare industry, gricd, 2021 [7] Nigerian last mile delivery firm Gricd delivers 4.2M COVID-19 vaccines using cold storage tech, appsAfrica, 2021 [8] Responding To The Covid-19 Crisis In Mongolia With A Climate-friendly Central Vaccine Store, World Bank, 2022. [9] SMILE: The Science and engineering behind SMILE, Ideabetic, Date Accessed: July 2022 [10] How the emergence of connected drones is helping the fight against COVID-19, GSMA, 2020 [11] Wingcopter: Improving Health Logistics Infrastructure In Peru, 2022

EXAMPLES OF ENGINEERING EXCELLENCE

Mitigating shocks to food distribution

Software and systems engineers optimised food value chains and drove innovations in e-commerce and food delivery to mitigate pandemic-related impacts on access to food.[1]

- Jumia Food Uganda, a food e-commerce leader in Africa, partnered with UNDP to connect informal market vendors to customers during the pandemic. To date, Jumia Food Uganda has been able to connect seven markets in Kampala to an e-commerce network, leveraging technology to formalise informal supply chains.[2]
- To address food insecurity during the pandemic in Fiji, a local technology venture, Cyber Foods, expanded its digital food delivery platform to provide groceries during lockdowns. The platform leveraged communication services (such as WhatsApp and Facebook), as well as mobile money providers to run its service to support both customers and local businesses.[3]
- During the pandemic in South Africa, the data intelligence company Farmers Assistant scaled the reach of their app which connects smallholder farmers to the entire food value chain. The Farmers Assistant app connected small-holder farmers to NGOs that needed food parcels, to grocery delivery companies, and to customers. The app also connected smallholder farmers to prospective funders and investors, which was particularly important given the barriers to accessing in-country funding.[4] Currently, Farmers Assistant is present in 20+ countries across Africa, Asia and Latin America.

Sourcing critical production inputs

The pandemic also disrupted access to critical production inputs and materials. Supply shortages and inventory storage challenges meant engineers had to help companies diversify their supply bases and explore new procurement channels.

- Scoutbee, a German AI-powered supplier, developed an AI-based supplier discovery platform that enabled organisations to find critical supplies. Scoutbee's AI technology searches through data on millions of suppliers, evaluating them against a set of pre-determined criteria and providing recommendations on best-fit.[5]

Emergency pandemic construction with drones

In the face of under capacity of key infrastructures, engineers supported the emergency construction of facilities such as hospitals and warehouses at unprecedented speed and scale.

- China's 'Fangcang' hospitals were constructed to provide beds for mild and moderate COVID-19 cases. The 'Fangcang' hospitals were built by converting existing public spaces (like stadiums) in only 10 days and were characterised by large scale and low-cost construction.[6] In addition to spearheading construction efforts, engineers worked to quickly develop the Fangcang hospitals' IT infrastructure and data management systems.[7]
- In South Africa, engineers transformed the Cape Town International Convention Centre into a field hospital in six weeks. This included constructing new oxygen infrastructure that allowed for oxygen to be piped to each of the centre's 862 beds.[8]
- In the UK, 200 engineers collaborated to rapidly design and construct the Nightingale hospitals[9] – a series of emergency hospitals commissioned to manage the surge of COVID-19 cases. The first Nightingale hospital was a temporary conversion of London's ExCeL exhibition centre, and was fitted with oxygen and ventilators, 80 separate wards, and nearly 500 fully equipped beds in only nine days.[10]
- To meet increases in warehousing demands relating to the rise of e-commerce, ~15 million square feet of 'super sheds' were built in the UK, including 49 new distribution warehouses in 2020 alone.[11]

Sources: [1] Supply chain challenges, lessons learned and opportunities, National Engineering Policy Center & Royal Academy of Engineering, 2020 [2] Connecting informal market vendors to e-commerce to reach consumers in the wake of Covid-19 and beyond, 2020 [3] Impactful Innovations: Insights from evaluating Cyber Food, GSMA, 2021. [4] A technology company founded by a woman is helping small-holder farmers survive lockdown, Health News, 2020 [5] SCOUTBEE, website [6] The Secret Of China To Build A Hospital In 10 Days, sacyr, 2021 [7] Expert interviews [8] Expert interviews. [9] NHS planes new Nightingale facilities in response to Omicron, NHS, 2021 [9] Expert interviews. [10] Coronavirus: How NHS Nightingale was built in just nine days, BBC, 2020 [11] Super sheds built across UK as online retail boom sparks warehouse demand, Saker-Clark, 2021

"Emergency construction jobs that would have taken years from start to finish, took weeks. Engineers working to build robust supply chains were essential to us being able to do this."

Engineer working on emergency pandemic construction

UNLOCKING ENGINEERING POTENTIAL FURTHER

Despite robust efforts to bolster supply chains, greater local investment is needed to build resilience against future shocks

The pandemic revealed a need to shorten supply chains and increase regional self-sufficiency.
The pandemic exposed the fragilities of long and complex global supply chains[1,2] and prompted a renewed interest in nearshoring[3] — the process where businesses prioritise the use of operations close to the final point of sale, shortening the supply chain and allowing for greater flexibility and collaboration.[4] Engineers have a key role to play in this process, from the side of supply chain optimisation, as well as increasing local production capacity as nearshoring requires a strong base of local producers *(see previous section 2.4)*.

The strengthening of regional supply chains is particularly important for importing countries with nascent manufacturing industries most harshly impacted by pandemic-related import delays.[5] However, despite many companies expressing plans to invest in nearshoring at the onset of the pandemic, this intention has not yet materialised. Instead, many companies favoured increasing their inventories and stockpiling critical goods[6] — which was often a faster and cheaper response in the middle of a pandemic.[6]

To ensure greater pandemic resilience moving forward, increased investment into nearshoring during 'peacetime' will be needed. This could in turn result in increased local job creation and skill accumulation.[7,8] Evaluating the potential environmental implications of this will also be an important role for engineers.[7]

Insufficient integration with and consideration of surrounding systems limited supply chain efficiency.
Supply chains do not exist in silos, but connect to and interact with other systems, such as a country's health system.[9] These other systems need to be taken into consideration when designing and modifying supply chains. For example, while the UK's Nightingale hospitals represented a feat of innovative engineering, staff shortages meant those hospitals were underused.[10] Similarly, integrating drones for last-mile delivery could only be achieved if drones were adopted into the country's health system and health workers were trained on how to use the drones.[11] Remaining sensitive to the constraints and needs of the operating environment will be critical going forward to maximise the impact of engineering contributions.

Efforts to digitise supply chains need to be more uniformly applied

A lack of uniform digitisation across the supply chain, including the slow pace of adoption in certain areas, hindered potential.
Across many sectors, digitisation was not adopted at the same rate along the supply chain. Certain actors continued using outdated or incompatible IT systems, while many others did not use digital systems at all, resulting in inefficiencies.[12,13] As a result, 85% of respondents from a study of supply chain executives across geographies and industries indicated that they struggled with 'inefficient digital technologies' in their supply chain during COVID-19.[13] Moving forward, it will be imperative to break down data silos and ensure data and communication systems are well integrated across supply chains. Increasing the compatibility and coordination of digital systems across all tiers will reinforce the gains from digitisation seen so far and further increase supply chain resilience.

Sources: **[1] Building back better: A sustainable, resilient recovery after COVID-19, OECD, 2020. [2] New perspectives: How COVID-19 has shifted sustainability priorities in the mobile sector, GSMA, 2020 [3] Global Supply Chains in a Post-Pandemic World, Sihi W, 2020. [4] How COVID-19 is reshaping supply chains, McKinsey and Company, 2021. [5] Here's how we can resolve the global supply chain crisis, UNCTAD, 2022. [6] How COVID-19 is reshaping supply chains, McKinsey and Company, 2021. [7] Reconstructing your supply chain with nearshoring, Jorge J, Bergen E, 2021 [8] The benefits and sustainability of short food supply chains, 2021.** [9] Expert Interviews. **[10] Was building the NHS Nightingale hospitals worth the money?, The Kings Fund, 2021.** [11] Expert Interviews. **[12] Supply chain disruption, Accenture. [13] Resetting supply chains for the next normal, McKinsey and Company, 2021.**

UNLOCKING ENGINEERING POTENTIAL FURTHER

Persistent skills gaps often drive this disparity and prevent efficient uptake of digital solutions.

Comprehensive digitisation was also constrained by limited technical and digital skills. The implementation of disruptive technologies such as IoT or AI, requires specialised technical skills and supply chain expertise, which were often in short supply.[1] In the UK, 35% of senior supply chain industry professionals believe that they do not have the skills capacity to support innovative solutions, while 15% believe that a lack of talent in digital skills is the main contributing factor to the inadequate use of smart machines.[2] Achieving widespread digitisation will therefore require investment in up- and re-skilling supply chain engineers and logisticians to ensure more comprehensive technical and digital capacity.[3] Filling these skills gaps across the entire global supply chain is needed to ensure flexible, data-driven, and resilient supply chains.

> **"We cannot be solely reliant on the US, China, and Europe for parts. For example, we've had plants built by German companies, but then faced sustainability challenges when we cannot source spare parts locally."**

Former health policymaker in Africa

Sources: [1] Addressing the skills gap in the supply chain industry, University of London, 2021 [2] Plugging The Digital Skills Gap To Maintain An Effective Supply Chain, Whatson S, 2021. [3] New perspectives: How COVID-19 has shifted sustainability priorities in the mobile sector, GSMA, 2020

CASE STUDY

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

THE INNOVATION

- Bridging the healthcare delivery gap through drone-enabled last-mile transport to remote communities in Africa.

IMPACT AT A GLANCE

- Created flexible last-mile supply chains that could quickly respond to changes in contexts and patients' needs.
- Provided access to medicine and vaccines for thousands of patients in remote locations in DRC, Malawi, and Mozambique.
- Facilitated increased speed of disease diagnosis and treatment for diseases like COVID-19.

ENABLING FACTORS

- Partnerships between drone service providers, private sector, and public health actors.
- Pre-established drone networks that laid a foundation that could be quickly redirected to the pandemic response.

CHALLENGES

- Technical innovation is not stand alone and requires integration into the full health system.
- Drone network cannot be developed during a crisis and must be set up in advance and kept warm during 'peacetime'.

CONTEXT AND NEED

COVID-19 exacerbated last-mile delivery challenges for vital medical products.

Around the world, natural disasters (such as cyclones or floods), poor road networks, and constrained healthcare systems in remote locations make the effective transport and delivery of essential medical items challenging. These issues were exacerbated during the pandemic, given restrictions on transport and public interaction, and created inequitable access to lifesaving medicines, vaccines, and COVID-19 tests for remote communities.

ENGINEERING CONTRIBUTION AND IMPACT

To expand last-mile reach, health tech stakeholders leveraged drone technology.

Since 2015, VillageReach, an NGO supporting tech-enabled pathways to primary healthcare, has partnered with local health officials, drone service providers, and private actors to establish a transport network using drone technology to reach remote communities. The NGO uses 'Swoop Aero' drone technology for bidirectional drones that use visual targets to land in areas without mobile access. VillageReach works with local governments to pivot existing medical transportation networks to include drones. During the pandemic, these drone networks were quickly adapted to include the transport of COVID-19 vaccines, medicines, and tests to and from remote communities and health facilities.

Sources: [1] Opportunities and limits of wastewater-based epidemiology for tracking global health and attainment of UN sustainable development goals, Sangeet Adhikari, Rolf U. Halden, 2022 [2] Wastewater network infrastructure in public health: Applications and learnings from the COVID-19 pandemic, Sharara et al, 2021

CASE STUDY

Having the right systems and skills in place to implement and iterate on the technology were key drivers of success.

Technological iteration was important. For example, engineers conducted test flights to ensure the drones were fit for purpose (including being resilient to harsh climates) and built redundancies into the drone systems which allowed them to switch from cellular to satellite communication in low-connectivity areas.

However, what proved most critical was ensuring that the technology was well integrated within the implementing ecosystem.

VillageReach supported the adoption of the drones into local district health networks. Acceptance and local ownership of the drone transport system was critical, and VillageReach played an important role in fostering relationships between different stakeholders to facilitate this system integration. Similarly, to respond to COVID-19, VillageReach had to tap into its pre-pandemic drone networks. This was key given the significant infrastructure, established ecosystems, and personnel required to initiate these networks, in addition to the limited time available to do so at the onset of the pandemic. This experience demonstrated the importance of investing in both physical and human capacity before a crisis hits.

Coordinating the drone technology to complement other transport mechanisms across the supply chain helped sustain the impact.

Drones do not replace other transport methods (like trucks or motorcycles) which are better suited for the transport of large products that are not cold-chain-dependent or that may have a longer shelf life. VillageReach used drones both for routine and on-demand direct transport of lightweight, cold-chain-dependent products whose delivery was time-sensitive. Increased integration of drones into the supply chains reduced the need for dry storage in health facilities and reduced wastage of high-value products (such as blood, vaccines, or oxycontin). Having this flexibility within the supply chain increased resilience against disruptions, and allowed healthcare workers in remote locations to respond to patient demands quickly.

Supporting COVID-19 relief efforts in Malawi

- 500 items of PPE for COVID-19 delivered.
- 42 health facilities served with over 10 flights a day.
- Over 3,300 flights and 94,000 km flown.
- 16,000 COVID-19 vaccines and a further 16,000 routine vaccines delivered and administered.
- 2,800 HIV and tuberculosis lab samples collected.

Piloting COVID-19 support in Mozambique

- During the pilot, drones transported 140 COVID-19 and 160 tuberculosis lab samples.
- Scaled to daily drone pick-ups of COVID-19 and other lab samples from three remote hospitals and three hard-to-reach health units, collecting over 600 lab samples after only one month.

Facilitating the continuation of essential health services in DRC

- 40 health facilities served routinely since December 2020.
- Over 3,100 flights and 142,000 km flown.
- 1,300 medical products transported, and 233,000 vaccine doses delivered.

Sources used for case study: **Interview with VillageReach's Drones for Health Program; Drone vaccine delivery for remote locations, VillageReach, 2020; Integrating drone transport into public health supply chains, VillageReach, 2020; Drones for Health: Boosting access to lifesaving products, VillageReach, 2020**

2.6

Supporting society's systems

THE CHALLENGE

Strong underlying systems were critical to stabilising societies in the chaos of the pandemic, and in helping them pivot to the new normal

Society's underlying systems and infrastructure had to hold strong against the pandemic's disruptions.
Modern societies function through a series of foundational systems. These include those that serve our essential needs, such as systems for energy or sanitation; those that make up our underlying physical infrastructure, such as the built environment and transport systems; and those that drive digital connectivity, such as telecommunications systems and their applications in online education or work. Engineers have long supported these building blocks of society, and this role was only heightened during COVID-19. As societies grappled with the disease, they needed support to keep essential functions running to meet core needs.

Strong systems were crucial to positive health outcomes.
Beyond enabling societies to function, these systems are important pre-conditions to positive health outcomes — a fact that rang especially true during COVID-19.[1] For instance, without access to clean water or sanitation, communities were unable to follow expected protocols of washing hands.[2] Without robust energy systems — one study suggests electricity access was inadequate in ~60% of health facilities in 46 L/MIC countries[3] — health facilities could not provide medical intervention to COVID-19 patients.

Resilience in one system often had domino effects in other systems.
At the same time, recognising the interconnectedness of our systems — such as between the built environment and the natural environment, or between digital infrastructure and the economy — proved critical to driving an effective response.[4]

Resilient systems not only helped societies persevere through the pandemic, but also supported their pivot to a new normal.
Around the world, both formal health measures and informal social norms shifted in response to COVID-19. Governments and private enterprises alike began instituting norms around social distancing, remote working, or new ways of interacting with public spaces. Without investment or adaption of the underlying systems and infrastructure to enable these interactions, societies would not have been able to adhere to these new norms, minimise infection risk, or navigate the new normal. Expanded digital infrastructure, for example, and the resulting increased digitisation of platforms for work and study, were both crucial to helping people sustain livelihoods remotely.

Sources: [1] Engineers are unsung heroes of global health, Madhukar Pai, 2022 [2] Expert interviews [3] Energy access is needed to maintain health during pandemics, Nature Energy, 2020 [4] Our vision for the built environment, IPFA, Date Accessed: July 2022

“ Systems are foundational aspects of society, and engineers are engaged in all these systems.”

Manager at leading engineering-for-health non-profit

ENGINEERING'S CONTRIBUTION

Engineers were essential to reinforcing or pioneering adaptations to strengthen society's underlying systems

> **"The fact that this wasn't headline news didn't mean it wasn't important. How [engineers] kept vital capabilities up and running was critical"**
>
> *Director at a leading telecommunications association*

Engineers bolstered society's systems to endure the pandemic.
Around the world, engineers tapped into cross-functional skills – design, prototyping, construction, operation, maintenance, and training[1] – to maintain essential services and critical infrastructure. In many cases, this cadre of engineers brought specific operational excellence and expertise, on top of strengths in research and design.

Their contribution was essential to societal health and general resilience.
Though perhaps not always recognised as such[2], these engineers were essential workers. In 2020 for instance, those working with communications infrastructure or at data centres were deemed essential workers in the US and UK[3]. Electrical engineers maintaining energy systems helped deliver critical medical interventions, such as the running of ventilators.[4] In some cases, these essential workers faced risks of direct contact with the virus via their work. For example, engineers working within sanitation systems facilitated the safe disposal of products contaminated by COVID-19, such as used masks and PPE.[5] Though often taking place in the background, engineering contributions made towards systems strengthening were critical to pandemic response and resilience.

Many of the strengthened systems will have a lasting impact beyond the pandemic.
In working to bolster these systems, engineers drove a paradigm shift in the pace and nature of digitisation they facilitated. So significant has the intervention in mobile and internet systems been[5], as well as the applications that are dependent on this (such as edtech software or digital collaboration tools), that the ways in which we work, study, and even socialise will be fundamentally different in a post-pandemic world. Similarly, the increased application of IoT and automation technology in maintaining buildings, transport, and energy and water utilities will herald a new era of infrastructure responsiveness and management.[6] Engineers played a key role in precipitating this new normal, which is also expected to bring co-benefits and positive impacts in areas such as green energy transition, air pollution, and global interconnectivity. At the same time, engineers will have to play a role in managing the risks that come with this increased digitisation – notably, resolving cybersecurity challenges.

Sources: [1] Water, Sanitation, Hygiene. Engineers without Borders, Date Accessed: July 2022. [2] Expert interviews [3] Data center staff classified as essential during pandemic, Data center dynamics, 2020 [4] Energy access is needed to maintain health during pandemics, Nature Energy, 2020 [5] Expert interviews [5] COVID-19 will accelerate the revolution in energy systems, World Economic Forum, 2020 [6] How COVID-19 has pushed technology companies over the technology transfer tipping point, McKinsey & Company, 2020 [6] The 5 most interesting start-ups in smart buildings, CM Industrial, 2021

EXAMPLES OF ENGINEERING EXCELLENCE

Ensuring reliable electricity access

The nature of energy demand changed from being concentrated in commercial centres to being distributed across residences[1,2] and engineers helped ensure access to reliable power.

- This involved the **use of digital solutions: drones, AI, or Lidar for routine service, IoT devices for tracking equipment,** or geospatial data to support operators and field engineers.[3,4] A survey of electric utilities across the Americas, Asia-Pacific, Europe, and the Middle East revealed that 84% of organisations increased the use of IoT applications during COVID-19 in 2020, and 42% had installed new IoT solutions in that time.[5,6]

- This also required **structural reorganisation from field operators and technicians,** in accordance with new regulations.[7] At UTE, the energy company serving 99% of Uruguay, engineers worked in rotations, isolated at control centres, or streamlined tasks like meter readings; managing to optimise processes to deliver services at ~50% capacity.[8]

- Providing **electricity for health** was also prioritised. Power Africa – a USAID electrification initiative in sub-Saharan Africa – provided $2.8 million in grants to solar energy players and engineering teams during the pandemic to bolster the provision of solar electricity to peri-urban and rural health facilities in Africa.[9] Through this intervention, the Lesotho-based off-grid energy company OnePower, partnered with South African-based Sustained Solar to **ship and install a containerised solar power solution to rural clinics in Lesotho.**[10]

Maintaining clean water and sanitation (WASH)

COVID-19 magnified a multitude of WASH-related issues, which environmental or civil engineers and technicians helped resolve. This included ensuring clean and secure water supplies, as well as effective solid waste management, at the level of system-wide utilities, as well as via community-specific intervention.[11,12,13]

- At the request of the Cambodian government, engineers from Engineers Without Borders built pedal-operated handwashing stations for health facilities, designed to withstand years of use. Following their success in health centres, there are plans to scale them in schools.[14,15]

- In Bangladesh, a collaboration between engineers at Bangladesh University of Engineering and Technology, officials at the Department of Public Health Engineering, and local NGOs developed specialised training for sanitation workers to manage solid waste (such as discarded PPE). In doing so, they built capacity for sanitation workers, changed mindsets around their role in the pandemic response, and informed updates to policy and guidelines on effective sanitation management.[16]

Sources: [1] How COVID-19 has changed energy networks for the better, PEI, 2021 [2] Energy transition and COVID-19 crisis: the role of engineers, Committee proceedings, WFEO, 2021 [3] IoT in utilities market brings resilience in wake of COVID-19, IoT World Today, 2020 [4] How engineers are keeping your power on during COVID-19, IEEE Transmitter, 2020 [5] Industrial IoT in the time of COVID-19 electric utilities, Inmarsat, 2020 [6] Electric utilities increasingly turning to IoT adoption due to COVID-19, Electric Review, 2021 [7] How engineers are keeping your power on during COVID-19, IEEE Transmitter, 2020 [8] Energy transition and COVID-19 crisis: the role of engineers, Committee proceedings, WFEO, 2021 , [9] Power Africa Covid-19 Response And Recovery, USAID, 2022 [10] Switching on 'Silent Power' for Clinics and Communities in Remote Lesotho, Power Africa, 2021 [11] Expert interviews [12] Role of sanitary engineers in prevention of COVID-19 pandemic, Darko Vujasinovik, 2020 [13] Engineers are unsung heroes of global health, Madhukar Pai, 2022 [14] Expert interviews [15] Buildings that keep us healthy and safe, Royal Academy of Engineering, 2021 [16] Expert interviews

EXAMPLES OF ENGINEERING EXCELLENCE

Adapting Heating, Ventilation and Cooling (HVAC) systems in buildings

Evidence soon indicated that COVID-19 transmission was primarily airborne. Given people spend 90% of their time in the built environment (which includes buildings and transport),[1] chances of infection were higher indoors. To address this, engineers contributed to research, guidelines, and improved technology for pandemic resilient infrastructure. This included HVAC systems for clean air supply, air filtering, or retrofitting.[2]

- In Germany, ebm-papst, a fan manufacturer, and Envio Systems, a smart buildings solution provider, brought IoT-enabled fans to buildings. The solution provided building managers with the tools and data needed to adapt their buildings' HVAC systems, including to meet COVID-19-safe ventilation requirements (set by indexes like RESET for health performance data for buildings).[3]
- Using lessons from the pandemic, One Lightwave, a startup in Canada, is developing a UV light-based sterilisation technology to kill viruses in buildings without harming people. [4]

Canadian schools revamped HVAC systems to be COVID-19 safe, utilising engineering expertise

Early in the pandemic, when there was still uncertainty around the virus's transmission, Canadian engineers (and associated industry bodies) pioneered research and guidelines on adequate indoor ventilation and mechanisms to develop pandemic resilient infrastructure. Given how critical this was in minimising the spread of the infection, it was soon adopted and scaled by government stakeholders.

In December 2020, for instance, the government of Quebec province requested schools to test their air quality and CO2 concentrations. Based on the findings, more than 90,000 CO2 monitors were installed in classrooms, and millions were invested into the renovation of school ventilation systems.[5]

Facilitating transportation upgrades

As the pandemic drove changes in how to better sanitise vehicles or in people's mobility patterns, engineers reimagined transportation systems.

- In Italy, engineers helped build 200km of light cycle paths to accommodate a ~60% increase in purchased bicycles in 2020. This brought co-benefits in health and reduced pollution and traffic.[6]
- Engineers associated with the Chinese Academy of Engineering worked on passenger traffic ventilation and decontamination technology, such as air purification using a mixture of plasma equipment and UV. Its use was recommended for the ventilation of both private cars and public transport (trains, buses, and ships).[7]
- In the UK, Cranfield University engineers, in partnership with Q-Flo – an innovation venture from Cambridge University – and the NHS, recorded airflow data in NHS ambulances, providing airflow maps of the ambulance's interior over various driving conditions. This was intended to help the integration of Q-Flo's virus filter system which captures and destroys virus molecules.[8] Similarly, engineers from the University of Birmingham, in partnership with NitroPep Ltd. and Pullman air conditioning, developed antimicrobial technology to be used in air filters to kill bacteria and viruses in seconds. This technology was tested onboard UK trains and is being developed by NitroPep to deliver it to market.[9]

Sources: [1] Expert interviews **[2] Addressing COVID-19 in buildings, Canadian Committee on Indoor Air Quality, Date Accessed: July 2022 [3] RESET, ebm-papst, and Envio Systems response to airborne pandemics and health, Envio, 2020** [4] Expert interviews [5] Expert interviews **[6] Energy transition and COVID-19 crisis: the role of engineers, Committee proceedings, WFEO, 2021** [7] Expert interviews [8] New research to enhance air filtering in ambulances, Cranfield University, 2021 **[9] New antimicrobial air filters tested on trains rapidly kill SARS-CoV-2 and other viruses, University of Birmingham, 2022**

EXAMPLES OF ENGINEERING EXCELLENCE

Strengthening connectivity to enable digital applications and services

COVID-19 accelerated our transition to digital living (including working and studying online). As demand for mobile and internet connectivity surged – an increase of ~50% in some markets[1] – infrastructure engineers bolstered network stability and pushed technology (such as 5G, spectrum, and cloud architecture)[2] to scale up vital links to information. Telecom operators also accelerated the digitisation of their business models, for example introducing online recharge, or bundling with other digital services such as e-pharmacy, insurance, or edtech.[3]

- Engineers globally strengthened IT infrastructure to reinforce network bandwidth. In China, more than 63,000 4G and 5G base stations were deployed in early March 2020. In Iran, engineers increased the speeds of fixed internet services and made capacity enhancements to the country-wide backbone network. In Italy, a series of network improvements by Telecom Italia led to a 37% increase in bandwidth on select routes.[4,5]
- During COVID-19, Safaricom in Kenya doubled fibre speeds, worked with regulators on extending spectrum, and prioritised front-line health workers with specialised products. Beyond its traditional services, it also established the 719 COVID-helpline in partnership with the government, and doubled mobile money transaction limits to support digital payments, in collaboration with the Central Bank.[6]

Amplifying the role of edtech

As schools shut worldwide, the adoption of edtech accelerated, such as the development of language apps, e-learning, and digital tests. Globally, investment into edtech grew by ~15% in 2020 to €6.5 billion.[7]

- Since 2013, Vodafone and UNHCR's Instant Network Schools programme has been delivering digital education to students in refugee camps, with engineers playing a role in establishing internet connectivity and building learning centres. During COVID-19, their reach expanded to DRC, South Sudan, and Egypt, among other African countries; and most recently, also to Ukraine.[8]
- In Jordan, the government worked with edtech providers like Edraak and Mawdoo3 to develop Darsak, a portal for e-learning in grades one to twelve and teacher training. Software engineers helped develop the digital portal and its content and applications.[9,10]

Pioneering platforms for work

COVID-19's spread meant much of the global workforce and many companies started working remotely; engineers helped drive a range of digital solutions in response. Beyond the rapid upgrading of existing software like Microsoft Teams and Zoom, given exponential growth in use of their services,[11,12] a host of other novel innovations were pursued.

- FabSkill, a Tunisian AI-powered, digital recruitment platform for jobseekers and employers alike expanded its technology and services during COVID-19 to become the first Tunisian platform for e-employment events and digital job fairs. By 2021, the platform had connected ~40,000 job seekers with ~500 organisations and hosted 30 e-job fairs for 30,000+ participants.[13]

Sources: [1] Mobile industry has never been more important to world's citizens, GSMA Newsroom, 2020 [2] Expert interviews [3] Energy transition and COVID-19 crisis: the role of engineers, Committee proceedings, WFEO, 2021 [4] Keeping the internet up and running in times of crisis, OECD, 2020 [5] Telecom security during a pandemic, Enisa, 2020 [6] Safaricom impact report, 2021 2022 [7] How has the pandemic changed the face of ed-tech, EU Start-ups, 2020 [8] Stories from our Instant Network volunteers, Vodafone, 2022 [9] Distance learning solutions, UNESCO [10] Edraak blog [11] Microsoft, Google, and Zoom are trying to keep up with demand for their now free work-from-home software, Vox, 2020 [12] Zoom, Microsoft Teams, and Slack Have Exploded Due to the COVID-19 Pandemic. Can They Hold onto This Growth?, GLE, 2020 [13] COVID-19: Using innovative technology to overcome the crisis and reshape the future of the economy, GSMA, 2021

UNLOCKING ENGINEERING POTENTIAL FURTHER

While these engineering inputs drove value during the pandemic, more seamless and systematic integration is needed for post-pandemic resilience

Engineers working to strengthen society's systems will be central to post-pandemic resilience.
COVID-19's devastating impact on societies the world-over was multifaceted, increasing unemployment, exacerbating poverty, and weakening the social fabric of communities. By some estimates, in the UK alone, the total societal cost of a future influenza-type pandemic could be £23 billion a year.[1] Therefore, building future resilience will involve strengthening society's health response and ensuring strength in the economy too. Engineers working with society's underlying systems will play a central role in this effort, by building new infrastructure for economic regeneration, and ensuring continuous access to essential services like electricity, water, and the internet.[2]

This will necessitate bringing engineering input in early to inform policymaking.
During COVID-19, engineers were often brought in late into policy and planning decisions, thereby unnecessarily exposing more people to infection.[3] Engineering experts in ventilation, for example, had put together taskforces within their industrial associations (ASHRAE in the Americas and REHVA in Europe)[4] to develop guidelines on adapting HVAC systems, before the government or country centres for disease control (CDCs) had recognised the need.[5] Being slow to bring in this expertise could have dire consequences. For example, failing to consult engineers early, health workers in a hospital in southern Africa were concerned that ventilation systems would spread COVID-19 indoors, and therefore chose to treat critically ill patients in parking lots outside – exposing them to other risks.[6] Similarly, coordination with sanitation engineers in some Bangladeshi municipalities was limited in the early days of the pandemic.[7] Therefore, while engineers acted before being asked, using more institutionalised mechanisms for coordination between policymakers and engineers in the future would enable a faster and more systematic response. This will require effort from policy-makers and engineers alike.

It will also be important to bring engineering and technical expertise to the public domain.
Norms around hand-washing have become commonplace but were met with hesitancy or confusion at the onset of the pandemic. To address this, engineers often had to pair their technical expertise with strong communication, such as developing public service announcements around using hand-washing stations.[8,9] Similarly, engineers at research institutions could have eased transitions to new ventilation requirements via stronger channels of communication with the media. It will also be important to expedite the time taken to disseminate research to the public; such as bypassing procedures for review and publication that can take years. Pivoting existing platforms for research toward a public audience could facilitate this transition.[10]

Adopting a systems approach will be critical.
Finally, building back stronger will involve continued recognition of how interconnected societies' systems are. Engineering interventions in transportation will, for example, involve closer integration with energy systems. This interconnectedness has been further entrenched during the pandemic, given the increased use of technology and digitisation in systems, defining them as a mix of physical and digital assets.[11,12] For example, built environment adaptations have combined physical air chillers with digital room sensors.[13] Therefore, by more robustly adopting a systems approach, which involves intentionally considering the parts, interactions, and boundaries of an intervention's system, engineers will better manage the increasing complexity and interconnectedness of systems. This would involve better cross-sector collaboration or systems integration (for example telecoms systems linking into energy systems).[14]

Sources: **[1] Infection resilient environments, time for a major upgrade, Royal Academy of Engineering, 2022** **[2] Energy transition and COVID-19 crisis: the role of engineers, Committee proceedings, WFEO, 2021** [3] Expert interviews [4] ASHRAE - American Society of Heating, Refrigeration and Air-Conditioning Engineers; REHVA - Federation of European Heating and Air-Conditioning [5] Expert interviews [6] Expert interviews [7] Expert interviews **[8] If you build it, will they come? Bangladesh during a pandemic. The Behaviourial Insights team, 2020** **[9] Sanitation workers, the forgotten frontline workers, WaterAid, 2021** [10] Expert interviews [11] A systems approach to infrastructure delivery, Institution of Civil Engineers, 2020 [12] Expert interview **[13] IoT and AI, cutting edge solutions against COVID, CobuildLab 2021**

UNLOCKING ENGINEERING POTENTIAL FURTHER

Engineers must also manage new risks of increased digitisation, as well as work to ensure inclusive access

Intervention efficacy will be improved by addressing cybersecurity risks and the realities of the digital divide.
As engineers continue to develop and expand digital solutions post-pandemic, there is a need to do this sustainably in two key areas. First, they will have to account for amplified exposure to cyber risk. A 2020 survey in Switzerland, for instance, indicated that one in seven people had experienced a cyber attack during the pandemic.[1] Second, expanded connectivity will need to be more equitably distributed. Digital exclusion is more likely to affect certain groups within and across countries, given constraints in income, infrastructure or digital skills.[2,3] Engineers should adopt both technical and collaboration tools to ensure reach to these communities.

> **"Hospital managers realised the importance of HVAC systems and adjusting infrastructure late – which led to vulnerable patients being treated in the hospital car parks."**
>
> *Former health policymaker in Africa*

Sources: [1] Expert interviews [2] Impact of COVID-19 on cybersecurity, Deloitte [3] Coronavirus has exposed the digital divide like never before, World Economic Forum

Engineers' role in accounting for climate implications in pandemic recovery

The pandemic had a mixed impact on the climate.
The decline in travel and economic activity created a significant but temporary decrease in pollution and greenhouse gas emissions.[4] In addition, major disruptions to traditional energy supply spurred growth in the renewable energy sector – which hit record growth rates in 2020.[5,6] However, not all trends were positive. The rise in single-use PPE created an increase in plastic waste, which was compounded by disruptions to recycling. Studies showed that, as of 2021, eight million tons of pandemic-associated plastic waste was generated globally, with over 25,000 tons entering the ocean.[7]

Engineers will need to play a central role in pushing for a green recovery from COVID-19.
International bodies and governments alike have called for pandemic recovery to be taken as an opportunity to 'build back better'. This means resisting a return to business as usual and instead stimulating recovery by investing in sustainable sectors and practices.[8] Engineers will be pivotal to this shift by spearheading green designs, innovations, and assessments. This will include efforts such as expanding renewable energy, facilitating shifts in the packaging industry,[9] optimising reusable consumer products and sustainable end-of-life practices, or building green transport options. In addition, engineers will be needed to ensure infrastructure networks can withstand increasing pressures from the impacts of climate change.[10]

A green recovery needs to facilitate a just transition for L/MICs.
Many countries risk falling behind in the shift towards greater environmental sustainability.[11] For example, during the pandemic, the off-grid renewable electricity and clean cooking products sectors regressed in Asia and sub-Saharan Africa, leaving many without access to energy.[12] Building back better will require ensuring environmental policies are socially inclusive, reduce inequality, and are backed with sustained funding for markets in L/MICs.[13]

Sources: [4] Will COVID-19 have a lasting impact on the environment, BBC Future, 2020 [5] Report: COVID-19 slows progress towards universal energy access, WHO, 2022 [6] Renewable energy defies Covid-19 to hit record growth in 2020, The Guardian, 2020 [7] Plastic waste release caused by COVID-19 and its fate in the global ocean, PNAS, 2021 [8] Building back better: A sustainable, resilient recovery after COVID-19, OECD, 2020 [9] How the packaging industry can navigate the coronavirus pandemic, McKinsey & Company, 2020 [10] Building back better: A sustainable, resilient recovery after COVID-19, OECD, 2020 [11] Report: COVID-19 slows progress towards universal energy access, WHO, 2022 [12] How COVID-19 is reversing energy access in the Global South, Energy Monitor, 2022 [13] Has COVID-19 pushed the plastic waste agenda backwards?, NS Packaging, 2020

CASE STUDY

Educational Initiatives (EI), an edtech provider in India, pivoted its model to help limit learning loss among students by combining digital and in-person innovation

THE INNOVATION

- Customising adaptive-learning technology for students unable to attend school during COVID-19 shutdowns in India.

IMPACT AT A GLANCE

- Learning loss mitigated for disadvantaged students, with students who received the intervention achieving results ~five times higher than the targets set for learning outcomes.
- Hybrid offline-online model pioneered for remote learning.
- Its success demonstrates the potential for institutionalising and scaling edtech in the formal education system in India.

ENABLING FACTORS

- Coordinated partnerships with parents, community members, and teachers bolstered technology uptake and efficacy.
- Nimble operations, continued testing and iteration, and data-driven decision-making in a chaotic operating context.

CHALLENGES

- Network infrastructure and access for technology solutions.
- Challenges of driving educational achievement or learning in remote learning environments with distractions at home.

CONTEXT AND NEED

In India, where educational attainment is an existing challenge for many, more than 1.5 million schools closed during the pandemic — disrupting learning for ~300 million children.[1]

As children across year groups were asked to stay at home, the government pushed a shift towards online learning. Yet, the efficacy and availability of digital learning solutions was fragmented and exacerbated by connectivity discrepancies in the country. More than 50% of Indian students lived without sufficient internet access.[2] The implications of this were severe: according to the World Bank, COVID-19-related school closures and resulting learning losses had the potential to deplete possible future earnings by nearly $450 billion in India.[3] Solving this challenge was a critical component of societal resilience during the pandemic.

ENGINEERING CONTRIBUTION AND IMPACT

The pandemic provided an opportunity to test the promise of edtech.

Though edtech solutions existed before the pandemic, the COVID-19 crisis amplified their necessity and provided an opportunity to test their value. Educational Initiatives (EI), a leading provider of digital learning solutions in India, stepped up to the task. Amongst other solutions, the social enterprise ran a web-based application called Mindspark, which provided K-12 students with lessons and activities in subjects such as maths, science,

Sources used for case study: [1] COVID-19 impact no education, ReliefWeb, 2022. [2] Over half Indian students don't have access to internet, Financial Express [3] COVID-19 impact no education, ReliefWeb, 2022. Interview with Ritesh Agarwal (Assistant Vice President of Educational Initiatives) and other key team members involved in Educational Initiative's participation in the Quality Education India Development Impact Bond (2019-2022), in partnership with Pratham Infotech Foundation in Uttar Pradesh state of India

CASE STUDY

and languages. EI's software engineers had programmed the solution, a personalised adaptive learning technology, to gauge and adapt the content based on a user's learning level. This effectively customised the software to improve students' outcomes in numeracy and literacy. The company served private and government school students across socioeconomic groups.

When schools shut down because of COVID-19, EI pivoted their model to deliver edtech in communities instead.

Before the pandemic, government school students, often those from India's lowest income and underserved communities, accessed the Mindspark software via dedicated Chromebooks installed in learning labs in schools. As the pandemic devastated the country and schools were closed, another solution had to be found. To reach students with some access to digital devices, EI's engineers began developing a custom mobile application for Mindspark. However, even where there was digital access, this was often only to low-tech devices (feature phones). In some districts, less than 20% of community members had access to smartphones or internet-enabled devices. To reach these children, EI worked with local NGOs to distribute Mindspark-installed Chromebooks in community centres, open spaces within villages or near community gathering spots. Field staff from NGOs were trained on using the software and supported children in accessing its content. Some of these NGOs, such as the Pratham Infotech Foundation, even began trainings for field staff and students alike on cyber security risks, including avoiding inappropriate material online or addressing cyberbullying.

The efficacy of the technology was dependent on collaboration with non-engineering disciplines and partners.

To navigate these extreme changes in the delivery context, EI worked hard to coordinate with stakeholders in its broader ecosystem. Collaboration with three groups was vital: parents, who were educated on the value of the software and provided tools and activities to support remote learning; broader community members, who provided spaces to run the community centres or shared their digital devices with parents; and teachers who, as members of the community, were brought on to provide pedagogical support where students faced challenges understanding the content.

Continued testing, failing, and iteration were also key to driving success.

At the same time, EI met with obstacles as it pivoted. To persevere, it needed to continuously and rapidly experiment and iterate at every step. When faced with continuous power outlets or bandwidth constraints at the community learning centres, field staff were equipped with power banks and raspberry Pi applications (micro solutions that enable mobile computing) to ensure sustained connectivity. When children became disengaged or distracted by other obligations at home, the team's engineers designed in-app games or mini quizzes to make the learning software more engaging. Moreover, there was ongoing study and use of data generated by the Mindspark software to plan for improvements in the technology.

By innovating quickly and sensitively, EI mitigated learning loss for some of India's most disadvantaged children.

During the COVID-19 pandemic, EI reached ~125,000 students across some of India's most underserved communities. Independent studies suggest that learning loss was mitigated for students benefiting from the software, and in some cases, gains were noted as well. In one state, numeracy and literacy outcomes for government school students with access to Mindspark were five times higher than the targets set, and than the scores of their peers without access to Mindspark. Building off this success, EI is partnering with state governments to explore how their technology and model can be adopted by the system and scaled across the state.

Chapter 3

Lessons learned and calls to action

Engineering contributions through COVID-19 drove impact at three levels: direct pandemic relief, supporting societal resilience, and unlocking lasting change beyond the pandemic

WHY DID ENGINEERS' CONTRIBUTIONS MATTER?

Driving direct pandemic relief

In relation to direct pandemic relief, engineering contributions during COVID-19 made an impact at different stages of relief efforts. For instance, in:

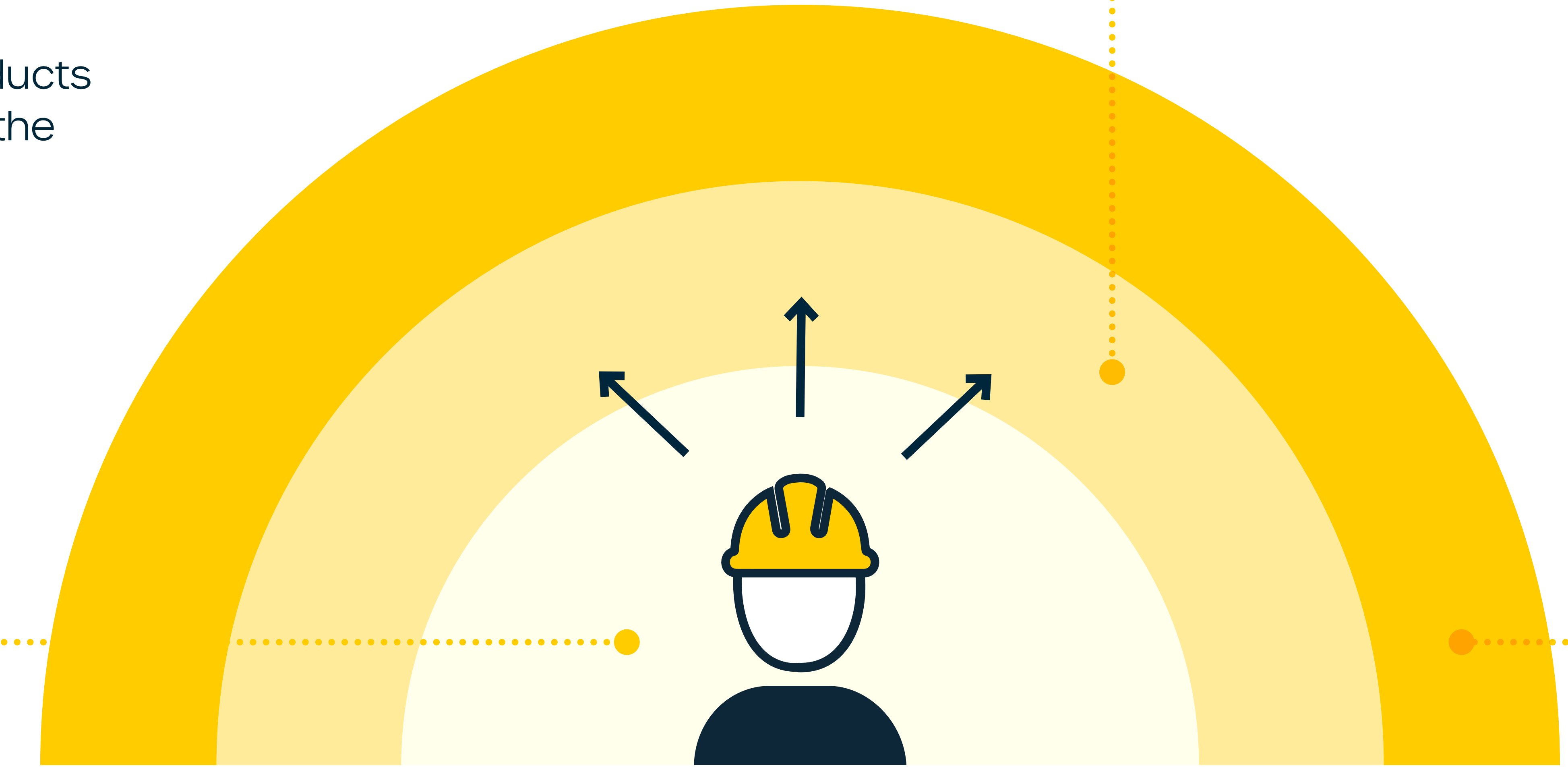
- **pandemic prevention**: enacting early warning systems by detecting and simulating viral spread, and analysing for potential future outbreaks;
- **public health preparedness:** designing, operating, and maintaining functional systems that could be quickly pivoted and adapted;
- **pandemic response:** innovating new medical products and services, and optimising processes to enable the swift deployment of solutions at scale.

Supporting broader societal resilience

Engineering contributions also impacted **broader societal resilience**, by ensuring essential services and systems were kept running during the pandemic. For example, engineers helped keep the lights on, enabled access to clean water and sanitation services, and adapted public spaces for safer interaction.

Unlocking transformative change that lasts beyond the pandemic

Finally, in some cases, engineering contributions unlocked change that will last beyond the pandemic and enable a more sustained recovery. For instance, developments in data analysis or health innovations have instilled real shifts in decision-making for the future; while the digitisation of services (such as remote work or education) has fundamentally shifted how we interact in society.



Capacity, coordination, and ecosystem factors helped make these engineering inputs impactful; replicating them would magnify the value of engineering in future pandemics

WHAT DROVE THIS ENGINEERING IMPACT?	HOW CAN THIS BE REPLICATED IN THE FUTURE?

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 run, strengthening health systems and industrial capacity. Engineers optimised solutions for low-resource contexts, such as portable labs for areas with minimal health infrastructure, which in the long term, will require more systematic work in resolving gaps, such as building up vaccine manufacturing capacity or expanding connectivity.

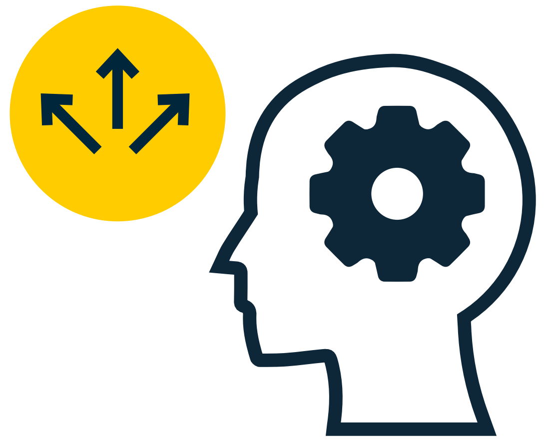
Applying systems thinking and a sensitivity to the wider context of an intervention. This included making a drone innovation work within existing health delivery systems, or engineering organisations working with community members to drive the uptake of new edtech solutions.

Improved planning and prioritisation

WHAT DROVE THIS ENGINEERING IMPACT? / **HOW CAN THIS BE REPLICATED IN THE FUTURE?**

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 better adapted their skills to deliver fit for purpose solutions.

Strengthened human capacity



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 effectively communicate with and build the trust and understanding of policymakers and the general public around complex and rapidly changing topics.

Expanded mechanisms for working together

There is a need to invest in better planning and prioritisation of initiatives, in skills and capacity building, and in greater mechanisms for collaboration

CALLS TO ACTION

INTERLINKED AND MUTUALLY REINFORCING ACTIONS

IMPROVED PLANNING AND PRIORITISATION
Identify structural gaps in pandemic resilience and redirect funding toward addressing them; leveraging systems thinking to do so.

STRENGTHENED HUMAN CAPACITY
Invest in skills, training, and capacity of engineers and domestic engineering ecosystems.

EXPANDED MECHANISMS FOR WORKING TOGETHER
Create and support mechanisms for collaboration across disciplines and countries, that persist in the context of crisis.

TARGET STAKEHOLDERS

- **ENGINEERING COMMUNITY**
- **LOCAL AND NATIONAL GOVERNMENTS**
- **PUBLIC HEALTH DECISION-MAKERS**
- **FUNDERS**
- **ACADEMIA AND RESEARCH GROUPS**

IMPROVED PLANNING AND PRIORITISATION 1/2

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

THE NEED

As demonstrated by the review:

- **Response efforts were often ineffective where systems thinking had not been applied,** or the interconnectedness of societal systems was not considered
- **By contrast, where there was a shared sense of purpose (or common plan), engineers were driven to innovate.** This was further enabled by access to risk-tolerant funding or expedited regulation.
- **Engineers needed to be brought into response planning early,** providing a diverse network of experts to draw on in times of crisis.
- **Decision-makers often had to rely on inadequate or biased datasets.**

DESIGN PRINCIPLES

- **Planning and prioritisation efforts can be kept 'alive'** by creating accountability mechanisms like a schedule for audits, regularly published updates, and maintaining public interest in increasing pandemic resilience.
- **Policymakers and funders should consider the long-term sustainability and climate implications of their initiatives.** This could include ensuring investments are (i) demand-led, (ii) have the potential to scale, (iii) have strong institutions to carry them forward, (iv) are 'future proof,' and (v) climate-smart.

IMPROVED PLANNING AND PRIORITISATION 2/2

POTENTIAL INTERVENTIONS

1. **Undertaking resilience audits which use a systems thinking approach to identify priority areas for strengthening institutions and response mechanisms**

   - **National and sub-national governments** to conduct risk and resilience audits that learn from the experience of COVID-19 so far and create plans in anticipation of potential future waves of COVID-19 or other pandemics. These reviews can deploy a 'critical capabilities' framework, which evaluates the industrial capability, skills and labour, national assets, resources, research and innovation, and networks and coordination capabilities within a nation.[1]

   - **Engineering academies and academia** can support governments in these efforts by translating research around national priorities and critical capabilities, grounded in systems thinking, into tools for policymakers in emergency planning.

2. **Removing bias from and improving core datasets and data systems**

   - **Public health policy-makers, national and local governments, and private actors** to review the comprehensiveness of datasets and data systems (such as national health data), including efforts to identify bias or exclusion of certain groups.

   - **Engineers to work with health, government, and civil society stakeholders** to resolve identified issues, such as better inclusion of marginalised groups in updated datasets and more rigorous data collection processes.

3. **Orienting emergency response taskforces to have greater engineering capability**

   - **Governments** to action learnings from resilience audits via formal preparedness and response task forces, with defined roles and responsibilities for individual departments to ensure accountability.

   - **Engineers and industry representatives** to be included in these taskforces to support problem definition as well as problem-solving, and so that engineering expertise can be deployed rapidly and to maximum effect. This includes planning for future pandemics (such as expertise in developing operational roadmaps against national strategies).

4. **Providing and coordinating funding around pre-defined priorities and common objectives**

   - **Funders** and **governments** to coordinate funding along the lines of identified priorities as per resilience audits or in international research and innovation agendas (such as the WHO priority pathogens list), and to create sustained funding streams towards building resilient and enabling environments.

   - **Funders** to use innovative funding mechanisms to unite innovators (including **private and public industry and entrepreneurs**) around a specific challenge (such as combatting a pandemic or designing tools for prevention). These funding mechanisms should set clear objectives, but provide freedom on the kind of innovation pursued and encourage risk-taking (such as challenge funds or moonshot funding).[2,3]

   - **Funders** to collaborate with **local entrepreneurs and innovators** who are closest to the issues being solved.

Sources: [1] Critical capabilities are the interconnected system of people, infrastructure and assets that build short and long-term resilience, namely: national assets (e.g., the physical and digital infrastructure), industrial capability, skills and labour, research and innovation, and networks and coordination. Read more in the Royal Academy of Engineering report: Critical capabilities: strengthening UK resilience, 2020 [2] Challenge Funds are competitive financing facilities which give grants with an explicit public purpose and select grant recipients on a competitive basis and grant significant discretion to the grantees, [3] 'Moonshot" funding is funding to take on inspirational and disruptive challenges, with a clear time frame and well-defined goals.

STRENGTHENED HUMAN CAPACITY 1/2

Bolster training and capacity of local engineers, building the skills needed for response and resilience to pandemics

THE NEED

As demonstrated by the review:

- **Prevention and response challenges persisted in countries that lacked engineering specialisations** like biomedical or data engineers.
- **There was a need to have sustainable, home-grown solutions** to meet context-specific issues; therefore, countries with skills gaps were comparatively disadvantaged.
- **Aside from bolstering advanced engineering specialisations, there was a need to support the development of those with broader technical skillsets** (such as laboratory technicians or maintenance teams).
- **Engineers were not always equipped with the 'soft' skills needed for interdisciplinary efforts** such as engaging health policymakers in technical communications or consulting diverse end users.

DESIGN PRINCIPLES

- **Core to these interventions would be investing in opportunities for women and engineers from minority backgrounds** to help bridge systematic gaps in equity and access.
- Beyond specific capacity building, fostering a **culture that values engineering contributions** could help increase awareness and appeal of the discipline in society, and in the management of future pandemics.
- It would be key to ensure theoretical training also provides pathways to practical application, such as **opportunities for engineering students to gain hands-on experience** in industry and the public sector so that **young engineers are empowered** with practical skills and experience.

STRENGTHENED HUMAN CAPACITY

2/2

POTENTIAL INTERVENTIONS

1. **Undertaking pandemic workforce planning to identify and address skills gaps for future responses**

   Governments, with the support of **engineering ecosystem players** and **public health players** to undertake strategic workforce planning that entails a review of:

   - **Demand factors:** the engineering skills that are needed to support both the public and private sector across pandemic preparedness, response, and recovery (such as ventilation experts, biomedical technicians, data engineers, or others).
   - **Supply factors:** the availability and quality of existing education and skilling programmes to address these needs.
     Ideally, this review would be embedded within wider national resilience planning. *(See page 97).*

2. **Short term: bridging capacity gaps via exchange programmes or one-off trainings**

   - **Engineering associations, academic and professional institutions and private industry players** with training initiatives to facilitate international exchange programmes around closing the skills gap in pandemic preparedness (such as one-off exchanges between countries with different capabilities in data, biomedical, or manufacturing skillsets).
   - **Governments, health security funders, and philanthropic funders** should support these initiatives by providing scholarships and research secondment budgets.

3. **Long-term: supporting local universities and training institutions to design curricula, teacher training, and academic-industry linkages that fill gaps in pandemic-specific skills**

   - **Academic institutions and engineering associations** to collaborate with **health and policy specialists** to develop curricula (such as dedicated courses on 'engineering in crises', or on practical applications of engineering for health) to equip engineering students for future pandemics. This would include both technical courses ('hard skills') and programmes on engineering approaches that are critical to crisis prevention and response, such as engineering and societal impact, leveraging human-centred design, systems thinking, circular economy, open science, or practising data equity.[1] In addition, courses could include a climate angle, including topics such as end of life of medical products or how to safeguard sustainability during a crisis.

Sources:[1] Data equity refers to the consideration, through an equity lens, of the ways in which data is collected, analysed, interpreted, and distributed. It underscores marginalised communities' unequal opportunities to access data and, at times, their harm from data's misuse. For more information, see: **Data Equity: What is It and Why Does It Matter?, Jili Consulting, 2022**

EXPANDED MECHANISMS TO WORK TOGETHER **1/2**

Create and support mechanisms for collaboration across disciplines and countries that persist through a crisis

THE NEED

As demonstrated by the review:

- **When engineers worked in silos,** without a means of consulting end users or health practitioners, their designs were less effective.
- **Mutual understanding and effective communication** were needed between engineers, health practitioners, and decision-makers.
- **In facilitating open science,** engineers faced challenges in effectively disseminating their findings and in accessing capacity-building support for technology transfer.
- **Growing distrust of health systems and experts** during the pandemic increased the need for effective science communication.

DESIGN PRINCIPLES

- **Equitable partnerships** should be prioritised in the design of international platforms or collaborations through **inclusive agenda-setting** and working to **build trust** between partners.
- **By ensuring a truly global approach to learning lessons,** including lessons learned **from innovators working in low-resource settings**, collaboration may lead to more meaningful and nimble problem-solving.
- Keeping collaborations 'warm' when not in use will be key; including collaborations on pandemic prevention and preparedness, as well as **active testing** (such as 'table-tops' or 'prepare and practice' exercises to simulate emergency response).
- Platforms should not limit collaboration to technical issues – for example, platforms can also be used by regulators to learn from international experiences.

EXPANDED MECHANISMS TO WORK TOGETHER 2/2

POTENTIAL INTERVENTIONS

1. **Designing and funding multi-sectoral innovation teams or programmes that link engineering with other disciplines**

   - **Funders** to require multisectoral collaboration in calls for proposals on health or pandemic innovations – such as ensuring an applicant team has both **clinical and engineering experts,** and, when appropriate, will gain inputs from **public authorities, health decision-makers, regulatory experts, or community stakeholders.**
   - **Engineering academies and ecosystem partners** to develop accelerators and incubators that provide long-term multisectoral inputs to **startups** innovating on pandemic recovery and prevention.
   - **Engineering academies, academia and ecosystem partners** to design capacity-building programmes for **public health actors and policymakers** to better understand and engage with engineering inputs.
   - **Public and private industry and health sector players** to institutionalise multisectoral collaboration in the design, development, delivery, and evaluation of interventions, such as through establishing permanent multisectoral positions within their teams, such as a 'Chief Engineering Officer.'

2. **Creating or strengthening digital collaboration platforms, leveraging momentum started in the pandemic**

   - **Public health and engineering ecosystem players** to consolidate and publicise existing platforms or forums for pandemic preparedness, resilience, and response, such as those on technology transfer, capacity building efforts, research coordination, and review and evaluation of existing projects.

3. **Supporting ongoing initiatives to increase the adoption and refining of open science and data sharing standards**

   - Both **public and private sector institutions** to review and adopt existing open science and data sharing guidelines (such as the GLoPID-R Roadmap for Data Sharing in Public Health Emergencies).[1]
   - **Engineering academies** to raise awareness on how to conduct open science and ensure that the principles of open science are understood and well used by potential collaborators and decision-makers.

4. **Developing effective communication between technical experts, policymakers, and the general public**

   - **Engineering academies, and academic and research institutions** (as part of their efforts to engage and educate broader stakeholders on the contributions of science and engineering) to run sessions on effective science communication for **engineering, public health, government, and civil society stakeholders.** These sessions should be participatory and could focus on topics such as translating technical findings for non-technical audiences, consulting and building trust with communities and end-users, or how to interpret the limitations of data in policymaking.

Sources: [1] GlOPID-R Roadmap for Data Sharing in Publich Health Emergencies, GLOPID-R, 2017

Bibliography and Interviews

Engineering X is an international collaboration founded by the Royal Academy of Engineering and Lloyd's Register Foundation that brings global experts together to engineer change. We take an evidence-based approach, create diverse and global expert communities around our challenges, and listen to unheard voices, particularly from the Global South, to inform our programmes. We bring together partners from around the world to tackle the most pressing engineering, safety, and sustainability problems and deliver impact.

The Royal Academy of Engineering is a UK charity that harnesses the power of engineering to build a sustainable society and an inclusive economy that works for everyone. In collaboration with our Fellows and partners, we're growing talent and developing skills for the future, driving innovation, building global partnerships, influencing policy and engaging the public.

Dalberg is an impact advisory group that brings together strategy consulting, design thinking, big data analytics, and research to address complex social and environmental challenges. We work collaboratively with communities, institutions, governments, and corporations to develop solutions that create impact at scale. With more than 29 locations worldwide and a diverse footprint, Dalberg is driven by a mission to build a world where all people, everywhere, can reach their full potential. For more information, visit www.dalberg.com.

Acknowledgements

We would like to thank the following individuals and their organisations for sharing their time, knowledge, and experience for this report.

Dr. Abebe G. Bayih	Africa Engagement Lead, Coalition for Epidemic Preparedness Innovations (CEPI)
Dr. Alexandra Smyth	Senior Policy Advisor, Royal Academy of Engineering
Dr. Andrew Clark	Director of Programmes, Royal Academy of Engineering
Dr. Anh Tran	Co-Founder & Chief Executive Officer FuturEcook and Pandemic Preparedness board member
Akbar Allana	Director of Quality and Marketing, Alsons Group
Adrian Bucher	Senior Data Analyst, UK Collaborative on Development Research (UKCDR)
Alauddin Ahmed	Project Manager, International Training Network Centre (ITN-BUET)
Andrew McNaughton	Chief Operating Officer, SYSTRA
Dr. Anne Quadgraas	Director of the MIT Sloan Health Systems Initiative, MIT Sloan
Audrey Battu	Senior Director of Essential Medicines, Clinton Health Access Initiative (CHAI)
Dr. Bilal Mateen	Senior Manager Digital Technology, Wellcome Trust
Prof. Carlos Cifuentes	Associate Professor in Human-Robot Interaction, Bristol Robotics Laboratory (BRL)
Caroline Soyars	Technical Associate, Clinton Health Access Initiative (CHAI)
Prof. Chun Zhang	Professor of Beijing Jiaotong University
Prof. Cindy Smith	Professor of Infrastructure and Environment, University of Glasgow and Pandemic Preparedness board member
Clayton Sims	Chief Technology Officer, Dimagi
Cordelia Burch	Senior Manager, Engineering X, Royal Academy of Engineering
Daniela Toale	Programme Manager COVID CIRCLE, UK Collaborative on Development Research (UKCDR)
Dennis Pye	Project Manager, U.K. Gas Technologies Limited
Dr. Dick Chamla	Head of Emergency Preparedness for Africa region, World Health Organization (WHO)
Eloise Todd	Co-founder, Pandemic Action Network
Florence Downs	Editorial Manager, Royal Academy of Engineering
Gemma Hummerston	Senior Editorial and Brand Manager, Royal Academy of Engineering
Prof. Geoff Chase	Professor of Mechanical Engineering, University of Canterbury
Dr. Gerald Douglas	Founder, OpenO2
Graham Pontin	Director of Policy, External Affairs, and Communications, International Federation of Consulting Engineering (FIDIC)
Hendrik Stassen	Engineering Project Manager, World Health Organization (WHO)
Jack Nugent	International Engineering Program Manager, Engineers Without Borders Australia
Prof. James Collins	Professor of Medical Engineering and Science, MIT
James Johnson	Grants Officer, Royal Academy of Engineering

James Steptoe	Global Sales Director, PureTech Process Systems
Jane Sutton	Head of Media and Engagement, Royal Academy of Engineering
Katie Cresswell-Maynard	Executive Director / Secretariat, Engineers Without Borders International
Laura Angeletti-du Toit	Chief Director Infrastructure and Technical management, Department of Health - Western Cape Government
Leith Greenslade	Coordinator, Every Breath Counts
Leo Wolansky	Director, Pandemic Prevention Institute | The Rockefeller Foundation
Prof. Liangzhu Wang	Professor of Building, Civil, and Environmental Engineering, Concordia University
Lin Huang	Deputy Director General, Department of International Cooperation, Chinese Academy of Engineering
Lichun Zheng	Program Officer, Division II, Department of International Cooperation, Chinese Academy of Engineering / Associate Professor at Northeastern University
Prof. Louise Thwaites	Associate Professor at Oxford University Clinical Research Unit, Ho Chi Minh City, Vietnam, and Pandemic Preparedness board member
Dr Long Sen To	Lecturer in Resilient Energy Systems, Loughborough University
Mark MacNaughton	Chief Operations Officer, The Biovac Institute
Dr Mark Smolinski	President, Ending Pandemics
Martha Gartley	Senior Technical Advisor for the Essential Medicines team, Clinton Health Access Initiative (CHAI)
Dr Martina Micheletti	Co-director, UCL Future Vaccine Manufacturing Research Hub
Matthew Roberts	Head of Finance & Facilities, Mercedes AMG High Performance Powertrains Ltd
Metin Akay	President, Institute of Electrical and Electronics Engineers (IEEE) Engineering Medicine and Biology Society
Dr. Mike Short CBE FREng	Chief Scientific Advisor, DIT and Pandemic Preparedness board member
Dr. Nelson Ogunshakin	Chief Executive Officer, International Federation of Consulting Engineering (FIDIC)
Dr. Nick Starkey	Director of Policy, Royal Academy of Engineering
Niels Birbaumer	Director General, Smart City Tech
Nisha Schumann	Acting Chief of Staff and Workstream Manager, COVID-19 Vaccine Delivery Partnership
Nitesh Jangir	Co-Founder, Coeo Labs and InnAccel
Nomita Divi	Executive Director, Ending Pandemics
Nour Sharara	Public Health Scientist, Biobot Analytics
Dr. Olivier Defawe	Drones for Health Programme Lead, VillageReach
Paulo Vela	Research Engineer, Universidad Peruana Cayetano Heredia
Prof. Peter Guthrie OBE FREng	Director of Research in Sustainable Development, Cambridge University and Pandemic Preparedness board chair
Peter Jarich	Head of GSMA Intelligence, GSMA
Pippa Cox	Communications Manager, Royal Academy of Engineering
Ranna Eardley-Patel	Sustainable Manufacturing Lead, Coalition for Epidemic Preparedness Innovations
Rajinder Suri	Chief Executive Officer, Developing Countries Vaccine Manufacturing Network (DCVMN)
Prof. Rebecca Shipley OBE	Director, UCL Institute of Healthcare Engineering and Pandemic Preparedness board member
Richard Tibbles	Product Lead, Learning Equality
Ritesh Agarwal	Assistant Vice President, Educational Initiatives
Shane McHugh	Head of International Partnerships, Royal Academy of Engineering
Dr. Shaun Fitzgerald OBE FREng	Director of Research in the Centre for Climate Repair, Cambridge University
Dr. Terence Carter	Technical Assistant, Clinton Health Access Initiative (CHAI) and member of South African National Department of Health: COVID-19 Hospital Readiness
Dr. Timothy Mtonga	Director of the Global Health Informatics Institute, OpenO2
Lord Toby Harris	Chair, National Preparedness Commission
Dr. Yu Zhu	Deputy Director, Division II, Department of International Cooperation, Chinese Academy of Engineering
Prof. Yuko Harayama	Vice President, Engineering Academy of Japan (EAJ)

Glossary and acronyms

3D printing — The action or process of making a physical object from a three-dimensional digital model, typically by laying down many thin layers of a material in succession.

Africa CDC — **Africa Centre for Disease Control and Prevention**

AI — **Artificial intelligence**. The theory and development of computer systems able to perform tasks normally requiring human intelligence, such as visual perception, speech recognition, decision-making, and translation between languages.

Big Data — Extremely large data sets that may be analysed computationally to reveal patterns, trends, and associations, especially relating to human behaviour and interactions.

Blow-fill-seal technology — Blow-fill-seal technology is a form of advanced aseptic manufacturing, where the container is formed, filled, and sealed in one continuous, automated system. Its advantages include reducing need for human intervention, reducing risk of microbial contamination and foreign particulates, allowing for many different container designs, facilitating high process quality and output, and being inexpensive compared to other packaging processes.

Brain drain — The emigration of highly trained or qualified people from a particular country.

CDC — **Centre for Disease Control**

Contact tracing — The process of attempting to identify people who have recently been in contact with someone diagnosed with an infectious disease, especially in order to treat or quarantine them.

CPAP device — **Continuous positive airway pressure device.** A CPAP device assists a patients breathing by delivering a flow of oxygen-enriched air at a constant pressure, and is connected to a mask, or hood, worn by the patient. CPAP devices are commonly used for sleep apnoea, and have also been used to assist the breathing of COVID-19 patients.

Data equity — Data equity refers to the consideration, through an equity lens, of the ways in which data is collected, analysed, interpreted, and distributed. It underscores marginalized communities' unequal opportunities to access data and, at times, the harm caused to them by data misuse.

DRC — **Democratic Republic of Congo**

Edtech — **Education Technology.** Digital technology used to facilitate learning.

EUA — **Emergency Use Authorisation.** An authorization granted to allow the use of a drug prior to full regulatory approval to facilitate availability of an unapproved product, or an unapproved use of an approved product, during a declared state of emergency.

EUL — **Use Listing.** The WHO Emergency Use Listing Procedure (EUL) is a risk-based procedure for assessing and listing unlicensed vaccines, therapeutics and in vitro diagnostics with the ultimate aim of expediting the availability of these products to people affected by a public health emergency.

EUR — **Euros**

Fill and finish — Fill and finish refers to the final step of the process where the substance of the vaccine is sent to the plant to be put in vials and distributed.

Formula 1	Formula One is the highest class of international racing for open-wheel single-seater formula racing cars sanctioned by the Fédération Internationale de l'Automobile.
Health tech	**Health technology.** The application of organized knowledge and skills in the form of devices, medicines, vaccines, procedures, and systems developed to solve a health problem and improve quality of lives.
HICs	**High-income countries.** As of 2022, the World Bank classes these as countries with Gross National Income (GNI) per capita above $13,205 USD.
HVAC	**Heating, ventilation, and air conditioning.**
IoT	**Internet of Things.** Internet of Things describes physical objects (or groups of objects) with sensors, processing ability, software, and other technologies that connect and exchange data with other devices and systems over the Internet or other communications networks.
IP	**Intellectual property.** Intangible property that is the result of creativity (such as an idea or design) and protected by law (such as patents or copyrights).
IPD	**Institut Pasteur de Dakar**
L/MICs	**Low- and middle-income countries.** As of 2022, the World Bank classes these as countries with GNI per capita below $13,205 USD.
LICs	**Low-income countries.** As of 2022, the World Bank classes these as countries with GNI per capita below $1,085 USD.
Lidar	A detection system which works on the principle of radar and uses light from a laser.
Living review	In academic publishing, a living review is a review article that is updated at intervals to reflect the latest research. Living reviews are typically published online.
Long COVID	Long COVID is a term used to describe those who suffer with COVID-19 related symptoms for longer than four weeks. Countries vary in their definition of what constitutes long COVID, and research is continuing to emerge on this, as it is a new field. In June 2022, the UK National Health Service (NHS) would term symptoms between four and 12 weeks as ongoing symptomatic COVID-19, and symptoms lasting longer than 12 weeks as post-COVID syndrome.
MHRA	Medicines and Healthcare products Regulatory Agency. An executive agency of the Department of Health and Social Care in the UK which s responsible for ensuring that medicines and medical devices work and are acceptably safe.
MoH	**Ministry of Health**
MoU	**Memorandum of Understanding.** A nonbinding agreement that states each party's intentions to take action, conduct a business transaction, or form a new partnership.
mRNA	**Messenger ribonucleic acid.** mRNA is a single-stranded molecule of RNA that corresponds to the genetic sequence of a gene and is read by a ribosome in the process of synthesizing a protein. mRNA vaccines were developed during the pandemic. These worked by introducing a piece of mRNA that corresponds to a viral protein, usually a small piece of a protein found on the virus's outer membrane. Both the Pfizer vaccine and Moderna vaccine, for example, used this technology.
NHS	**National Health Service.** The National Health Service is the publicly funded healthcare system in England.
ODA	**Official development assistance.** A category used by the Development Assistance Committee (DAC) of the Organisation for Economic Co-operation and Development (OECD) to measure foreign aid.

Open science	The movement to make scientific research (including publications, data, physical samples, and software) transparent and accessible to all levels of society (amateur or professional). Open science includes practices such as publishing open research.
Open source	In software and computer programming, open source is when the source code is made freely available and with permission for the public to modify and redistribute the software. Open source aims to encourage open collaboration.
PHC	**Primary Healthcare Centre**
PPE	**Personal protective equipment.** This is equipment worn to minimize exposure to hazards. It includes masks, gloves, and gowns.
Preprint	In academic publishing, a preprint is a version of a scholarly or scientific paper that precedes formal peer review and publication in a peer-reviewed journal.
Project CARE	Project COVID-19 African Rapid Entrepreneurs. Between March 2020 and September 2021, the Royal Academy of Engineering ran Project CARE to support 59 entrepreneurs across 11 countries with materials to manufacture PPE or grants to pivot their businesses to respond to the impacts of COVID-19 in their communities.
PSA	**Pressure swing adsorption.** PSA is a technology used in producing oxygen.
R&D	**Research and development**
RDTs	**Rapid Diagnostic Tests.** A rapid diagnostic test is a medical diagnostic test that is quick and easy to perform and is suitable for preliminary or emergency medical screening. The most widely used for COVID-19 are SARS-Cov-2 antigen rapid diagnostic tests (Ag-RDT).
Systems thinking	Systems thinking is an approach to understanding complexity within the world by looking at it in terms of wholes and relationships rather than by splitting it down into its parts; as well as looking at the relationships and interactions within and between component parts of the system.
Technology transfer	The movement of data, designs, inventions, materials, software, technical knowledge or trade secrets from one organisation to another.
Telehealth	The provision of healthcare remotely by means of telecommunications technology (such as by phone or video call).
TRIPS	**Trade-Related Aspects of Intellectual Property Rights.** An international legal agreement between all the member nations of the World Trade Organization. It establishes minimum standards for the regulation by national governments of different forms of intellectual property, as applied to nationals of other WTO member nations.
USD	**United States Dollars**
WHO	**World Health Organization**
WTO	**World Trade Organization**

Bibliography

3D printed face shields for medics and professionals, Prusa Research, 2020

5 ways women and girls have been the hardest hit by Covid-19, OXFAM, 2020

5G: Empowering Recovery and Fighting Misinformation in Europe, GSMA, 2020

6 African nations chosen for mRNA vaccine production, Devex, 2022

A comprehensive condition monitoring solution for the healthcare industry, Gricd, 2021

A patent waiver of COVID vaccines is right and fair, Nature, 2021

A Power Boost for COVID-19 Clinical Trials, Hopkins Bloomberg Public Health, 2020

A rapid review of the engineering approaches to mitigate the risk of COVID-19 transmission on public transport, National Engineering Policy Centre & Royal Academy of Engineering, 2020

A systems approach to infrastructure delivery, Institution of Civil Engineers, 2020

A technology company founded by a woman is helping small-holder farmers survive lockdown, Health News, 2020

Accounting for uncertainty during a pandemic, Zelner et al., 2021

Addressing COVID-19 in buildings, Canadian Committee on Indoor Air Quality, Date Accessed: July 2022

Addressing Market Failures: The Role of CEPI in Bridging the Innovation Gap to Prevent the Next Pandemic, Pandemic Action Network, 2021

Addressing the skills gap in the supply chain industry, University of London, 2021

Advice from Dr. Anne Woolridge, Chair of the ISWA Working Group on Healthcare Waste, EKA Industrie Medien, 2020

Africa is bringing vaccine manufacturing home, Nature, 2022

Africa needs vaccines. What would it take to make them here? McKinsey, 2021

Africa's digital solutions to tackle COVID-19, European Investment Bank, 2020

Africa's most vulnerable countries have few ventilators — or none at all, The Washington Post, 2020

Afrox medical oxygen supply statement, Afrox, 2021

AI for healthcare, Imperial College, 2020

AI for Impact : Mobile Big Data Analytics to combat challenges including COVID-19, GSMA, 2020

AI4I Webinar Series : Using mobile big data analytics to combat global challenges inc. COVID-19, GSMA, 2020

Algeria Begins Producing a Coronavirus Vaccine, Al-Fanar Media, 2021

Ambitious vaccine plan requires different training approach, University World News Africa Edition, 2021

An overview of Covid-19 in Malawi: Scotland-Malawi Oxygen Supply Coordination Group, ScotlandMalawi, 2021

Applications of predictive modelling early in the COVID-19 epidemic, The Lancet Digital Health, 2020

Assessing critical gaps in COVID-19 testing capacity: the case of delayed results in Ecuador, BMC Public Health, 2021

Bacardi makes hand sanitisers, Bacardi, 2020

BioNTech to ship mRNA vaccine factory kits to Africa, Reuters, 2022

Brain Drain – The loss of engineers and doctors in India, University Times, 2021

Breakthrough Change Accelerator, Pfizer, Accessed 2022

BRING O2 To Fill Oxygen Gap in Five Countries, Partners In Health, 2022

Brown Ph.D. student working to correct skin color bias in pulse oximeters, Brown, 2022

Building a multisystemic understanding of societal resilience to the COVID-19 pandemic, British Medical Journal, reliefweb, 2021

Building back better: A sustainable, resilient recovery after COVID-19, OECD, 2020

Buildings that keep us healthy and safe, Royal Academy of Engineering, 2021

By How Much Are Countries Underreporting COVID-19 Cases and Deaths?, Council on Foreign Relations, 2021

C3.AI COVID-19 Data Lake, C3.AI, Date Accessed: July 2022

CallGenie - Video Calls Direct to Their TV, Age Space, Date Accessed: July 2022

Case Study: PODD: Look Closely and You Will See Empowering Communities for Early Disease Detection, Ending Pandemics, 2019

CEPI and Institut Pasteur de Dakar partner to advance COVID-19 vaccine manufacturing in Africa, CEPI, 2022

Commcare In Burkina Faso: How An Existing App At Scale Was Adapted For COVID-19, Exemplars in Global Health, 2021

CommCare, Design Powerful Mobile and Web Apps, Dimagi, Date Accessed: July 2022

Connecting informal market vendors to e-commerce to reach consumers in the wake of Covid-19 and beyond, UNDP, 2020

Considerations for PPE reprocessing based on international practices, National Engineering Policy Centre & Royal Academy of Engineering, 2020

Coronavirus has exposed the digital divide like never before, World Economic Forum, 2020

Coronavirus: How NHS Nightingale was built in just nine days, BBC, 2020

Coronavirus: India's race to build a low-cost ventilator to save Covid-19 patients, BBC, 2020

Coronavirus: inside story of how Mercedes F1 and academics fast-tracked life saving breathing aid, The Conversation, 2020

Cost of Personal Protective Equipment During the First Wave of COVID-19, Cambridge University Press, 2021

COVID 19: Engineering a resilient future, National Engineering Policy Centre & Royal Academy of Engineering, 2020

COVID research tracker, UKCDR, Date Accessed: July 2022

Covid: how Excel may have caused loss of 16,000 test results in England, The Guardian, 2020

Covid: Pulse oxygen monitors work less well on darker skin, experts say, BBC, 2021

COVID-19 African Rapid Entrepreneurs Impact report: March 2020 to November 2021, Royal Academy of Engineering

COVID-19 Brief: Impact on Food Security, U.S. Global Leadership Coalition, 2022

COVID-19 Crisis Response: Digital Development Joint Action Plan and Call for Action, World Bank, ITU, GSMA & World Economic Forum, 2020

COVID-19 crisis, Energy and Engineers in Uruguay, WFEO/FMOI, 2021,

COVID-19 data on Native Americans is 'a national disgrace.' This scientist is fighting to be counted, Science.org, 2020

COVID-19 diagnostics: preserving manufacturing capacity for future pandemics, Hannay et al, 2022

COVID-19 impact no education, ReliefWeb, 2022.

COVID-19 Infection Rate In Rio's Favelas Far Exceeds Official Count - a new study says, NPR, 2020

COVID-19 infections by race: What's behind the health disparities?, Mayo Clinic, 2022

COVID-19 oxygen emergency impacting more than half a million people in low- and middle-income countries every day, as demand surges, WHO, 2021

COVID-19 Oxygen Needs Tracker, PATH, 2022

COVID-19 Pandemic Disproportionately Affected Women in the Americas, PAHO, 2022

COVID-19 Research Project Tracker by UKCDR & GloPID-R, UKCDR, Accessed June 2022

COVID-19 Respiratory Care Response Coordination Project, PATH, 2021

COVID-19 situation update worldwide, European Centre for Disease Prevention and Control, 2022

COVID-19: Using innovative technology to overcome the crisis and reshape the future of the economy, GSMA, 2021

COVID-19 vaccines: Why some African states can't use their vaccines, BBC, 2021

COVID-19 will accelerate the revolution in energy systems, World Economic Forum, 2020

COVID-19: Collaboration is the engine of global science – especially for developing countries, World Economic Forum, 2020

COVID-19: The impact on workers in global supply chains, Lewry J, 2020

COVID-19: Using innovative technology to overcome the crisis and reshape the future of the economy, GSMA, 2021

Coviu 2 years on, Coviu, 2022

Critical capabilities: strengthening UK resilience, Royal Academy of Engineering, 2021

Customized design and 3D printing of face seal for an N95 filtering facepiece respirator, Cai et al, 2018

Data center staff classified as essential during pandemic, Data center dynamics, 2020

Data Platform Tracks Hospital Bed Capacity During COVID-19 Outbreak, Health Analytics, 2020

Data science and AI in the age of COVID-19, The Alan Turing Institute, 2021

Detect COVID-19 in as Little as 5 Minutes, Abbot, 2020

Digital Poverty and its Impact on Education Inequality, Learning Hive, Date Accessed: July 2022

Distance learning solutions, UNESCO, Date Accessed: July 2022

Drivers of the higher COVID-19 incidence, morbidity and mortality among minority ethnic groups, GOV.UK, 2020

Drones for Health: Boosting access to lifesaving products, VillageReach, 2020

Efficient and targeted COVID-19 border testing via reinforcement learning, Hamsa et al, Nature, 2021

Electric utilities increasingly turning to IoT adoption due to COVID-19, Electric Review, 2021

Energy access is needed to maintain health during pandemics, Nature Energy, 2020

Energy transition and COVID-19 crisis: the role of engineers, Committee proceedings, WFEO, 2021

Engineering better care, Royal Academy of Engineering, 2017

Engineers are unsung heroes of global health, Madhukar P, 2022

Ensuring Equity as Wastewater Testing Matures in the United States, Mathematica, 2022

EpiHacks, a Process for Technologists and Health Experts to Cocreate Optimal Solutions for Disease Prevention and Control: User-Centered Design Approach, JMIR Publications, 2021

Esri, COVID-19 overview, Accessed 2022

Estimates of long COVID are startingly high. Here's how to understand them, STAT, 2022

Ethnic and racial disparities in COVID-19-related deaths: counting the trees, hiding the forest, Yaya et al, 2020

Export restrictions do not help fight COVID-19, UNCTAD, 2021

Facilitators and barriers to engagement with contact tracing during infectious disease: A rapid review of the evidence, Megnin-Viggars et al, 2020

Factoring gender into innovation for better outcomes, WIPO, 2017

First of its kind Cintocare Hospital, issuu, 2021

FIT for Women: Safe and Decent PPE, Women in Global Health, 2022

Fix the Mask, Date Accessed: July 2022

Formalbs' 3D Printed Naspharyngeal Test Swabs Honoured as a World Changing DIea by Fast Cmpany, Formlas, 2021

Four lessons the pandemic has taught us about health data, Steventon, 2021

From clothing production to PPE manufacturing: factories pivot during the pandemic, Better Work, 2020

Funding and undertaking research during the first year of the COVID-19 pandemic: Lessons for Funders, UKCDR and GLOPID-R, 2021

Global oxygen suppliers commit to closing oxygen gaps in low- and middle-income countries, Access to Medicine Foundation, 2021

Global shortage of personal protective equipment, Burki T. 2020

Global Supply Chains in a Post-Pandemic World, Sihi W, 2020.

Has COVID-19 pushed the plastic waste agenda backwards?, NS Packaging, 2020

Health systems resilience in managing the COVID-19 pandemic: lessons from 28 countries, Haldane et al., 2021.

Health technology report, ATSE, 2020

Healthcare worker capacity, McKinsey

Here's how we can resolve the global supply chain crisis, UNCTAD, 2022.

How a Novel 'Incubation Sandbox' Helped Speed Up Data Analysis in Pfizer's COVID-19 Vaccine Trial, Pfizer, Accessed 2022

How Asia's clothing factories switched to making PPE – but sweatshop problems live on, The Conversation, 2020

How coronavirus spread across the globe - visualised, The Guardian, 2020

How COVID broke the evidence pipeline, Nature, 2021

How COVID-19 has changed energy networks for the better, PEI, 2021

How COVID-19 has pushed technology companies over the technology transfer tipping point, McKinsey & Company, 2020

How COVID-19 impacted supply chains and what comes next, EY, 2021

How COVID-19 is reshaping supply chains, McKinsey and Company, 2021

How COVID-19 is reversing energy access in the Global South, Energy Monitor, 2022

How did you get to the issuance of a million certificates of education?, Edraak, 2021

How engineers are keeping your power on during COVID-19, IEEE Transmitter, 2020

How has the pandemic changed the face of ed-tech, EU Start-ups, 2020

How innovation in wastewater monitoring helps track down deadly diseases in Latin America, World Bank, 2021

How Telehealth company Coviu used the pandemic to boost their business, Australian Institute of Company Directors, 2020

How the emergence of connected drones is helping the fight against COVID-19, GSMA, 2020

How the packaging industry can navigate the coronavirus pandemic, McKinsey & Company, 2020

How volunteers from tech companies like Amazon, Apple and Google built a coronavirus-tracking site in six days, CNBC, 2020

Humanitarian supply chains during COVID-19: systems failures, recovery and emerging alternatives, Lowe et al., 2020

Hundreds of AI tools have been built to catch covid. None of them helped., MIT Technology Review, 2021

'If it comes, it will overwhelm us': Malawi braces for coronavirus, Vidal J, 2020.

If you build it, will they come? Bangladesh during a pandemic. The Behaviourial Insights team, 2020

Impact of COVID-19 on different ethnic minority groups, UK Parliament, 2020

Impact of COVID-19 on people's livelihoods, their health and our food systems, WHO, 2020

Impact of COVID-19 on cybersecurity, Deloitte, 2020

Impact of COVID-19 on the supply chain industry, PWC, 2021

Impactful Innovations: Insights from evaluating Cyber Food, GSMA, 2021.

In Low-Income Countries Fundamental Data Issues Remain for COVID-19 Response, Thematic Research Network on Data and Statistics, 2020

India now manufactures 4.5 lakh PPE suits a day in the fight against Covid-19, mint, 2020

India's Informal Workers Under Lockdown, Shubhangi Gokhroo, 2021

Industrial IoT in the time of COVID-19 electric utilities, Inmarsat, 2020

Infection resilient environments, time for a major upgrade, Royal Academy of Engineering, 2022

Infection Resilient Environments: Buildings that keep us healthy and safe, National Engineering Policy Centre, 2021

Innovating production and manufacture to meet the challenge of COVID-19, Astrazeneca, 2021

Innovation ecosystems and start-ups in the Mediterranean as a means of recovering from the COVID-19 crisis, European Committee of the Regions, 2021

Innovation in a crisis: webinar series, Royal Academy of Engineering, 2021

Innovative point-of-care molecular diagnostic test for COVID-19 in India, Gupta, Nivedita et al., 2022

Innovative point-of-care molecular diagnostic test for COVID-19 in India, The Lancet, 2022

Insights From Africa's Covid-19 Response: Repurposing Manufacturing, Tony Blair Institute for Global Change, 2020.

Instrat Website, Accessed 2022

Intellectual Property, innovation, and access, World Intellectual Property Organization, 2020

Intermittent occupancy combined with ventilation: An efficient strategy for the reduction of airborne transmission indoors, Melikov A, Ai Z, Markov D, 2020

IoT and AI, cutting edge solutions against COVID, CobuildLab 2021

IoT and the coffee supply chain, DIGI, 2021

IoT and the Supply Chain: How Machine Learning Eases Bottlenecks, DIGI, 2021

IoT in utilities market brings resilience in wake of COVID-19, IoT World Today, 2020

Johns Hopkins Coronavirus Resource Center passes 1 billion views, John Hopkins, 2021

Johns Hopkins, Coronavirus Research Center, Global Map, Date Accessed: July 2022

Keeping everyone and everything connected: How temporary access to spectrum can ease congestion during the COVID-19 crisis, GSMA, 2021

Keeping the internet up and running in times of crisis, OECD, 2020

Keys to Deploying Rapid Response Software in a Crisis: Lessons Learned Building Software for COVID-19 Contact Tracing Programs, Linux Foundation Public Health, 2021

Labour market developments: The unfolding COVID-19 crisis, OECD, 2021.

Labour rights abuse in global supply chains for PPE through COVID-19 – issues and solutions, British Medical Association, 2021

Lack of a real IP waiver on COVID-19 tools is a disappointing failure for people, Medecins Sans Frontieres, 2022

Latest updates for Africa CDC on progress made in COVID-19 vaccinations on the continent, Africa CDC COVID-19 Vaccine Dashboard, Accessed June 2022

Latin America's Coronavirus Crisis: Why it Disproportionally Affects the Poor, Australian Institute of International Affairs, 2020

Learning Equality, Kolibri, Date Accessed: July 2022

Lessons and risks of medical device deployment in a global pandemic, The Lancet, Shipley et al, 2021

Living Mapping Review, UKCDR, Accessed: July 2022

Long-term monitoring of SARS-COV-2 RNA in wastewater in Brazil: A more responsive and economical approach, Ieda Carolina Mantovani Claro et al, 2021

Malysia: Concerns over labour abuse to meet rubber gloves demand, Aljazeera, 2020

MASCIR develops a 100% Moroccan Diagnostic Kit for COVID-19 Testing, MASCIR, 2020

Medical PPE unfit for women on COVID-19 frontlines, Owings L, 2021.

Meeting challenges from COVID-19, National Engineering Policy Centre & Royal Academy of Engineering, 2020

Merck Collaborates with Innovative Biotech to Support Establishment of First Vaccine Production, Merck, 2021

Microsoft, Google, and Zoom are trying to keep up with demand for their now free work-from-home software, Vox, 2020

Moderna, WHO Set for Vaccine Clash as Patents Threaten mRNA Use, Bloomberg UK, 2022

Mobile industry has never been more important to world's citizens, GSMA Newsroom, 2020

Morocco starts construction of COVID vaccine plant, Aljazeera, 2022

New antimicrobial air filters tested on trains rapidly kill SARS-CoV-2 and other viruses, University of Birmingham, 2022

New Artificial Intelligence projects funded to tackle health inequalities, NHS, 2021

New dataset released for one of the most populous provinces in the Democratic Republic of the Congo, Grid3, 2020

New perspectives: How COVID-19 has shifted sustainability priorities in the mobile sector, GSMA, 2020

New research to enhance air filtering in ambulances, Cranfield University, 2021

New vaccine campaigns target rural Americans to address disparities, The Guardian, 2021

NHS planes new Nightingale facilities in response to Omicron, NHS, 2021

Nigerian last mile delivery firm Gricd delivers 4.2M COVID-19 vaccines using cold storage tech, appsAfrica, 2021

Number of coronavirus (COVID-19) tests performed in the most impact countries worldwide as of June 27, 2022, Statisa, Date Accessed: June 2022

Number of supply chain disruptions worldwide from 2019 to 2021, Statisa, 2022

One in 3 death certificates were wrong before coronavirus. It's about to get even worse., USA Today, 2020

Open science takes on the coronavirus pandemic, Nature, 2020

OpenSAFELY, Date Accessed: July 2022

Our vision for the built environment, IPFA, Date Accessed: July 2022

Over half Indian students don't have access to internet, Financial Express, 2022

Pandemic Precarity: COVID-19 is exacerbating and exposing inequalities in the American Heartland, Brea L. Perry, et al, 2021

Pandemic Prevention Institute, The Rockefeller Foundation, Date Accessed: July 2022

Penn Engineers Create Faster and Cheaper COVID-19 Testing With Pencil Lead, Penn Engineering Today, 2021

People have lost trust in healthcare systems because of COVID. How can the damage be healed?, World Economic Forum, 2022

Personal data of thousands of COVID-19 patients leaked in Moscow, Human Rights Watch, 2020

Plastic waste release caused by COVID-19 and its fate in the global ocean, PNAS, 2021

Plugging The Digital Skills Gap To Maintain An Effective Supply Chain, Whatson S, 2021

Port to patient: Improving country cold chains for COVID-19 vaccines, McKinsey and Company, 2021.

Post Covid-19 value chains: options for reshoring production back to Europe in a globalised economy, European Parliament, 2020

Power Africa Covid-19 Response And Recovery, USAID, 2022

Preprints in times of COVID19: the time is ripe for agreeing on terminology and good practices, BMC Medical Ethics, 2021

Preventing the next pandemic - Zoonotic diseases and how to break the chain of transmission, UNEP, 2020

Privacy, security, and public health in a pandemic year, McKinsey & Co, 2020

Project CARE, COVID-19 African Rapid Entrepreneurs Impact report: March 2020 to November 2021, Royal Academy of Engineering, 2021

Prospects for local manufacturing of COVID-19 vaccines in Africa, Devex, 2022

Qingdao Port: a Chinese model for the construction and operation of the intelligent port of the future, 2021.

Rapid review of engineering factors that will influence the spread of COVID-19 in hospital environments, National Engineering Policy Centre & Royal Academy of Engineering, 2020

Rebuilding trust in healthcare, Deloitte, 2021

Reconstructing your supply chain with nearshoring, Jorge J, Bergen E, 2021

Reimagining our pandemic problems with the mindset of an engineer, MIT Technology Review, 2021

Relief for Informal Workers: Falling through the Cracks in COVID-19, CGAP, 2020

Removing administrative barriers, improving regulatory delivery, OECD, 2020

Renewable energy defies Covid-19 to hit record growth in 2020, The Guardian, 2020

Report: COVID-19 slows progress towards universal energy access, WHO, 2022

Researchers call out lack of diversity in COVID-19 clinical trials, Medical News Today, 2020

RESET, ebm-papst, and Envio Systems response to airborne pandemics and health, Envio, 2020

Resetting supply chains for the next normal, McKinsey and Company, 2021.

Responding To The Covid-19 Crisis In Mongolia With A Climate-friendly Central Vaccine Store, World Bank, 2022.

Rockefeller Foundation Pandemic Prevention Institute online resources, Date Accessed: July 2022

Role of sanitary engineers in prevention of COVID-19 pandemic, Darko Vujasinovik, 2020

Role of systems engineering attributes in enhancing supply chain resilience: Healthcare in context of COVID-19 pandemic, Hossain N et al, 2022.

Sanitation workers, the forgotten frontline workers, WaterAid, 2021

Sanitiser: Sharing what we have learned, Brewdog, 2020

Saving Lives and Livelihoods Four Areas of Focus: COVID-19 Vaccines for Africa, Mastercard Foundation, 2022

Scientists develop Covid-19 testing lab in a backpack, Queen Mary University of London

SCOUTBEE, Date Accessed: July 2022

Senegal nears completion of 'bespoke' vaccine manufacturing facility, Devex, 2022

Senegal: EIB provides €75 million to Institut Pasteur de Dakar for new vaccine manufacturing facility, European Investment Bank, 2022

Shortage of personal protective equipment endangering helath workers worldwide, WHO, 2020

SMILE: The Science and engineering behind SMILE, Ideabetic, Date Accessed: July 2022

Social isolation and loneliness among older people: advocacy brief, WHO, 2021

Solar energy ensures reliable power to India's rural health clinics, Energizing rural India, 2021

Solar panels power clinics in Peru, Partners in Health, 2022

Solutions to COVID-19 data sharing, The Lancet Digital Health, 2020

South African scientists copy Moderna's COVID vaccine, Nature, 2022

South Korea is reporting intimate details of COVID-19 cases: has it helped?, Nature, 2020

Spira Wave, 10x Beta, 2022

State of BI & Analytics Report 2020, Sisense, 2020

Stimulating R&D for a faster and better recovery, Royal Academy of Engineering, 2020

Stories from our Instant Network volunteers, Vodafone, 2022

Super sheds built across UK as online retail boom sparks warehouse demand, Saker-Clark, 2021

State of BI & Analytics Report 2020, Sisense, 2020

Supply chain challenges, lessons learned and opportunities, National Engineering Policy Centre & Royal Academy of Engineering, 2020

Supply chain disruption: Repurposed supply chains of the future must have resilience and responsibility at their heart, Accenture, 2022

Supply chain disruptions and the effects on the global economy, ECB, 2021

Surveillance Technology In Thailand, Cambodia, And Tanzania: Case Study From Ending Pandemics, Exemplars in Global Health, 2022

Switching on 'Silent Power' for Clinics and Communities in Remote Lesotho, Power Africa, 2021

Telecom security during a pandemic, Enisa, 2020

The 4 Key Reasons the U.S. Is So Behind on Coronavirus Testing, The Atlantic, 2020

The benefits and sustainability of short food supply chains, Food facts for healthy choices, 2021.

The 5 most interesting start-ups in smart buildings, CM Industrial, 2021

The future of vaccine manufacturing in Africa, Brookings, 2022

The global rise of 3D printing during the COVID-19 pandemic, Nature reviews materials, 2020

The Hard Lessons of Modeling the Coronavirus Pandemic, Quant Magazine, 2021

The impact the TRIPS waiver would have on Covid-19 and why it's so important, Bond, 2022

The inventor inspired by wanting to keep his daughter safe, BBC, 2020

The Lancet Commission on diagnostics: transforming access to diagnostics, Lancet, 2021

The Lancet Global Health, Supplementary Appendix, 2021

The lightening fast quest for COVID vaccines, and what it means for other diseases, Nature, 2020 Entrepreneurship during a pandemic, Storr et al, 2021

The mRNA technology transfer hub, WHO, 2021

The myriad ways sewage surveillance is helping fight COVID around the world, Nature, 2021

The OpenO2 Mobile Workshops, Website, Accessed July 2022

The Oxygen Plant-in-a-Box: Innovation drives a key response to COVID-19, UNICEF Supply Division, 2021

The Pandemic Has Snapped Communication Lines Between Schools And Students In India, UN Foundation, 2021

The President's Special Awards for Pandemic Service, Royal Academy of Engineering, 2020

The rise of e-commerce in the post-pandemic world, Burke J, 2022.

The Rise of the Pandemic Dashboard, Bloomberg, 2021

The role of data in a world reshaped by COVID-19, Penn Today, 2020

The Secret Of China To Build A Hospital In 10 Days, Sacyr, 2021

The Unequal Impacts of Covid-19 on Global Garment Supply Chains, LeBaron G et al., 2021.

The World Bank in Malawi, The World Bank, Date Accessed: July 2022

The World Health Organization launches WHO Health Alert on WhatsApp, Whatsapp, Date Accessed: July 2022

Thinking like an engineer, Implications for the education system, Royal Academy of Engineering, 2014

This is how COVID-19 is affecting informal workers, World Economic Forum, 2020

Transparent Medical Mask, Hello Face, Date Accessed: July 2022

Two thirds of the world's school-age children have no internet access at home, new UNICEF-ITU report says, UNICEF, 2020

Using AI to improve back office efficiency in the NHS, NHSX, 2022

Using Data Innovation to Improve Health Outcomes in Uganda, UNICEF, 2021

Using Genomic Sequencing to Monitor Covid Variants and Subvariants in Wastewater, Biobot, 2022

Using mobile big data to help inform the fight against COVID-19 in the Democratic Republic of Congo, GSMA, 2020

Using technology to get through the pandemic, ATSE, 2020

UVD Robots Autonomous Disinfection, UVD Robots, 2022

Variants, Misinformation, and 'Brain Drain' — The COVID-19 Vaccine Experience in Brazil, India, and Africa, National Academies, 2021

Venitlator Challenge UK marks the end of the consortium after delivering 13,437 ventilators to the NHS, Smiths, 2020

Ventilator Challenge hailed a success as UK production finishes, Gov.uk, 2020

Ventilator market set to return to pre-pandemic levels in 2021, Merical Device Network, 2021

Vital equipment to fight Covid-19 crisis in Africa, Scottish Government, 2021.

Was building the NHS Nightingale hospitals worth the money?, The Kings Fund, 2021.

Wastewater surveillance as a long-term tool for resilience, Arcadis, 2021

Water, Sanitation, Hygiene. Engineers without Borders.

Weekly epidemiological update on COVID-19 - 15 June 2022, WHO, 2022

What can the government do to ensure it has the right networks to help with future emergencies?, Royal Academy of Engineering, 2021

What longer delivery times say about global supply chains, World Economic Forum, 2021.

WHO announces first technology recipients of mRNA vaccine hub with strong support from African and European partners, WHO, 2022

WHO launches a chatbot on Facebook Messenger to combat COVID-19 misinformation, WHO, 2020

Why AI Failed to Live Up to Its Potential During the Pandemic, Harvard Business Review, 2022

Why intellectual property and pandemics don't mix, Brookings, 2021

Why many countries failed at COVID contact-tracing — but some got it right, Nature, 2020

Why open science is critical to combatting COVID-19, OECD, 2020

Why the Pandemic Has Disrupted Supply Chains, Helper et al., 2021.

Will COVID-19 have a lasting impact on the environment, BBC Future, 2020

Wingcopter: Improving Health Logistics Infrastructure In Peru, Post & Parcel, 2022

Women and minorities are lost in engineering 'brain drain', The Times,2021

Zoom, Microsoft Teams, and Slack Have Exploded Due to the COVID-19 Pandemic. Can They Hold onto This Growth?, GLE, 2020