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POSTPANDEMIC ENGINEERING

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

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LINKING ENGINEERING AND SOCIETY

A Word from the NAE Chair

Guest Editor's Note

Features

News and Notes

A Word from the Chair

Linking Engineering and Society

Donald C. Winter,
Chair, NAE

"Linking engineering and society" is both the tag line of *The Bridge* and, I believe, an appropriate title for this column as I reflect on the role of the NAE at this time of rapid societal change.

Societal changes precipitated by technology are nothing new, dating back at least to the original Industrial Revolution in the late 18th and early 19th centuries. What is arguably new today is the pace of transformation.

While the first Industrial Revolution took decades to develop, today we are seeing exceedingly rapid changes in the ways we live, work, and care for the young and old as we adapt to the covid-19 pandemic. Many of these societal changes have been enabled by recently developed technologies, particularly the internet. The responses to the pandemic have accelerated the evolution and adoption of many of the technologies that leverage the capabilities of the internet to communicate. What had been a slow exploration of the use of virtual gatherings to conduct business, educate, and socialize has, in less than a year, become a commonly accepted and defining element of society.

Furthermore, the impact of the wholesale adoption of virtual meetings is already expanding well beyond the domain of the cyber community. Whether virtual meetings ever totally obviate the need for brick-and-mortar offices, it is becoming evident that significant, permanent changes are coming to the role of such facilities, the composition of the cities they are located in, and the nature of the supporting infrastructures. The same is true of the academic community, from elementary school to university. These changes are likely to be further expanded and accelerated by developments in robotics and artificial intelligence, extending the domains impacted to the agricultural and manufacturing communities as well.

As these impacts unfold, responses by private industry and various levels of government will need to keep pace. While private industry may be able to fund its responses through existing mechanisms, government-funded efforts will need to accommodate the budgetary implications and recognize the opportunity costs associated with new initiatives. Furthermore, the initiatives of both private industry and government will need the development of supportive public policy.

Public policy development is a complex process that is inherently political, not necessarily in the sense of political parties but simply in reflecting multiple constituencies that have diverse, and often conflicting, priorities and agendas. As I noted in my remarks at the NAE annual meeting last October,[1] the challenge of decision making constitutes a significant dilemma for federal, state, and local governments as few politicians have the formal training to fully comprehend the technical considerations that underlie these issues.

While individual aspects of societal change may be analytically addressable, such changes are inherently parts of very complex systems. Norm Augustine addressed the challenges of dealing with such problems in his epilogue to the winter issue of *The Bridge*,[2] noting the ambiguities inherent in the identification of figures of merit for such complex systems and citing examples: "What is the exchange rate between tons of carbon emitted into the atmosphere and its social cost? Is it appropriate to put millions of people out of work, many of them into poverty, in order to save thousands of lives in a pandemic?"

While the National Academies have a well-earned reputation for providing independent, objective, and nonpartisan advice to government decision makers, the policy issues stemming from the great societal changes we are just starting to see will put added emphasis on

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[1] Remarks by NAE Chair. The Bridge 50(4):92–93.

[2] Augustine NR. 2020. Toward an engineering 3.0. The Bridge 50(4):79–82.

the need to abide by the NRC's exacting processes to ensure that our advice continues to be recognized as independent, objective, and nonpartisan. At a time of great partisan division in our nation, it is incumbent upon us to rise above such matters and provide advice that is above reproach.

As I have been ruminating about this challenge, I am reminded of a lesson I learned a number of years ago about the delivery of assessments and advice to government officials. ADM (ret.) Bill Studeman taught me that the best way to get the confidence of politicians was to first tell them both what you know and what you don't know and only then, tell them what you think. They were good words then, and they are good words now.

Guest Editor's Note

Digitization to Transform Manufacturing

Jennie S. Hwang (NAE) is CEO of H-Technologies Group.

In the digital transformation era, a transcendent moment for US manufacturing on the global stage has arrived with the confluence of the evolving Fourth Industrial Revolution (Industry 4.0), global geopolitical uncertainties, and the coronavirus pandemic. It is appropriate to take stock of the future of US manufacturing. What will it take to garner competitive prowess and catalyze a virtuous innovation-manufacturing cycle?

This issue is dedicated to the future of manufacturing. A stellar slate of experts present diverse experiences and perspectives from industry, a national laboratory, and academia. Together the articles provide informative coverage and holistic views on the future of advanced manufacturing, leveraging new and emerging technologies, desired infrastructure, innovative approaches, and a resilient supply chain to fortify US manufacturing competitiveness in the coming years.

The lodestar for the future of manufacturing is innovation. One of the most acclaimed engineers and accomplished businessmen in the 20th century and the author of a must-read book, *Only the Paranoid Survive*, Andy Grove (2010), writes: "Startups are a wonderful thing…as technology goes from prototype to mass production…this is the phase where companies scale up. They work out design details, figure out how to make things affordably, build factories, and hire people by the thousands. Scaling is hard work but necessary to make innovation matter."

Indeed, scaling up reveals products' intricacies and captures processes' nuances, building invaluable know-how, knowledge, and innovative capacity. Manufacturing spurs innovation, and innovation propels manufacturing. In the larger picture, manufacturing also makes incalculable contributions to technological development and deployment, the workforce, and the nation's continued prosperity in the competitive global sphere.

In This Issue

In the opening article I highlight the role of emerging technologies in advancing the manufacturing ecosystem and the convergent trend of technologies. The article also includes strategic business questions to be considered both to brace for challenges to the supply chain, workforce, and operations and to embrace opportunities that have emerged from the current mega-events.

In the second article, **Thomas Kurfess** and Howard Grimes discuss manufacturing and supply chain ecosystem innovations and the critical role of the digital thread in ensuring a secure, resilient, and adaptable manufacturing ecosystem and enabling augmentation of the human workforce. They explain the utility of the concepts of a "cyberphysical passport" and "born qualified" for operational production, and offer a thought-provoking comparison between ride-sharing and the manufacturing and supply chain ecosystem.

In the next article, "The Local Factory of the Future for Producing Individualized Products," **Yoram Koren** showcases, with intriguing and creative illustrations, the manufacturing system architecture that enables the production of mass-individualized items, such as car interiors designed by the customer. He envisions that this capability and infrastructure will change the landscape of the manufacturing industry, with significant benefits for the economy and job market as well as consumer satisfaction.

Behrokh Khoshnevis then discusses "telefacturing" as a new manufacturing paradigm utilizing the components of Industry 4.0 to enable offsite work in support of production. He outlines the advantages of telefacturing—for example, reduced risk of disease contagion from worker proximity, fewer worker injuries from accidents with equipment on the factory floor, elimination of time-consuming commutes—and the continued technological and system-level advances needed for success.

Barbara Goldstein and Kate Remley focus on the next-generation industrial internet of things (IIoT), describing a government research program related to communication and sensing for wireless connectivity and IIoT technology. The research, at the US National Institute of Standards and Technology, is intended to support modern manufacturing in achieving the speed and reliability required to perform in factory-floor operations, the harshest of radio-propagation environments.

The sixth article illustrates the role of academic makerspaces in contributing to the future of manufacturing and discusses valuable lessons learned during the pandemic. The authors, James McGuffin-Cawley and Vincent Wilczynski, include case studies with compelling accounts of several very effective joint ventures of university makerspaces, manufacturers, and regulators. They conclude with opportunities for continued collaboration.

Hau Lee presents considerations for designing the global supply chain in the new normal after the pandemic. He discusses the relevance of end-to-end landed-cost analysis and explains the importance of avoiding overreaction and of designing a resilient global supply chain characterized by agility, responsiveness, and a capacity-ready platform.

The final article, by **Ajay Malshe**, **Dereje Agonafer**, Salil Bapat, and Jian Cao, illuminates the application of frugal engineering for social innovations to deliver social equity. The authors present examples of frugally engineered social innovation around the world, and make a compelling case for the need to apply such an approach to address inequities in the United States.

The Path Forward

As the global landscape continues to change, the future remains the most precious commodity. Charles F. Kettering, an American inventor and accomplished engineer, conveyed it well: "My interest is in the future because I am going to spend the rest of my life there."

For the future, national recognition of the importance of digitized manufacturing to the workforce, the job market, and the national economy and security—and their interrelations—is paramount.

What is the path forward for US manufacturing? Future manufacturing will hinge on the prompt and effective adoption of frontier technologies; a well-educated and cultivated workforce; government encouragement, support, and well-balanced regulations; and constant innovation and the implementation of innovative ideas in a timely fashion.

I hope this issue sparks thoughts and actions about the role of future manufacturing to the engineering community, workforce, ecosystem, competitiveness, and ultimately the country's prosperity from all walks of professionals and all levels of the government.

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"Never let a crisis go to waste."
What are the lessons from the pandemic crisis to benefit manufacturing?

Future Manufacturing: Bracing for and Embracing the Postpandemic Era

Jennie Hwang (NAE) is CEO of H-Technologies Group.

Jennie S. Hwang

As the world is entering the Fourth Industrial Revolution (dubbed Industry 4.0), one recurring question for manufacturing is what will be involved in terms of running a business and making products. The previous industrial revolution brought advances in electronics and information technology that enabled astounding economic prosperity and manufacturing automation. What does the Fourth Industrial Revolution entail? How will it affect the international standing of US manufacturing?

Impacts of Industry 4.0 and the Pandemic for Manufacturing

One way to define Industry 4.0 is the integration of cyberphysical systems, cloud and edge technology, high-performance computing, the internet of things and internet of services, and their interoperability and interaction with humans in real time to maximize value creation. Industry 4.0 will leverage digital technologies, advanced artificial intelligence, and reliable wireless connectivity to advance autonomous, intelligent cyberphysical systems (Hwang 2016). One of the elegant fruits of Industry 4.0 is intelligent manufacturing, which is manifested in the smart factory infrastructure.

Adding to this dynamic environment is the coronavirus pandemic, which has resulted in unprecedented disruptions in virtually every aspect of life. From a 30,000-foot view, global macroeconomics is facing gusty headwinds, bracing for impacts from social distancing, lockdowns, and economic slow-downs and shutdowns. Compounding these impacts, the world's two largest economies—the United States and China—are butting heads on trade and geopolitical disharmonies.

Against this formidable backdrop, what are the lessons from the pandemic crisis to benefit future endeavors in industry? How should the manufacturing sector respond? And what are the main issues to be tackled in the near and long term?

There will be a new normal in business and manufacturing, just as in daily life. There is a saying, "Never let a crisis go to waste." For manufacturing, the current crisis is expected to propel progress toward fulfilling the potential of Industry 4.0. The pandemic has made the global manufacturing sector think more deeply and work harder to meet the need for innovative ways to run and monitor operations.

> *AI can identify manufacturing quality issues in real time and spot faults on the production floor faster than humans.*

This article examines five fronts that are deemed essential to advanced manufacturing going forward: the role of new and emerging technologies; revised business strategies for outsourcing, with engineering as the core; data-driven manufacturing operation; supply chain strategy and management; and changes in workforce practices and skills. These five areas are expected to dictate the global competitiveness of manufacturing.

The need to look forward with a new perspective was well captured by robot pioneer Seiuemon Inaba, who created the largest manufacturer of industrial robots in the world (Fanuc Corporation, a spin-off from Fujitsu Ltd.): "There is history behind technology, but for engineers, the past doesn't exist. There is only creativity, always looking to what is next" (Tsuneoka 2020).

Role of New and Emerging Technologies

Industry 4.0 is expected to pull manufacturing into an intelligence-directed and technology-centric smart factory infrastructure characterized by agility, flexibility, automation, autonomy, and cost efficiency. Advanced manufacturing hinges on the development, deployment, and implementation of next-generation wireless technology (e.g., 5G and higher), the internet of things (IoT), advanced artificial intelligence (AI), and high-performance computing (cloud and edge).

One challenge is the seamless incorporation and coordination of these foundational technologies. Another is management and protection from cyberrisks and quantum attacks, an area that demands ongoing effort. It is essential to put the evolving technologies together to perform as a reliable cyberphysical system in the manufacturing landscape.

Those challenges are an area of ongoing global competition among scientists, engineers, companies, and countries. The ability to leverage technologies by integrating them in timely, creative, and reliable ways will afford competitors the upper hand, leading to business success and economic rewards as well as the nation's competitive edge. Government investment and regulatory policies will play an important role.

AI and machine learning (ML) have become everyday terms, although their potential is not fully developed. On one hand, there is exuberance about evolving capabilities that promise to advance business and manufacturing. On the other, there is trepidation about unknown or possible unintended consequences.

AI processes data through ML and deep learning neural networks by collecting data, analyzing information, creating and training a model, and ultimately making decisions based on real-time events. It is expected that next-generation AI will not only create a model based on learning from continually generated *meaningful* new data but also advance that model through *unsupervised* learning to understand cause and effect (Toews 2020). For example, AI can identify manufacturing quality issues in real time and spot faults on the production floor faster than humans through monitoring and machine-to-machine and human-to-machine communication, thanks to superconnectivity and speedy, low-latency, high-capacity communication technology.

As the future of the internet is expected to move to wireless, it will depend on next-generation wireless technology, the gateway to IoT connectivity for greater levels of automation and autonomy. IoT sensors embedded in products and machines provide information about product performance during service life through data exchange between the production line and the product. This is a great use case for advanced manufacturing, making tomorrow's factories run faster, more economically, and with more agility, flexibility, and autonomy.

The convergence of AI and IoT will create an intelligent network of devices that can gather and analyze voluminous data—from raw materials, production lines, finished products, warehouse activities, and customer complaints—remotely in real time and translate the data into intelligence and actionable steps locally. The IoT can also capture data on energy use, maintenance records, workers' safety, and other operational parameters.

In addition, connected, intelligent machines can trigger maintenance processes autonomously. Data analytics can facilitate the detection of process inefficiencies and thus reduce production costs and enhance product quality. It is also possible to monitor how customers use the products, helping companies with customer service, warranty management, and product design.

Better use of evolving technologies to enable real-time contextual understanding and monitoring of the manufacturing operation and environment leads to smarter decisions. Smart factory infrastructure can improve manufacturing and autonomous on-demand production.

To achieve these goals, one question to consider is, What is needed to accelerate the adoption of new technologies—to effectively leverage AI, IoT, 5G, and bolt-on technologies and supply chains in a timely way to achieve reliable manufacturing operations?

Revised Business Strategies for Outsourcing

The first order of business for manufacturers is to revisit and strategize their business model, with particular attention to the question of outsourcing—offshore vs. onshore procurement. Simply put, this is about finding a better or more cost-effective way to have products made or services rendered, freeing up resources and time for essential or long-term mission-critical tasks.

For the past 3 decades, technology-driven industries have been characterized by fast-paced technological development, down-spiral pricing, and market globalization. They also have been the top drivers behind manufacturing outsourcing. In a competitive climate and with sound business justification, the outsourcing of certain functions can be advantageous and a smart business move.

In the United States, it is reasonably fair to say that the electronics industry essentially pioneered the implementation of outsourcing in the late 1980s and early 1990s (depending on how the starting point is defined). Gradually but steadily, manufacturing outsourcing (on- or offshore) has spilled over to other sectors, from pharmaceutical to consumer staples, as well as to other operational functions, such as human resources and information technology management. With globalization, the scope of outsourcing has continued expanding and its capabilities have proliferated, so that it is an integral part of supply chain management and business strategy.

In a competitive climate and with sound business justification, the outsourcing of certain functions can be advantageous.

Manufacturing outsourcing can offer a number of advantages in business aspects such as the following:

- economics (cost savings)
- improvement in business focus
- operational efficiency
- technological prowess
- capital allocation
- time to volume
- speed to market
- geographical advantage
- proximity to customers
- risk shared or transferred among ecosystem participants
- streamlining (reduced complexity) of business.

In the aggregate, these potential advantages offer tremendous appeal to a business, particularly in meeting immediate competitive needs. The benefits can be vividly evident when a goal-oriented and well-thought-out strategy is effectively executed.

But caution is in order to ensure that technology-based companies do not forgo core engineering competencies, including manufacturing technology, by outsourcing.

It is always a strategic decision to take advantage of the benefits of outsourcing without losing foundational knowledge and know-how. The decision requires assessing core competencies and sorting out the functions or products for outsourcing from those that need to stay in-house. Even if the decision is made to outsource a product or function, in-house engineering competencies are needed to pose the right questions in order to select the right service provider to produce quality products as intended. To outsource a task is one thing; to give up a core knowledge base is something else entirely.

To outsource a task is one thing; to give up a core knowledge base is something else entirely.

Outsourcing should be considered as a well-planned strategy, not as a relief tactic. And the strategy should distinguish between a temporary lift and long-term business enhancement.

The following questions are important to address when considering decisions about factory siting:

- Are factories logically, strategically, and preemptively distributed in terms of geographical locations to ensure reliable manufacturing operation?
- Is there a need for redundancy of factories?
- What are the critical criteria for redundant factories?

A number of years ago, during a dinner meeting with Kazuo Inamori, founder and chair of Kyocera Corporation, I asked about his view of outsourcing manufacturing. He replied candidly (paraphrased), "How can an engineer not do manufacturing and an engineering company not produce products!" I appreciated his sentiment.

In a product development cycle—from innovative concept to technology development, manufacture of the product, and introduction of the product to the marketplace—each milestone is essential to the product's eventual success. The spirit and the principle of manufacturing are part of a product and should be thoroughly embraced and incorporated with or without outsourcing.

It is prudent and wise business practice for original equipment and original design manufacturers to continue acquiring and maintaining engineering strength and know-how to ensure future readiness. Government can and should play a role in incentivizing and reinvigorating the country's manufacturing prowess.

Data-Driven Manufacturing Operation

Creativity propels technology, which in turn builds a new paradigm. With human-machine teaming, for example, synergistic performance is achieved by integrating judgment-focused humans and prediction-focused AI agents. AI should be responsibly implemented to augment human cognition and capabilities without causing ethical and social concerns—an ongoing challenge.

One of the challenges of deploying technologies such as AI as reliable tools is the lack of sufficient relevant, bias-free, and accurate data. AI requires a vast amount of data to function as desired. Accordingly, preparing AI and edge computing to facilitate manufacturing operations by initiating a robust program to collect, clean, manage, prune, and use data is increasingly important.

Data tell the story! With privacy and security precautions, data capabilities for remotely monitoring factories can provide a clearer view of operations, equipment performance, and maintenance, allowing the operation to speed up production, reduce waste, and avoid downtime by quickly identifying maintenance and production issues. Identification and extraction of relevant data to feed into artificial intelligence can facilitate the prediction of production and supply chain problems. Factories can shift from reactive analytics, reporting on what happened, to proactive analysis of what could happen and suggested actions, asking the right questions at the right time and solving problems in real time. For today's factory and in preparation for the future, figure 1 illustrates the IPC Connected Factory Exchange (CFX), enabling contextualized data exchanges and machine-to-machine interactions to help move manufacturers toward smart factories.

Manufacturing companies need to develop a thorough understanding of the available technologies that can be utilized to translate business objectives into business roadmaps for operational excellence to produce competitive, reliable, and economical products that perform in the intended marketplace in a timely fashion. The smart factory of the future is poised to run essentially

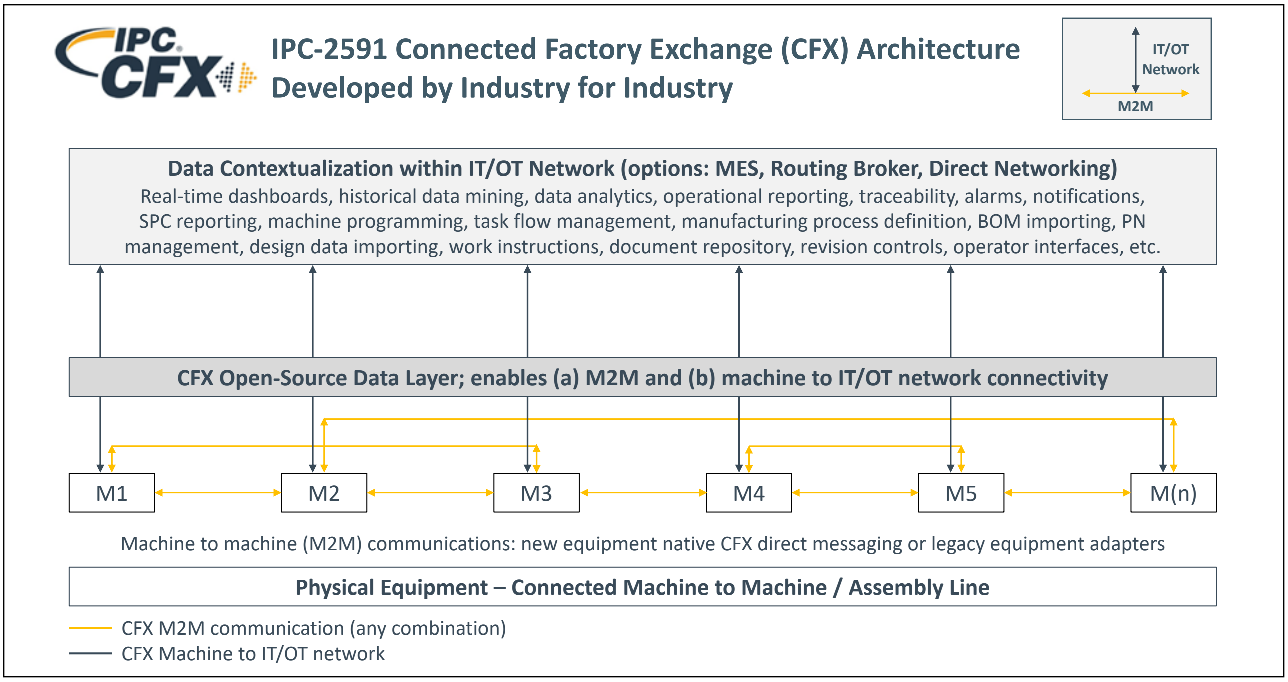

FIGURE 1 Connected Factory Exchange (CFX) architecture developed by industry for industry. BOM = bill of materials; IT/OT = information technology/operations technology; M1… = machine 1…; MES = manufacturing execution system; PN = part number; SPC = statistical process control. Courtesy of IPC Association, Matt Kelly, chief technologist.

autonomously without human intervention on the production floor, learning and adapting in real time with self-correcting and self-optimizing ability.[1]

In the manufacturing environment of the future production facilities and logistics systems will be synchronized without the need for on-site human tasks.

Supply Chain Strategy and Management

In the postpandemic era, inventory and supply chain management will be even more important for manufacturing efficiency and even a manufacturer's viability. Plans must be developed to address immediate needs as well as medium- and long-term strategies.

In the long run, factories' ability to keep track and control of inventory in terms of dollar value and days' worth is crucial to a company's bottom line. Doing well in this area reduces the likelihood of production outpacing demand and avoids cash flow traps.

Using cyberphysical systems, supply chains can be fully integrated and automated. Such systems deployed throughout the value chain generate the link between data and material flows, enabling complete and constant visibility of the supply chain. For example, IoT devices can be outfitted at checkpoints in the distribution process to keep track of parts and products as they are shipped from factory to warehouse and customer sites. Such real-time tracking enables the formulation of reliable inventory forecasts, timely reaction to unexpected changes in the production line, and avoidance of unscheduled downtimes.

What are the lessons learned from the pandemic crisis? I suggest several pragmatic questions that should be addressed strategically and operationally:

- Is a reliable dependency of the chain of suppliers in place?
- What is the technology used to monitor the supply chain?
- Is a risk management program in place?
- What is the risk mitigation plan and its order of priority?
- Are policies and procedures to address risks and threats in place?
- Do all strategic raw materials have alternate source(s), if justified?

[1] Another viable approach is to leverage the digital twin concept to create virtual counterparts of physical assets (Kube 2018) to optimize data flows from design stage to process engineering to manufacturing to the customer.

- Do all mission-critical components have alternate source(s), if justified?
- What is the desired level of visibility throughout the supply chain?
- What is the predictability of the supply chain?
- Is there an adequate system in place to ensure internal and external cybersecurity to minimize cybersecurity-related risks and disruptions to the supply chain?

Weighing overseas (offshore) sources against domestic (onshore) sources in terms of quality, cost, delivery time, and in-time availability is a strategic as well as an operational imperative. Implementing newly available technologies to minimize risk and optimize the efficiency of supply chain management is increasingly a necessity.

Changes in Workforce Practices and Skills

The pandemic catalyzed remote work, and the required social distancing has prompted the need for more sophisticated ways to monitor factory operations, including the farther and faster deployment of data management and analytics. As the pandemic continues and social distancing remains advisable, near- and long-term plans should be formulated and implemented to ensure workers' safety and health while optimizing workforce productivity and manufacturing efficiency.

Remote work and social distancing have prompted the need for more sophisticated ways to monitor factory operations.

Unlike other industry sectors, manufacturing still depends on the physical presence, to some extent, of skilled and well-trained workers. But some functions can be performed remotely (e.g., through work from home). One of the advantages of remote work is the removal of geographical barriers in hiring, enabling employers to seek the best-skilled workers regardless of where that talent resides.

Many in the workforce have cited the flexibility of off-site work as an advantage. One recent survey found that more than 75 percent of respondents would like to continue working remotely at least occasionally, and more than half want it to be their primary way of working after the pandemic crisis ends (Torry 2020). Asked what it is about remote work that has worked well, respondents' top three answers were no commute, reduced meetings, and fewer distractions. In a separate survey, 87 percent of workers wanted the ability to choose where, how, and when they worked, blending office-based and remote work (Reuters 2020).

As wireless technology becomes more available and more reliable for required connectivity, so will innovations in how people work to achieve maximum efficiency and output, including in their work from home. Going forward, a hybrid work model is most likely to be implemented throughout the companies and organizations, although the extent may vary depending on the nature of the business and the organizational operation.

With the massive amounts of data generated from different checkpoints, data management is crucial, including efforts to ensure data quality, accuracy, and security. Over the next decade, a skilled and educated workforce, bolstered by continuing education and training programs—especially in data science, data engineering, advanced computing, and system integration—will be essential to manufacturing competitiveness in the global landscape.

Concluding Remarks

I have been engaged for more than 3 decades in electronic hardware innovation and manufacturing, in both hands-on and advisory capacities, for onshore and offshore operations ranging from fledgling entrepreneurial businesses to robust enterprises operating on three continents. This firsthand experience has shaped my perspectives in manufacturing.

The best way to prepare for tomorrow—and further unexpected crises—is to do today's work well. Technologies' benefits for manufacturing are abundant, yet challenges remain. The implementation of technologies is not a one-time or one-size-fits-all decision. It calls for continuing and targeted efforts. As Industry 4.0 strides ahead, the adoption of new, evolving technologies is critical to a business's viability and its effectiveness in confronting the challenges resulting from the pandemic, associated blows to the economy, and ongoing Sino-US tensions and trade uncertainty.

The pandemic crisis has created an unprecedented opportunity to boost individual manufacturers' competitive edge as well as the country's global competitiveness in manufacturing. "Winners" will be those that work most effectively with emerging technologies and adapt adroitly to the changing environment. The manufacturing workforce's ability to adapt to change has been tested and in many ways enhanced, and supply chain management is expected to be more resilient.

There is a rainbow after the storm. Crises can create opportunities to build a better normal, and that is certainly true now. Let's brace for the challenges and embrace the opportunities!

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The digital thread makes it possible to digitally verify products, deploy the latest technologies for manufacturing, and strengthen the workforce.

The Role of the Digital Thread for Security, Resilience, and Adaptability in Manufacturing

Thomas Kurfess

Howard Grimes

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Howard D. Grimes

The manufacturing sector is dramatically evolving with recent technical and digital advances. Among these, the digital thread is revolutionizing manufacturing operations well beyond the historic downloading of programs to computer numerically controlled (CNC) machine tools and the uploading of edited programs from CNC controllers.

The digital thread is "the communication framework that enables a connected data flow and integrated view of the asset's data throughout its lifecycle across traditionally siloed functional perspectives" (Leiva 2016). It is pervasive around the world and has changed the way society operates; for example, map apps are used to provide time-optimal directions to destinations using real-time traffic feedback.

The digital thread makes it possible to digitally verify products, ensure that the latest technologies are deployed across the entire manufacturing ecosystem, and strengthen the workforce by making each individual more efficient and effective. These three foundational advanced manufacturing concepts will ensure a next-generation secure, resilient, and adaptable man-

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ufacturing ecosystem and sustainably support current and future needs of society (Lynn et al. 2020).

Digital Verification of Products: "Born Qualified" and the Cyberphysical Passport

The driver for "born qualified" manufacturing[1] is to change the qualification paradigm for low-volume, high-value, and high-consequence parts that are essential for high-risk industries such as defense, energy, aerospace, and health (Roach et al. 2018). As a complement to born qualified manufacturing, we introduce *cyberphysical passports* (CPPs) for advanced manufacturing.

A CPP enables digital identification, tracking, and verification of parts and products in a uniform, hierarchical fashion with a framework that is extensible to a variety of processes (mechanical, chemical, electromagnetic, etc.). It is a mechanism to capture and digitize an encrypted and verifiable structure for physical parameters as well as embodied energy for every part and for aggregated products throughout the supply chain, and consequently provides a "root of trust" for the entire supply chain and manufacturing process (Grimes et al. 2020).

Born qualified and CPPs are operationalized during production with the use of a variety of sensors to ensure product quality and integrity. The CPP records and stores information from these sensors such as every motion of a machine tool, the type of tooling used for machining, energy consumption, and process parameters. In short, the CPP records everything about the part and the process used to make it.

When the product arrives at its destination, it can be considered born qualified and accepted based on its CPP. The receiver of the part knows that it is genuine (not counterfeit), was made to specifications, and there was no tampering with the production process. The CPP is a cornerstone of the secured supply chain.

Deploying and Leveraging the Latest Technologies

The digital thread facilitates delivery of the latest technologies to the end user in the manufacturing supply chain, tightly and securely integrating the supply chain and supplying data on manufacturing operations. It can be used to gather information on manufacturing operations and systems as well as to drive and update these systems.

Secure Updates

Manufacturing system updates happen in the same manner that computers or smartphones are updated: pushed to the equipment from the original vendor or third parties that support the various manufacturing systems. This must be done in a secure fashion and significant care must be taken to ensure that manufacturing systems such as 3D printers, machine tools, or robots are not disabled or "bricked."

> *A cyberphysical passport enables digital identification, tracking, and verification of parts and products.*

Plug-and-play hardware will also be deployed for updating system hardware in much the same fashion as printers, speakers, or human-machine interfaces are deployed on computers. Other means for deploying updates include wireless communication such as Bluetooth, Wi-Fi, and Zigbee.

Open communication protocols such as MTConnect and OPC UA (Open Platform Communications Unified Architecture) are currently used to communicate between machines. The implementation of communication systems in manufacturing operations must be done in a manner that is cybersecure to protect against tampering with equipment and processes, and to protect intellectual property stored and used on the production systems (Lynn et al. 2018).

Consistency in Product Quality

CPPs will capture and digitize information generated by production systems that transmit data on process capabilities as well as product quality and integrity. Data from production systems will also be used for global process improvement.

It is widely known, for example, that the 3D printing process has a substantial number of variables that can generate inconsistency in part quality. Such inconsistencies often manifest themselves in material characteristics such as precipitates in the manufactured component, residual stresses, and toughness. Many parameters can be adjusted in the 3D printing process,

[1] "Born qualified" refers to parts produced through metal additive manufacturing that emerge from the print bed ready for direct use, even in critical structures such as vehicles, airplanes, and power plants.

each of which can slightly or significantly modify the final characteristics of the product.

AI and ML Models

Researchers have been successful in the implementation of artificial intelligence (AI) and machine learning (ML) techniques for modeling the additive manufacturing process and optimizing multiple parameters to achieve specified part characteristics. But these parameters vary from system to system based on a variety of machine, material, geometry, and environmental factors. Even a particular machine's performance can vary over its lifespan. Thus, it is important for AI/ML models to be constantly updated, and digital thread data are critical for developing accurate models.

Accurate models have been generated for very specific machines, geometries, process parameters, and materials, and significant research is underway to transfer models from one machine, material, and geometry configuration to others. Such an approach is not limited to additive manufacturing but is applicable to subtractive (e.g., machining), injection molding, chemical, biopharma, and many other manufacturing processes and operations (Ahuett and Kurfess 2018).

An operator can use a smartphone to scan data that are correct, reducing potential error from manual keyboard inputs.

In addition, machine suppliers and end users can securely exchange model-generated data to develop and deploy new models. For example, a company producing a powder bed 3D printer may use a proprietary model to ensure part quality. This model resides in the cloud with the advantage of securing process information for the machine users.

At the same time, the data from the machine are needed to optimize the model by the machine supplier, which receives production information from the machine's sensors while the end user receives a CPP for each part produced. Thus, the end user always has fully updated information about the machine's capabilities and the machine supplier always has an updated model using data directly from the machine. This scenario is beneficial to both parties.

If such machines are developed to be more open, then there is also the possibility that third-party models and drivers could be employed to drive the machine, enabling the rapid deployment of new technology from a variety of research teams to the ecosystem. However, such a capability does raise concerns (e.g., intellectual property, safety, and warranty) that must be considered.

Strengthening the Workforce

Notwithstanding significant advances in automation and AI, humans are and will remain a critical part of the manufacturing ecosystem. In fact, technologies leveraging the digital thread in the manufacturing sector are ideal for augmenting the human workforce.

Automation in Product Inspection and Training

Some digital thread capabilities employ widely available technologies. For example, mobile phone cameras (or low-cost USB/web cameras) can be used to visually inspect parts, allowing the machine operator to concentrate on other duties. Such inspections can easily "pass" parts deemed acceptable and flag those that might have a quality issue. In an era of 6-sigma quality, this means that an operator is not inspecting thousands of parts but only the few that have a higher probability of not being acceptable, significantly reducing the cognitive load on the operator.

Similarly, with radio frequency identification tags, QR codes, and bar codes, the operator can use a smartphone to scan data that are correct, reducing potential error from manual keyboard inputs. Bluetooth-enabled manual metrology tools such as micrometers and calipers can also enable secure, traceable, and error-free product and process validation, enhancing the utility of the CPP.

By monitoring the results of manual operations, additional training can be optimized for individual workers as necessary. For example, if an operator's micrometer readings have a significant quantified distribution (e.g., standard deviation) a personalized training program can be developed and suggested for the operator to improve skills related to micrometer repeatability. Such monitoring does raise privacy issues that must be considered.

Augmented, Virtual, and Extended Reality

Augmented reality (AR), virtual reality (VR), and extended reality (XR, which refers to all real and virtual environments generated by computer technology and wearables) will play a key role in strengthening and training the manufacturing workforce. Such devices can be a direct and intuitive means for input to human operators.

In any production facility, safety glasses are required, and using AR goggles in place of safety glasses is an easy and relatively inexpensive proposition. These goggles may be used to verify that proper procedures are followed or to provide guidance to line workers. For example, for installing new inserts on machine tools the location of the insert can be easily identified and highlighted in the AR goggles. The appropriate tool can then be identified to replace the worn insert, and step-by-step instructions can be visually conveyed to the technician to ensure that she correctly and safely replaces the insert.

Another use of AI/ML and AR is in augmenting the capacity of manufacturing system operators to reduce their cognitive load. Figure 1 illustrates the utility of AR goggles in quality assessment. The images were generated and processed by a smartphone camera, but they could also easily be executed in cloud operations.

The original photos (A, C, E, G) show a machined part before and after surfacing. Image processing readily reveals whether the surfacing has been properly completed (B, D) or not (F, H). AR goggles can be used to highlight irregularities for the operator, preventing the need to visually inspect each piece. While some processing is currently available on AR goggles, next-generation units will be able to locally process images for faster results.

Simple image processing algorithms can determine that all the straight lines of the blank have been replaced by the concentric circles of the finished part. These analytic techniques are relatively simple to implement and, by reducing the cognitive load on the operator, result in improved efficiency, quality, and job performance (Urbina et al. 2018).

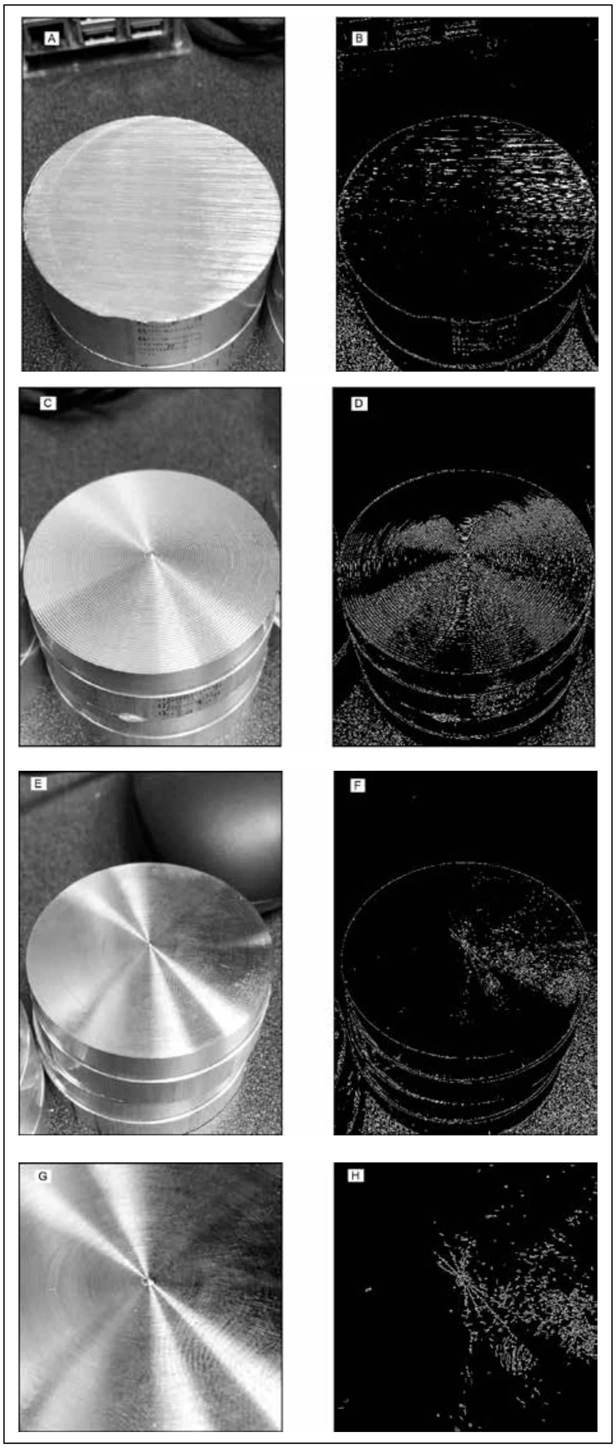

FIGURE 1 (A) Original image of saw-cut blank part before it is loaded into a lathe for a facing operation. (B) Processed image highlighting straight lines on the blank from the sawing operation. (C) Original image of the part after the facing operation, which produces concentric circles on the surface. (D) Processed image highlighting concentric circles. (E, G) Original image and close-up of improperly surfaced blank; (F, H) processed image and close-up highlighting irregularities of a part that must be refinished or discarded.

Illustration: The Rideshare Market

A comparison to the rideshare market demonstrates how the digital thread results in a manufacturing and supply chain ecosystem that is secure, resilient, and adaptable. There are three key elements to this comparison: (1) connecting the customer to the supplier, (2) the born qualified concept, and (3) leveraging and extending the capabilities of a well-trained workforce. A machine tool is the exemplar for this discussion, but it is applicable to a variety of manufacturing operations.

The first element, connecting the customer to the supplier, is straightforward. A rideshare app connects an individual who requires a ride to a driver. The same is true for machine tools that are online. A service, perhaps the machine tool original equipment manufacturer (OEM), that understands the capability and availability of the machine and its operator can connect the machine shop with potential customers.

A highly resilient and robust supply chain favors local suppliers that can rapidly deliver qualified products with minimal lead time.

The second element, born qualified, is instantiated in the rideshare scenario by the map displayed on the rider's smartphone. This map shows riders that they are not being "taken for a ride" and that the driver is following a preset approach to the destination. Information such as distance, time to destination, and cost is also conveyed to the customer. Thus, the rideshare app provides transactional security for both drivers and riders.

In manufacturing, the service can transmit the necessary programming for the machine tool, the raw materials (e.g., castings, bar stock, tooling), and the process parameters necessary to produce the part on the machine. Data from the machining process, as well as any subsequent inspection, can confirm that the appropriate manufacturing protocols were followed and that the part meets all specifications. This information becomes an element of the product's CPP. When the final part is delivered to the customer, there is no need to inspect it as its qualification is validated by its CPP. The service thus provides transactional security for the machine tool, the raw materials, and the process parameters used to produce the part on a machine.

The third element, leveraging and extending the capabilities of a well-trained workforce, is represented by the map used by the driver in the rideshare example. This map is an automatic feature and includes step-by-step instructions that are modified in real time based on traffic conditions, so no potential exists for driver error regarding the route to the destination. The driver does not need to know the exact route or traffic patterns as the app supplies this information.

The same is true for the machinist who receives programs and parameters used in the manufacturing process. AR is used to guide the machinist in setting up and running the machine. Information supplied by the AR systems may come from AI or human experts depending on the scenario.

This approach can also be used to train both the operator and the AI system. As the operator is setting up the machine, AR systems can explain the setup process, thereby educating the operator. AI/ML systems can also learn when a human is the expert to provide guidance to the operator. Such an approach ensures that the operator is continuously learning and that the AI/ML models are constantly capturing new content. This method is commonly used by automotive companies to train their autopilot systems: ML algorithms constantly monitor both the vehicle's sensor signals and the driver's reactions to signals representing the environment around the vehicle (Parto et al. 2020).

Conclusions

The digital thread makes it possible to digitally verify products, ensure that the latest technologies are deployed to the entire manufacturing ecosystem, and make workers more efficient and effective:

- The innovations described in this paper ensure that each product is made according to specification and the production process is not maliciously manipulated. The product is born qualified and validated by its cyberphysical passport, which guarantees that it is genuine and not counterfeit.
- Manufacturing requests can be rapidly and securely presented and fulfilled by a wide, vetted, and continuously updated supplier base. This base constitutes a highly resilient and robust supply chain, favoring local suppliers that can rapidly deliver qualified product with minimal lead time.
- Leveraging AR facilitates workforce augmentation and training, yielding a modernized staff with continually updated skills.
- Data flowing to and from production operations ensure that digital twins of production processes and equipment are fully up to date, and that process models and

capabilities are available to the entire manufacturing enterprise, from large multinational corporations to small and medium-sized manufacturers.

Consider the need to rapidly produce complex commodities, like respirators, and how the digital thread enables a new approach. Rather than stockpiling the entire respirator or its components, digital stockpiles of *designs* for metal machined components or injection molds for plastic components can be generated, stored, and constantly updated. When these components are needed, they can be outsourced to local qualified and vetted job shops where they are born qualified and rapidly delivered to the OEM.

Furthermore, if 1000 parts are needed in 24 hours, rather than one large facility producing all of them, 50 smaller local shops could each produce 20 parts, enabling a rapid turnaround. Such a supply chain also ensures a resilient production base because the loss of a smaller shop (due to a disaster such as fire or flooding—or perhaps a pandemic outbreak) does not shut down the entire supply chain. Components could be brought to assembly points where staff, perhaps not experts but enabled by AR, could do the final assembly and packing of a product that is validated by its CPP and the CPPs of its components.

The digital thread can be used to securely scale and certify a variety of production sectors such as clean energy, semiconductors, biomedical (e.g., vaccines), and energy-intensive industries. In addition, combining the digital thread with the concepts of born qualified and the cyberphysical passport can secure production capabilities necessary for defense and national security.

The application space is boundless and ensures a secure, modern, resilient, and state-of-the-art supply chain. The digital thread also can democratize advanced manufacturing capabilities, favoring small, local, and nimble operations that are inherently good for the "mom and pop" shops that are the backbone of US manufacturing. It strengthens US manufacturing capabilities and global competitiveness, and affords significant opportunities for economic growth for small and medium-sized manufacturers, directly benefiting the middle class by providing high-paying job opportunities to a highly skilled and continuously upgraded workforce.

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Mass individualization factories will create local manufacturing jobs and novel research areas in manufacturing operations.

The Local Factory of the Future for Producing Individualized Products

Yoram Koren

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My vision for 21st century innovation in the manufacturing industry is the establishment of a new type of factory for producing individualized products for a single customer at an affordable price. Such factories will be located close to customers and designed for cost-effective, large-scale production of a variety of individual products.

Two key technologies that enable the production of mass-individualized products are 3D printing machines (Murr 2016) and the manufacturing system architecture (the way machines are both placed in the system and connected to each other; Koren and Shpitalni 2010).

One type of individual product is the design of car interiors to fit a customer's specific needs and preferences. Realizing this vision requires new software that will enable an ordinary buyer to design the unique interior of her own car.

Individual products will be manufactured in local factories because interaction with the buyer is an essential element in the success of this new industry. This contrasts with the globalization trend that started around 2000 in the manufacturing industry and facilitates the production of products in distant countries (Koren 2010).

I believe that mass individualization factories will dramatically change the landscape of the manufacturing industry, establish many local manufacturing jobs, and create novel research areas in manufacturing operations.

Historic Trends in Modern Manufacturing

The history of modern manufacturing began around 1850, when the automobile industry started and cars were produced locally, one at a time, each for an individual buyer (figure 1). In 1913 Henry Ford's moving assembly line was invented, which led to mass production, peaking in 1955, when only seven types of cars were produced by the Big Three in the United States. Mass customization was introduced around 1980, with more models and options offered by the manufacturer for selection by the individual customer.

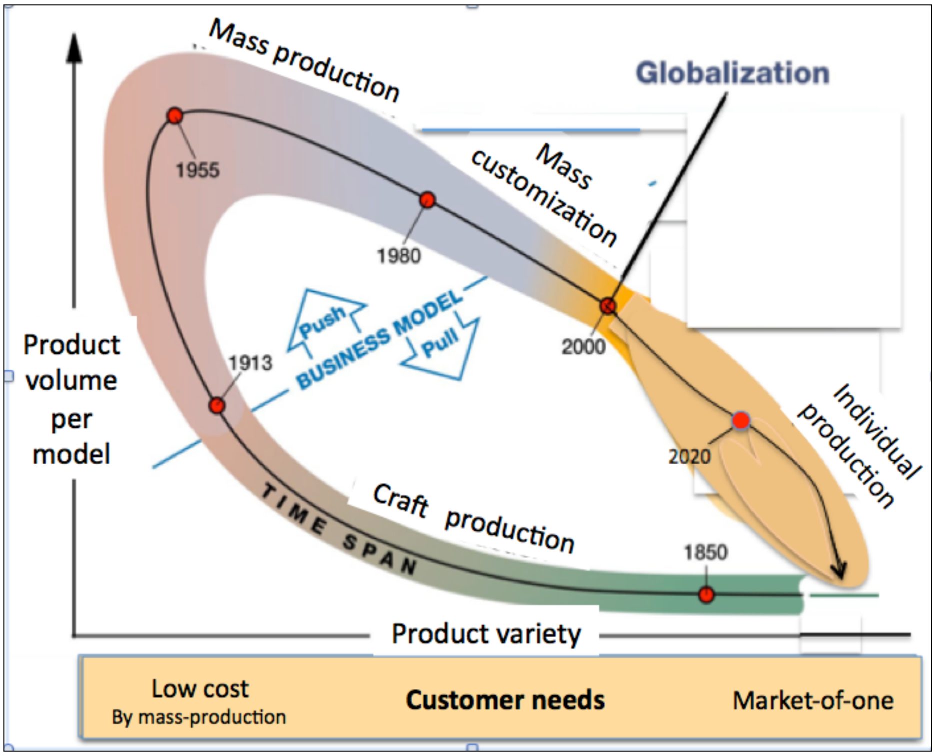

FIGURE 1 Product volume versus variety in four manufacturing paradigms over time: craft production, the prevailing approach until 1913 when Henry Ford introduced the assembly line; mass production (1913–80), which lowered both cost and product variety (mass production peaked in 1955, when the Big Three US auto makers offered just seven models); mass customization (since roughly 1980); and, with the ramp-up in globalization at the turn of this century, individual production, which will be initiated in the 2020s, thus returning to outfitting cars to the individual consumer's needs but at low cost compared with craft production.

Now the trend is toward individualization (Clifton 2018; Kanecko et al. 2017). The internet and social networks are changing the market, making it easy for customers to come up with new ideas and unique products (Jiang et al. 2016). As shown in figure 1, the societal shift from craft production to mass production to mass customization and now individual production is coming full circle—but from market-of-one for the wealthy to market-of-one for the ordinary buyer.

Table 1 summarizes the differences among three consecutive paradigms: mass production, mass customization, and mass individualization (Koren et al. 2015). With mass production the factory scheduling is fixed—1000 products a day on the same production system with the same part program. Mass individualization—each product is different and requires another set of manufacturing operations (that each takes a different amount of time)—entails completely new mathematical challenges in scheduling and in system operations. Another challenge is that new interfaces are needed to allow ordinary consumers to connect with the mass individualization factory of the future.

TABLE 1 Product type and customer's role in three manufacturing paradigms

Paradigm	Product architecture	Product type	Customer's role
Mass production	Unified	Identical products	Choose a product
Mass customization	Modular	Product with options	Choose an offered option
Mass individualization	Open architecture	Buyer's designed product	Involved in his/her unique product design

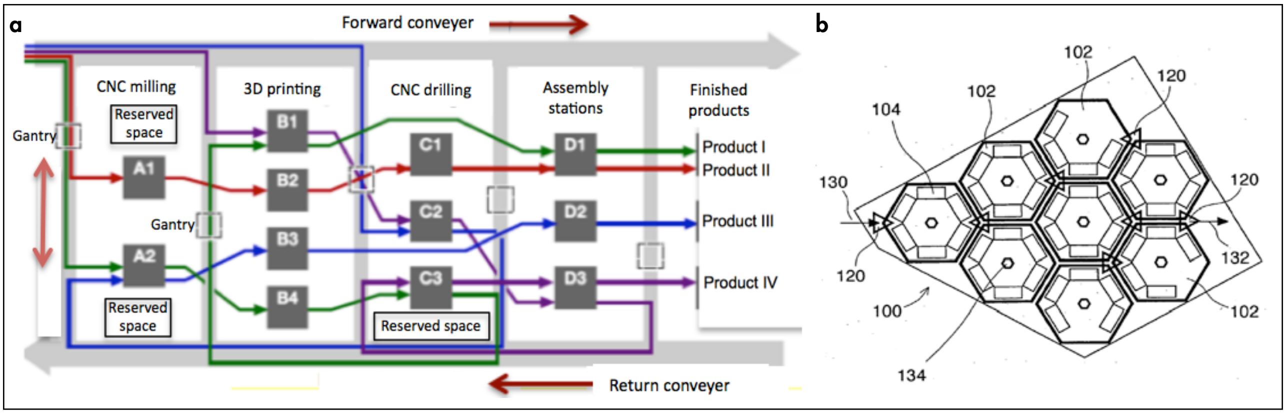

FIGURE 2 Two manufacturing system architectures of a factory for manufacturing mass individualized products. **(a)** Simultaneous production of four individual products through various manufacturing phases. A gantry brings parts from the conveyor to the machines in the cell and when a machine finishes the task, the gantry takes the part back to the conveyor, which moves the part to the next cell (e.g., from CNC milling to 3D printing), and so on to the finished product. **(b)** Diagram of the whole factory (100) organization and product progression. Materials enter on one side (130) and finished products emerge on the other side (132), transported through the system on a loop conveyor (120). Hexagons (102) represent manufacturing cells, each with 4–6 machines (e.g., milling machines, 3D printers, welding machines) or assembly stations (104). Cell controllers (134) are connected to a central controller that coordinates the traffic of all products. CNC = computer numerical control.

Mass Individualization Factories

I will elaborate on two types of mass individualization factories:

1. A factory that can produce numerous individual products at affordable cost, thanks to manufacturing system architectures that enable the simultaneous production of a variety of market-of-one products.
2. An assembly factory for building individualized vehicle interiors and other open architecture products (which comprise a fixed platform and modules that can be added and swapped; Koren et al. 2013) that require manual assembly of components chosen by customers.

Mass Individualization Factory for Producing a Variety of Individual Products

The mass individualization factory of the future that I envision enables the manufacture of many individualized products (e.g., a decorative garden fountain, a small metal roof for an outside door, or an individual prosthetic ordered by a hospital).

For this factory I propose two types of manufacturing system architectures, depicted in figure 2 (Gu and Koren 2018; Koren and Hill 2005). The system architecture is the most critical factor in making the factory responsive to market changes (e.g., type of products, quantities) and thus economically successful.

The system architecture determines the layout of machines in the system and the way they are connected to each other. (Upon finishing a machine's sequence of operations, the connectivity between machines determines to which machines the item is transferred to continue its production.) For a mass individualization factory the manufacturing system should enable these three features:

1. transfer of the product from any machine to any other machine in the system,
2. simultaneous production of several different individualized products, and
3. space reserved for the rapid addition of machines in the future.

For example, the factory system in figure 2a has spots for four machines in every production stage, with reserved spaces for adding two milling machines and one drilling machine in the future. The diagram is based on modified system architecture of the reconfigurable manufacturing system (RMS) architecture (Koren 2010), which has been in use by Chrysler, Ford, and GM since the turn of the century. It is an ideal framework to deal with the "unpredictability of market requirements and the frequent changes induced by technological innovations. For this reason, firms are more and more addressing the need to be responsive at affordable cost" (Napoleone et al. 2018, p. 3815).

In addition to a typical RMS architecture, figure 2a depicts a return conveyor (or a gantry), which allows the transfer of a product from any stage to any other stage in the system, and integrates 3D printing machines (i.e., additive manufacturing) (Rogge et al. 2017), computerized numerical control (CNC) machines, and assembly stations in a single, coherent system whose operations are synchronized for the simultaneous manufacture of four different products (shown with purple, green, red, blue lines).

Another system architecture for the mass individualization factory is featured in figure 2b (Koren and Hill 2005), which depicts eight manufacturing cells (102), each with four to six manufacturing machines (e.g., milling machines, 3D printers, welding machine; 104) or assembly stations with workers. The system comprises 45 machines and processes (e.g., assembly). A gantry or loop conveyor (120) connects all machines and assembly stations.

The fact that every assembly station and machine can be connected to any other maximizes the ability to produce simultaneously a variety of individualized products. In addition, it is easy to replace machines or controllers, which are integrated rapidly like plug-and-play modules. This system architecture is an enormous advantage in a rapidly changing world in which new processes are invented quickly.

Cell controllers (134) for the manufacturing operations are connected to a central controller that coordinates the traffic of all products. Materials enter on one side of the factory (130) and finished products emerge on the other side (132).

Figure 2 shows two options to connect a variety of machines in a manufacturing system. Another emerging option is to move parts between machines in the system with autonomous mobile robots that use obstacle avoidance algorithms (Borenstein and Koren 1991) to avoid collisions with machines and workers. In complex systems this method will require a large floor space. Impediments to implementing cost-effective individual production may include the need for coatings or post-processing stages (e.g., for heat treatments).

Customer Design and Assembly of Vehicle Interior

Imagine that a car interior is an open space and every individual buyer can design it according to his or her individual needs and preferences, subject to safety constraints (Koren 2005). Buyers will use software to select from internet hardware modules designed and produced by third-party companies (the cloud in figure 3) that may design furniture or appliances to fit into the car, or dog seats, or any other items that a customer may want. All options will have the defined mechanical and electrical interfaces needed to attach to the chassis.

The equivalent software example is in smartphones. Many individuals and companies invent applications and phone buyers decide which apps to upload.

Potential interest in (and the market for) individual customer design of car interiors is enormous. There has been substantial progress toward autonomous driving, but the inside of the vehicle has not changed in 100 years. The 1908 Ford Model T had a driver and passenger in the front seats and three passengers in the back seat; the typical car interior is the same today.

Every assembly station and machine can be connected to any other, maximizing the ability to produce simultaneously a variety of individualized products.

The challenge is to accommodate many individual customers in the design of their car interior. The software system illustrated in figure 3 could facilitate this. Customers would select from a database of available interior components to design their dream car, possibly assisted by cloud-based design algorithms (Wu et al. 2015); the software would identify design conflicts (30 in figure 3).

The source of the drawing in figure 3 is a 2006 patent application (Koren et al. 2006). Although it was abandoned, a search on this application shows that 34 new US patents are based on it, including those of Ford Motor Co., Mazda, Boeing, Johnson Controls, IBM, and Lear Corp.

But implementation of the concept of the individual buyer’s design of a car interior raises a nontechnical challenge: Buyers are confused by too many choices (Iyengar and Kamenica 2010). When the car interior design concept is realized, a new profession will probably emerge: designers of car interiors who assist buyers with their choices.

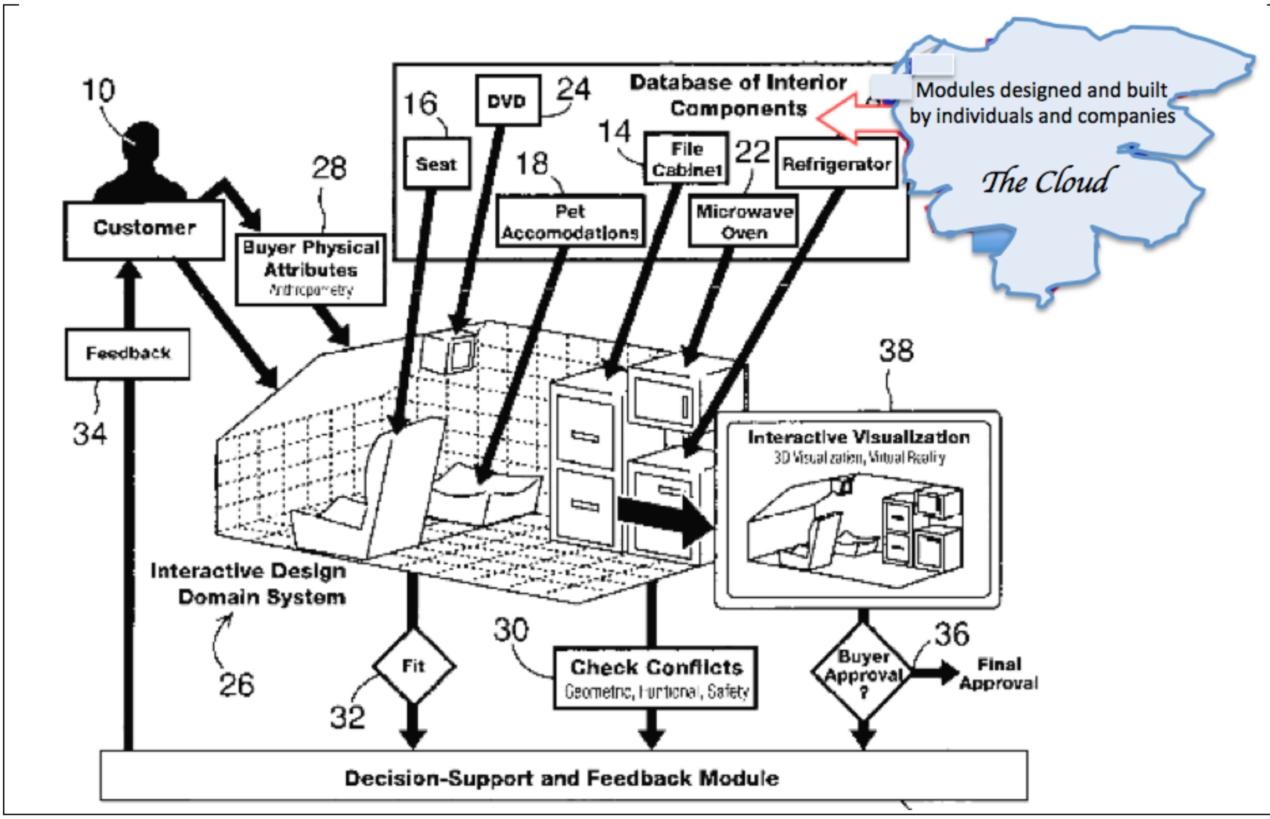

FIGURE 3 Schematic of a software system facilitates the customer's (10) interior design of a vehicle and automatically identifies design conflicts (30). Adapted from Koren et al. (2006).

Assembly of Open Architecture Products

The auto interior design method may be generalized to a broader category of open architecture products (OAPs; Koren et al. 2013) (also called open platform products), comprising a fixed platform with defined mechanical and electrical interfaces. The OAP platform enables the addition of a variety of modules that may be designed and produced by different manufacturing companies, as long as the modules are designed with the mechanical and electrical interfaces defined by the platform manufacturer to allow their easy and safe integration. Customers choose their desired modules.

The integration of a variety of hardware modules in a platform, using the method depicted in figure 3, adapts the product functionality to the user's specific needs and preference. A major challenge is the development of OAP design software for use by nonprofessional customer-designers.

Following are examples of open architecture products:

- a hospital bed to which mechanical and electrical components and devices can be added to accommodate a patient's medical or physical condition
- an office chair designed to allow the addition of accessories that fit the buyer's desire and needs
- a refrigerator interior with interfaces for components such as special shelves or a rotary platform that facilitates finding things
- a machine tool designed to add a variety of machining and milling heads for different applications.

The assembly of automobile interiors and OAPs must be done in local factories because close interaction with buyers on product design and specifications is essential.

Challenges

As manufacturing practice moves toward individualized products, customers will place their orders and factories will have to convert them for implementation. Software needs to be developed to help customers turn their ideas into digital models for factory production.

Algorithms will schedule the production of each individual product, while the system is simultaneously producing a variety of individual products. Optimal scheduling should maintain the maximum number of machines busy nearly continuously even as each product needs a different processing time on several machines. It will be a challenge to build software that schedules different individual orders while optimizing system operations. Artificial intelligence will have a major role in such scheduling in the production system. AI software can group similar products for production so that the system is synchronized to optimize efficiency. This synchronization will require digital twin models (Rosen et al. 2015).[1]

Economic Impacts of Local Factories for Individualized Products

Factories for individual production and shops for auto interior assembly cannot be located offshore because in most cases direct communication between the customer and the factory will be needed to avoid misunderstandings. Local factories will also reduce the time from order to delivery—buyers will want their customized product as soon as possible, not in 3 months from an overseas producer. Establishing many such factories will create numerous local manufacturing jobs and greatly benefit local economies. More broadly, with traditional manufacturing, when it "bids farewell [through offshoring], engineering and production know-how depart as well, and innovation activities eventually follow. We can trace how this happened in the US" (Kota et al. 2018). In contrast, with individualized production, technologies and practices will remain in the United States.

The experience of strong economies around the world shows that a nation needs both R&D and manufacturing activities to maintain a healthy 21st century industrial ecosystem.

I hope the US government will find ways to support US industry in developing mass individualization factories, and that agencies will encourage the US research community to develop the science base for the emerging mass-individualization paradigm.

[1] In 2001 my colleagues and I tested the first prototype of the digital twins on our manufacturing system at the University of Michigan's NSF-sponsored Engineering Research Center for Reconfigurable Manufacturing Systems.

Conclusions

Mass individualization shifts the product design focus from a large manufacturer to the individual buyer and multiple companies that invent and offer personalized modules to suit customer needs and tastes.

I predict that 10 years from now the norm will be that the customer sends requirements to a local factory that produces individualized products for delivery in a timely manner. Manufacturing enterprises will introduce consumer products with open platform hardware that will facilitate the integration of mechanical and electromechanical modules. The number of options in certain individualized products (such as auto interiors) will depend on the creativity and ingenuity of both the customer and the companies that produce modules for integration in the product.

The discussion and figures in this paper effectively illustrate the concept of individualized products and suggest practical implementations of manufacturing systems to produce them. The emergence of many small innovative companies will sustain continuous steady growth in the manufacturing sector and boost the economy.

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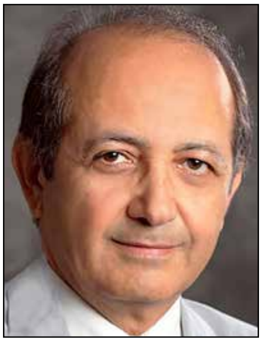
Dedication

This paper is dedicated to the memory of my daughter, Esther (Asi) Koren, who passed away at age 49 in our house on October 28, 2020, a couple of days after I finished the draft of this paper. She had cancer. Asi established and managed the Ana House to help many girls who experienced difficulties in their life.

Telefacturing is based on telecontrol and telerobotics, and effectively utilizes most components of Industry 4.0.

Telefacturing: A New Manufacturing Paradigm for Worker Safety and Other Benefits



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Behrokh Khoshnevis

The US manufacturing sector, which employs about 13 million workers (Weston 2019), has been hit hard by the covid-19 pandemic in part because most jobs entail physical activities (e.g., fabrication, assembly, testing, packaging, material handling) that cannot be done remotely. Worker proximity in closed spaces greatly facilitates contagion.

The extensive disruptions call for fundamental changes to ensure post-pandemic survival and promote growth in many human endeavors, including manufacturing. This article introduces a new manufacturing paradigm that is in perfect conformance with the principles of the emerging 4th Industrial Revolution, to offer the manufacturing sector effective approaches for dealing with pandemic conditions as well as many other challenges.

According to a survey conducted in March 2020 by the National Association of Manufacturers (NAM 2020) about 80 percent of US manufacturing companies expected that the pandemic would have a considerable financial impact on their business, and 53 percent expected that their operations would also be impacted by the pandemic. Unfortunately, these bleak expectations became a certainty. According to the US Bureau of Labor Statistics, in 2020 the manufacturing sector lost 1.3 million jobs by the month of May (BLS 2020). Some major manufacturing companies temporarily closed their facilities and laid off a portion of their employees, and the prospect of bankruptcy for others is quite real.

Historical Perspective

The history of human social and technological evolution has repeatedly shown that, much as in evolutionary biology, major disruptions in human societies lead to the emergence of new social structures and norms as well as new sociotechnical paradigms. Given the severity of the disruptions caused by the covid-19 pandemic in almost all aspects of life around the world, the emergence of new social norms and new sociotechnical systems should be expected in the coming years.

Lessons from the Medieval Plague

In 1347 the bubonic plague reached Europe and in just 4 years claimed the lives of about 40 percent of the population (Lienhard 2003). Outbreaks continued for decades and by the time it receded nearly a century later Europe had lost three-quarters of its populace to the so-called Black Death—the greatest calamity that humanity has faced in known history.

> *Major disruptions can lead to the emergence of new social structures and norms as well as new sociotechnical paradigms.*

What ensued in the wake of this deadly pandemic was not all doom and gloom, however. The plague spared many wealthy survivors, but left far too few workers for their ventures, so labor became much more valuable. Demand for higher wages soared, and even minutes spent on work were counted. Accurate time keeping became important, and innovations in clockwork rose, as did the use of timepieces.

Because 14th century medicine had failed to save victims of the plague, medical practice took a radically different direction, away from often superstitious treatments toward objective experimentation and the creation of practical, and more effective, medical knowledge. Attention to general knowledge also grew, books were written, and the invention of the printing press in 1440 enabled the rapid distribution and growth of the emerging knowledge and information.

Because of the reduced workforce, efficiency had to increase through innovative methods and technologies, which led to the emergence, primarily in cities, of lucrative businesses based on craftsmanship, signaling the dawn of the industrial age. Peasants, seeking alternatives to serfdom, were attracted to these prosperous industrial activities and sites.

In these and other ways the plague rocked the foundation of the medieval world and marked the beginning of the end of feudalism. Europe was reborn and became a center of culture, science, and technology for the next few centuries.

Although no pandemic is expected to be as devastating as the plague in medieval Europe, the history is still relevant, as demonstrated by the significant impacts of covid-19 on the world's complex sociotechnical and economical ecosystems in just a few months.

Lessons from Modern History

Disruptive technological evolutions since the mid-1800s have had major impacts on how goods were produced and services rendered, and how the related work was done. They are referred to as industrial revolutions because their impacts were not incremental but monumental.

The Fourth Industrial Revolution is bringing together manufacturing and supply chain operations with recent advances in digital technologies, including cloud computing, artificial intelligence (AI), big data analytics,, machine learning, augmented reality, the internet of things (IoT), simulation/digital twin, and additive manufacturing (AM)/3D printing. Together these can provide a holistic and interconnected environment for manufacturing operations as well as functions related to supply chains and customers.

A New Manufacturing Paradigm: Telefacturing

Simple tasks have already been automated in most American manufacturing plants, and further automation is recommended (e.g., Okorie et al. 2020; PWC 2020) to reduce the spread of covid-19 by decreasing worker density. But additional automation will mean further layoffs.

Furthermore, more complex manufacturing tasks still rely on human intelligence and dexterity. Automation of such operations is an expensive proposition that requires major investment in hardware and more skilled (i.e., higher-paid) workers to maintain them.

Recent developments, collectively known as Industry 4.0, can be used to create other modes of automation that allow manufacturing workers to safely perform their tasks from a remote location such as their home office or a dedicated neighborhood hub. The latter would be outfitted with the necessary equipment and software and connected to the manufacturing facility through a high-speed broadband network. The hub can also serve as a place for some social contact for those who do not like the isolation of working at home.

Telefacturing is based on telecontrol and telerobotics, and effectively utilizes most components of Industry 4.0 (Siebel 2019). It benefits from the current state of the art in virtual and augmented reality, remote sensing (using 2D and 3D vision systems, and various noncontact and tactile sensing technologies), haptics systems, remote actuation mechanisms, and enabling algorithmic, computing, and telecommunication networks based on 5G technology. Following are examples of the use of Industry 4.0 components in telefacturing:

- Telerobots and machinery in a telefacturing setting would be equipped with a multitude of sensors and possibly several actuators all connected to an IoT module dedicated to the robot/machine and with computing and storage capabilities.
- The operation of the system in real time could generate massive amounts of data; the quantity would depend on the number of pieces of equipment, ongoing operations, and frequency of sensory data collection. Processing of the data would be partly performed by the IoT modules, which collectively form a computation/storage cloud, possibly in addition to a public cloud commissioned by the company.
- AI-based analysis of the generated big data may be used for applications such as worker performance evaluation and adaptive schedule optimization.
- Machine learning software using deep learning algorithms can learn from the operator to perform segments of operations autonomously. The remote worker would thus be relieved from managing details of operations and need only to send gestures and other forms of communication (e.g., in natural language) to the machine. For example, after completion of a segment of a task the remote robot, having learned to pick up a certain tool, would do so without needing an operator command. This arrangement would eventually leave to the operator only the tasks that require human intelligence and creativity (e.g., addressing an unpredicted event). Creative thinking is only in the realm of the human mind and is likely to remain so for the foreseeable future.
- Augmented reality can be used to train new remote workers by superimposing on their computer screen instructions, pictures, and video that relate to the physical scene in the factory.
- AM/3D printing machines may be used for certain fabrication operations. Because they are almost totally autonomous and do not require intermittent operator engagement for activities such as tool change, they are ideal for teleoperation. Many commercial AM machines can be easily operated through the internet.

Advantages of Telefacturing

Telefacturing will bring human intelligence and dexterous mechanical manipulation abilities to factories to operate machines and to assist robots, all without requiring the presence of humans. There are numerous advantages to this proposed approach, including assurance of human safety, reduced asset damage, lower real estate and other costs, enhanced sustainability, elimination of worker transportation, flexible work hours, the possibility for workers to work concurrently at multiple factories, and job opportunities for the disabled, the elderly, and others (Khoshnevis 2015.

Remote workers would be relieved from managing operational details and simply send communications (e.g., in natural language) to the machine.

Safety

Aside from workers who contract an illness in congested manufacturing workspaces, over half a million occupational injuries occur annually in the US manufacturing sector, with annual costs of about $20 billion (NSC 2019). Telefacturing can nearly eliminate on-the-job disease contraction and occupational injuries by eliminating worker exposure to these risks.

Asset Damage Prevention

When humans work directly with machines, accidents resulting from their errors can cause not only injuries but also significant economic loss due to damaged machinery, tools, work pieces, and products. With teleoperation workers do not interact directly with the machinery. In addition, intelligent fail-safe systems for collision avoidance and other impact reduction measures can be effected through software to prevent machines from following accidental operator gestures and orders that violate allowable machine motions and actions.

Reduced Costs for Factory Real Estate, Energy, and Operation

Telefacturing facilities need not be located in or near cities. They can be located on inexpensive land in remote areas, preferably near an electric grid and with easy highway and/or railroad access.

> *Telefacturing can dramatically improve the environment by substantially reducing the number of cars on the road during rush hour.*

Furthermore, a teleoperated factory does not require accommodation of basic human needs such as lighting, air conditioning, food services (which are subject to regulatory control and require their own staffing), and restroom facilities. Collectively, these can amount to sizable savings in operating and overhead costs.

Telefacturing sites would still need to accommodate engineers and technicians to service and repair machinery, but those employees would be far fewer than operational workers.

Sustainability and Reduced Environmental Impacts

Less consumption of energy and resources will reduce environmental impacts. Telefacturing is also a more sustainable approach primarily because of its conservation of the energy that would otherwise be consumed in transportation of numerous people on a daily basis (as discussed below). Transportation, at least currently, primarily uses fossil fuel and as such creates significant amounts of harmful emissions that are threatening the planet. Telefacturing can dramatically improve the environment by substantially reducing the number of cars on the road.

Elimination of Worker Commutes

Worker transportation between home and factory, often during rush hour, is costly, takes a toll on workers' time, energy, and productivity, and presents accident risks. Carpooling, public transit, and use of a company shuttle service expose workers to a higher risk of contracting contagious diseases.

Commuting can also indirectly have an important real cost for companies, which may be compelled to hire local workers although nonlocal candidates may be more suitable. Transportation costs deter some potential employees from taking jobs that would require them to spend a significant portion of their income and time on their commute.

Flexible Work Hours and Location

Workers who do not have to be on site at certain times could choose their own work hours as allowed and specified by a computerized schedule posted on a secure internet site. In addition, the convenience of working from home or at a nearby teleoperation hub, which could be situated in an office building with a more comfortable and less imposing environment than that of a typical factory, should give workers a liberating feeling and job satisfaction that enhance their physical and psychological health, and hence their efficiency and productivity.

Possibility of Working for Multiple Factories

Telefacturing workers could operate in freelance mode and for multiple factories. Once they complete their assigned job at one factory, they could do an internet search on dedicated sites about available jobs requiring their specific expertise at factories elsewhere, even around the world. This would be advantageous as well for manufacturers operating in sites with limited local availability of needed skills. Certification and authentication would assure factory management about the quality and reliability of remote workers. A web-based system would keep track of comments and ratings for each worker per job performed; similarly, workers could rate employers.

The web-based systems to support this option could become a telefacturing internet business (TIB) with great potential for success.

New Job Opportunities for Disadvantaged Workers

By eliminating long commutes and by providing force amplification through remote control devices, telefacturing is ideal for those who have difficulty moving around or performing heavy tasks that require strong muscle power. It would provide employment opportunities for people who may otherwise be unemployed and at risk of poverty, including the disabled and the elderly (the latter population is growing rapidly as life expectancy steadily increases).

Telefacturing can also provide employment opportunities for others, such as those who do not have a car or access to transit to get to a workplace, or women who have been categorically denied the kind of work that requires "muscle power."

Laboratory-Based Education

The extension of telefacturing technologies to laboratory-based education would both facilitate offsite learning and enhance safety. During the pandemic most schools and universities resorted to online teaching, which in many respects has been very effective and of course safe. However, courses that depend on laboratory experiments suffered because of the indirect execution of experiments by lab technicians or teaching assistants instead of the students themselves, or in many cases the complete elimination of the lab component.

With telefacturing technologies it will be possible for students to perform their own lab experiments and observe the results from a remote location without the pandemic-associated risks of close proximity with others. Furthermore, as I have known over the years of cases of exposure to harmful chemicals, explosions, and other mishaps, the remote approach will eliminate the hazards of certain lab experiments that may be unsafe (occasionally even fatal).

Essential Related R&D Activities

Research and development are needed to advance several fields and set the stage for successful implementation of telefacturing.

Characterization and Classification of Manufacturing Activities

For selected manufacturing domains (e.g., machining of mechanical parts, casting and foundry, electronics), activities such as fabrication, assembly, testing and quality control, material handling and storage, and packaging should be characterized with respect to the metrics that are important in human-machine interactions. These could include scale, weight, required accuracy, required execution speed, limit on operator response time, limit on system latency, workcell visibility and audibility, and workcell design and robot work envelope relationship.

Hierarchy of Implementation

Related practices in remotely controlled activities and missions such as space travel and exploration, telesurgery, and drone control should be studied to identify applicable approaches for at least some candidate tasks in manufacturing.

Telefacturing is ideal for those who have difficulty moving around or performing heavy tasks.

Obviously, operator tasks that involve turning machines on or off, setting control knobs and valves, watching for critical conditions to take such actions, and the like are the simplest and least expensive tasks to be done through telefacturing, because they generally can be done by mere electronic or electromechanical modules (e.g., relays, sensors) and do not require the addition of expensive hardware such as robots. Operations such as measurement, quality control, and packaging could also easily be done through telefacturing.

Next are tasks that can be performed with relatively inexpensive robots; such tasks include picking randomly arriving objects from a conveyor and placing them in selected bins or packages, for example. Separation of recyclable objects from trash passing on conveyor belt, which is usually performed by human operators and is often not hygienic, may be done by operators at home who simply click on the recyclable object that they see on their monitor. Control of material handling and storage/retrieval operations may be done through remotely driven forklifts and other equipment.

The next and more challenging class of tasks would require more accuracy, analogous to telesurgery. These include small mechanical assembly such as that involved in electronics components on custom-designed, low-batch-size circuit boards. Mechanical component machining and larger-scale module assembly may be more challenging tasks but certainly feasible.

Simulation Studies

Human operators are good at first-degree prediction, but their ability to control in a timely manner diminishes rapidly with higher-order prediction. Realistic simulation tools should be developed for machine operator training, much as flight simulators are used to train pilots without risking the pilot or the plane. Sites offering simulated training are another new business opportunity. Special training sites, preferably at telefacturing hubs, may be equipped with remote control, haptic feedback devices, and advanced graphics (e.g., using virtual reality) to train the workforce for new jobs.

Management System Design

Many aspects of management—including training, supervision, reward system, enterprise resource planning, operations planning, scheduling, and control—could be streamlined and made more adaptive and effective with telefacturing. Each of these management functions should be analyzed and new management systems developed for implementation of the telefacturing paradigm.

Conclusion

In areas other than manufacturing, telerobotics with real-time sensory feedback are currently in use. These include drones in various applications such as emergency medical services, land and building surveys, agriculture, and search and rescue. Another application that has shown impressive progress is telesurgery, which can make a physician's service available in remote locations. Finally, advanced applications of telerobotics are in space projects such as on-orbit satellite servicing or rover mission control on the moon and Mars.

For manufacturing, telefacturing offers an opportunity for both established robotics companies and future start-ups to embark on the creation of specialized telerobotics systems. A possible starting point is the development of less expensive systems for handling simple manufacturing jobs such as remotely controllable pick-and-place and inspection robots, material handling robots, and storage/retrieval machines.

With progress in the areas discussed above, telefacturing can be the way of the future for manufacturing, offering advantages in worker safety, environmental sustainability, productivity and efficiency, employment opportunities, and cost and time management.

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Through measurements and standards, NIST aims to facilitate the postpandemic adoption of efficient, secure, and decentralized technology for the industrial sector.

Next-Generation IIoT: A Convergence of Technology Revolutions

Barbara Goldstein

Kate Remley

Barbara L. Goldstein and Kate A. Remley

The pandemic forced many on a personal journey of digital transformation akin to that required of industry and much of the workforce. People had to come to terms with the fact that the usual ways of doing business could not simply be continued.

From Digitization to Digitalization to Digital Transformation

The shift from an office to a home environment required successful *digitization*—having automation tools in place and the necessary information in a digital format compatible with those tools. This transformation is parallel to manufacturers reaping the benefits of the Third Industrial Revolution, when manual tasks were automated with computers and robotics.

After digital readiness comes connection—in the home and to the broader world—and the ability to transmit and interpret data as they flow from system to system, location to location. This is comparable to progressing from the third to the Fourth Industrial Revolution, which added connectivity to the robotics and infrastructure of a stand-alone factory.

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Just as individuals are relearning how to work in a geographically dispersed but interconnected world, in this era of *digitalization* manufacturers are reshaping their business models to automate supply and logistics by directly linking inventory and logistics systems across the supply chain, to automate equipment repair and maintenance through interconnected vendor/manufacturer systems, and to gather information directly from products in the field to adapt and accelerate the development of the next generation of offerings.

The manufacturing sector is looking to decentralize decisions and enable manufacturing tools to communicate and cooperate in real time.

The next step, *digital transformation*, the hallmark of Industry 4.0, has no playbook. It is a system-level restructuring that evolves once machine-to-machine automation can be trusted not only to inform workers but to run operations. Postpandemic manufacturing will likely build on these goals by capitalizing on decentralized systems that allow flexible and reconfigurable factory floors, and by leveraging low-cost yet accurate internet of things (IoT)–based technologies to maximize productivity and efficiency. All are important for economic recovery and will allow small and midsize factories to better compete in the global marketplace.

Here we describe some of the research underway at the National Institute of Standards and Technology (NIST) to support manufacturing in the postpandemic world.

The Factory of the Future

The pandemic made it even more urgent that manufacturers accelerate their journey from digitization to full digital transformation—not just adopting automation tools but learning how to leverage them into new ways of doing business.

Over the past decade or so, the manufacturing sector has embraced the use of wireless industrial internet of things (IIoT) technologies for factory enterprise applications, such as asset and supply chain management. Moving forward, particularly in the postpandemic world, the manufacturing sector is looking to decentralize decisions, implement remote monitoring of physical processes, and enable manufacturing tools to communicate and cooperate with each other in real time.

High reliability will be critical in such machine-to-machine (M2M) real-time manufacturing processes. Low-cost, low-profile sensors and actuators operating accurately at high speeds will allow decentralization as machines talk to each other, monitoring their status and taking themselves offline before damage can occur.

The development of reliable wireless M2M communications in a highly reflective, dynamically changing factory floor environment is also a key enabler of IIoT, motivating system designers to investigate new wireless technologies such as adaptive millimeter-wave (mmWave) networks that can reconfigure on the fly and reliably transfer large amounts of data over wide bandwidths.

Testing and verifying the performance of adaptive networks in an over-the-air (OTA) condition is not a trivial undertaking and is the focus of much research at NIST. As humans are removed from the decision-making loop, it is essential that machines draw on accurate and always available information.

Trends in Sensing

Sensors bridge the physical and digital worlds, feeding information about the former to the automation tools that industry increasingly trusts to not only monitor and diagnose but predict and act—at speeds that don't allow for human oversight.

Sensors must be reliable reporters of conditions on the ground, so that digital twins are faithful mimics of a factory environment, machine-driven controls respond to real conditions, and equipment self-diagnoses are based on accurate information. NIST is addressing this need through the NIST on a Chip (NOAC) program,[1] which is developing quantum-based sensors that are fit-to-function and reliable in the field without needing calibration, and can be trusted to give either the right answer or no answer at all.

The sensors being developed in the NOAC program draw their intrinsic accuracy from fundamental properties of nature, such as the fact that a cesium atom can be counted on to always vibrate at a known frequency—otherwise it wouldn't be cesium. In fact, the entire Inter-

[1] https://www.nist.gov/noac

national System of Units (SI, or metric system) was redefined in 2019 to be based only on such fundamental properties, making obsolete the last physical artifact, a platinum-iridium cylinder (stored in a vault outside Paris) that was by definition equal to 1 kilogram no matter what it really weighed. This recent sweeping redefinition of the metric system created new opportunities for sensing, unleashing a wave of innovation that is just beginning to enable creative ways for in situ sensors to draw on nature and their operating environment to ensure that they provide SI-traceable, reliable measurements.

The NOAC program is shrinking the precision measurement technology that is currently available only at national metrology institutes like NIST into a suite of sensors that can be embedded directly in equipment or deployed on a factory floor. The following sections describe a few of the nearly two dozen sensors being developed in the program.

Chip-Scale Atomic Clocks

Precision timekeeping is fundamental to applications in communications, financial transactions, aviation, and GPS. The first chip-scale atomic clock was created by NIST in 2004. It laid the foundation for the NOAC program by showing that it's possible to shrink a labfull of complex equipment, which previously required a team of highly trained staff to operate, to a device the size of a grain of rice (NIST 2004)!

Chip-scale clocks are now commercially available, and NIST is working on the next generation of them that will operate at optical frequencies (Newman et al. 2019; NIST 2019). These more sensitive clocks have at their heart a vapor cell the size of a coffee bean (figure 1). The clocks could be invaluable in manufacturing synchronization for robot-to-robot communications, monitoring of machine tool life, and overall factory efficiency, among other applications.

Photonic Thermometers

The current "gold standard" for temperature is the platinum resistance thermometer, which is fragile and vulnerable to humidity, requires expensive calibrations, and is difficult to miniaturize. NIST is developing a replacement (figure 2) based on the relationship between temperature and the optical properties of materials, leading to a sensor that will be inexpensive, small, portable, and robust, with applications to manufacturing process control and instrumentation, among many others.[2]

[2] https://www.nist.gov/programs-projects/photonic-thermometry

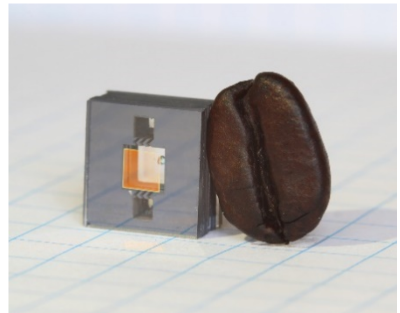

FIGURE 1 The heart of a second-generation chip-scale atomic clock, next to a coffee bean for size reference. Photo credit: Matthew Hummon, NIST.

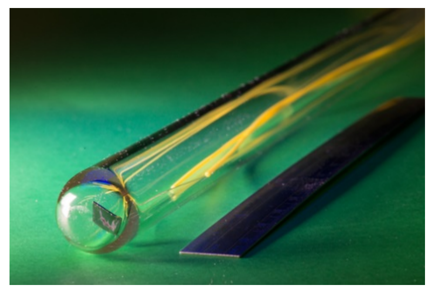

FIGURE 2 Close-up of a photonic thermometer prototype, showing the top of a chip-based temperature sensor. The chip is about 1.5 cm (0.6 in) wide. Photo credit: Curt Suplee, NIST.

Electric-Field Sensors

Advanced manufacturing takes place in electronically noisy environments and it's critical to characterize both unintended electromagnetic emissions and intentional communication signals sent wirelessly in a dynamic environment. The best commercial instruments are accurate to only within 10 percent.

To address this need, NIST has prototyped a fundamentally new type of sensor (figure 3) based on Rydberg atoms, which, because of the highly excited state of their outermost electron, are extremely sensitive to electric fields (Holloway et al. 2014). These prototype sensors have been shown to outperform current sensors in both sensitivity and accuracy (good to about 4 percent), never need to be calibrated, and have the potential to be shrunk to a chip-scale package.

Wanted: Fast, Reliable Wireless Connectivity for Harsh Radio-Propagation Environments

Automation-driven factories rely on not only a steady stream of accurate sensor information but also uninterrupted and unambiguous connectivity. The growing

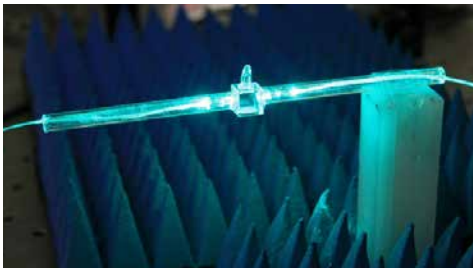

FIGURE 3 Fiber-coupled vapor cell for quantum-based *e*-field measurements using Rydberg atoms. Photo credit: NIST.

trend toward augmenting or replacing wired connections with wireless channels comports with the postpandemic need for decentralization and M2M communications.

Why Wireless

On the factory floor, wireless connectivity offers many benefits over wired solutions, such as the elimination of costly cabling, mobility, configuration flexibility, and improved efficiency in operations (Lee et al. 2020; Liu et al. 2019). Wireless connections can also be used in otherwise impractical locations; for example, low-power monitoring devices can eliminate the difficulties inherent in physically routing cables (Ferreira et al. 2013). The relatively low cost and flexibility of wireless technology infrastructure are especially important for small and midsize factories (Candell et al. 2018).

Much of the focus on wireless connectivity for IIoT technology relates to its deployment in workcell-sized environments. A workcell typically consists of a single or a few machines. While the size of factories varies considerably, the size of a workcell is typically on the order of 10 m or less per side (Lee et al. 2020). A focus on requirements for the workcell rather than for the entire factory provides a better picture of user requirements (Candell et al. 2019). Basic assumptions for user requirements in workcells might include (i) no more than one communication system failure every 1000 years; (ii) individual transmissions that are independent, allowing multiple traffic channels to coexist; and (iii) a single wireless link used in certain scenarios involving multiple sensors/regulators (Lee et al. 2020).

Recent wireless standards are aimed at providing reliability and latency to meet requirements at the workcell level for the discrete manufacturing sector. For example, IEEE 802.11ax[3] provides simulated latencies on the order of 1–5 ms. However, no wireless standard or technology can yet provide the sub-ms latencies that will be needed for power electronics systems control and other applications that are highly constrained by latency, especially in intraworkcell and intramachine wireless use cases (table 1; Candell and Kashef 2017; Candell et al. 2018). This is because current industrial wireless technologies were, generally, designed for the process manufacturing industry, where sensing and control can successfully happen on the order of seconds. For future discrete manufacturing applications, events between sensors and monitors/controls must be communicated within milliseconds or less.

Manufacturers have indicated that decentralized wireless would be a flexible and robust means of manufacturing communication for use in intraworkcell and intramachine cases if latencies can be reduced (Candell et al. 2018). For example, for a programmable logic controller (PLC) to provide feedback to an industrial machine based on sensor data, latencies significantly less than the typical PLC scan cycles of 10 ms would be required. How much less would depend on the number of stations and the multiple-access scheme used. Ideally, communication links of 100 sensors would provide ultrareliable factory floor operation. Until resolved technologically, these gaps will affect manufacturers' ability to trust the viability of decentralized wireless IIoT networks.

There is thus great interest in developing robust wireless technology that addresses the unique requirements of sensor communications, latency, reliability, and flexibility in IIoT applications. However, the industrial workcell environment is one of the most challenging for wireless system deployment because of the high reflectivity (including the potential for three-dimensional reflections) and dynamically changing conditions (including intermittent blockage of a channel due to moving elements such as robotic arms or autonomous vehicles). Understanding the range of potential channel impairments is essential for developing robust hardware and network protocols, and is a topic of current research.

The coupling of advanced analytics (such as channel estimation) and statistically based channel modeling with accurate real-time assessment will allow the development of wireless hardware that can make use of multiple redundant channels, each with the potential for ultrawideband capacity. Current NIST research uses machine learning to identify and replicate key electromagnetic features of

[3] https://www.ieee802.org/11/Reports/tgax_update.htm

		Flow-based					Job-based						Safety			
		Process Monitoring	Supervisory Control	Feedback Control	Alarm Conditions	In-situ Inspection	Factory Monitoring	Assembly: Sensing	Assembly: Actuation	Robots: Supervision	Robots: Feedback Control	Quality Inspection	Fall Prevention	Confined Spaces	Critical Event Detection	Human-Machine Colocation
Home/Office	IEEE 802.11	●	●	◐	◐	-	●	◐	◐	◐	◐	◐	○	○	◐	○
	IEEE 802.15.1	○	○	○	○	○	○	◐	◐	◐	○	●	○	◐	○	○
Industrial	IEEE 802.15.4 TDMA	●	●	◐	◐	-	●	◷	◷	◷	◷	◐	◷	◐	◐	○
	IEEE 802.15.4 CSMA	◐	◐	○	○	-	●	◷	◷	◷	◷	◐	◷	◐	◐	○
	IEEE 802.11 TDMA	⋇	⋇	⋇	⋇	-	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇
	VLBR WAN	●	●	○	◐	-	●	◷	◷	◷	◷	◷	◷	○	○	○
Satellite	Geostationary	◐	◐	○	○	○	○	○	○	○	○	○	○	○	○	○
	Low-earth Orbit	◐	◐	○	○	○	○	○	○	○	○	○	○	○	○	○
	VLBR WAN	◐	◐	○	◐	○	◷	◷	◷	◷	◷	◷	◷	○	○	○
Tracking	RFID	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Optical	Indoor Dispersive	⋇	⋇	⋇	⋇	○	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇
	Free-space	◐	◐	◐	◐	○	○	○	○	○	○	○	○	○	○	○
Cellular	Legacy	◐	◐	○	○	-	○	○	○	○	○	○	◷	◷	◷	◷
	4G	◐	◐	○	◷	-	○	○	○	○	○	○	◷	◷	◷	◷
	5G	⋇	⋇	⋇	⋇	-	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇
Land-mobile	All types	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Specialty	Leaky Coax	◐	◐	-	◐	◐	◐	-	-	○	○	-	○	◐	◐	-

		Back-haul				Tracking					Security						Remote			Maint.		
		Nearby or Indoor	Distant: LOS	Distant: BLOS	Geographically Remote	Indoor Machine Localization	Materials in Storage	Materials in Production	Tools	Personnel	Voice and Video Communica	Video Surveillance	Drone-based Surveillance	Grounds Control	Spectrum Monitoring Data	Personnel Authorization	Well-head Monitoring	Pipeline Monitoring	Tank Level Monitoring	Machine Health Monitoring	Building Automation	Augmented Reality
Home/Office	IEEE 802.11	●	●	●	-	◐	ϟ	ϟ	ϟ	ϟ	●	●	●	●	●	●	◐	○	◐	◐	●	●
	IEEE 802.15.1	○	○	○	○	○	○	ϟ	●	◐	▼	▼	▼	○	○	◐	○	○	○	◐	○	▼
Industrial	IEEE 802.15.4 TDMA	▼	▼	▼	▼	◐	ϟ	ϟ	ϟ	◐	▼	▼	▼	◐	▼	○	●	●	●	●	●	▼
	IEEE 802.15.4 CSMA	▼	▼	▼	▼	◐	ϟ	ϟ	ϟ	◐	▼	▼	▼	◐	○	○	◐	◐	◐	●	●	▼
	IEEE 802.11 TDMA	-	-	-	-	⋇	-	-	-	-	-	-	-	⋇	-	-	⋇	⋇	⋇	⋇	⋇	-
	VLBR WAN	▼	▼	▼	▼	◐	◐	◐	◐	◐	▼	▼	▼	◷	○	○	○	○	○	◐	◐	○
Satellite	Geostationary	○	○	○	◐	○	○	○	○	○	◐	◐	○	◐	◐	◐	◐	◐	◐	○	○	◐
	Low-earth Orbit	○	○	◐	◐	○	○	○	○	○	◐	◐	◐	◐	◐	◐	◐	◐	◐	◐	○	◐
	VLBR WAN	▼	▼	▼	▼	○	○	○	○	◐	▼	▼	▼	◐	○	○	○	○	○	◐	○	▼
Tracking	RFID	-	-	-	-	○	●	●	●	●	-	-	-	-	-	-	-	-	-	-	-	-
Optical	Indoor Dispersive	⋇	○	○	○	⋇	ϟ	ϟ	ϟ	ϟ	⋇	⋇	○	○	⋇	○	○	○	○	⋇	○	○
	Free-space	●	●	●	○	◐	○	○	○	○	●	●	○	○	○	○	●	○	●	○	○	●
Cellular	Legacy	◐	◐	◐	◐	○	○	○	○	○	○	○	○	○	⋇	◐	◐	◐	◐	◐	▼	▼
	4G	◐	◐	◐	◐	○	○	○	○	○	●	●	◐	●	●	●	◐	◐	◐	○	○	○
	5G	●	●	●	○	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇	⋇
Land-mobile	All types	▼	▼	○	○	○	○	○	○	○	◐	○	○	●	○	◐	○	○	○	○	○	○
Specialty	Leaky Coax	◐	○	○	○	◐	●	●	○	○	○	○	○	●	○	●	○	○	○	◐	◐	○

Legend: ●: Technology fully supports problem domain, ◐: Supports problem domain with practicality, throughput, latency, reliability, or energy limitations, ϟ: Energy requirements of assumed battery-powered devices prevent applicability, ◷: Latency prevent applicability, ▼: Throughput prevents applicability, ⋇: Emerging technology or evolution may support problem domain, ○: Not recommended, -: Not considered by authors.

TABLE 1 Current wireless standards (Candell and Kashef 2017; Candell et al. 2018) do not address the needs of workcell communications, which are highlighted in the red ("job-based"), black ("safety"), and blue ("tracking") boxes. BLOS = beyond line of sight; CSMA = carrier-sense multiple access; LOS = line of sight; RFID = radio frequency identification; TDMA = time-division multiple access; VLBR WAN = very low bit rate wide area networks.

industrial wireless channels for repeatable, laboratory-based testing, which we describe next.

Characterizing the Environment in Space and Time

As mentioned, one of the foundational building blocks for developing spatial-temporal models of the industrial environment is verified channel-propagation measurements. Such measurements are often carried out in representative environments to study important channel features such as path loss, reflectivity (or multipath), coherence time (how quickly a channel dynamically changes), and spatial characteristics such as the angle of arrival (AoA) of direct and reflected signals. Several research groups are collecting such data in factory environments to facilitate standards development and hardware design.

In our research at NIST we use a synthetic aperture–based channel measurement system to characterize the 3D spatial-temporal characteristics of the industrial propagation channel, coupled with machine learning techniques to identify the most typical and prominent features in the environment, as described in the next subsection.

Assessing OTA Wireless Device Performance in the Workcell

Wireless devices with integrated antennas, such as most IoT devices, require OTA verification of performance. Certification bodies have developed rigorous tests for cell phones and some work has been done on IoT device characterization (CTIA 2020). However, much of this work is focused on whether the device meets radiated

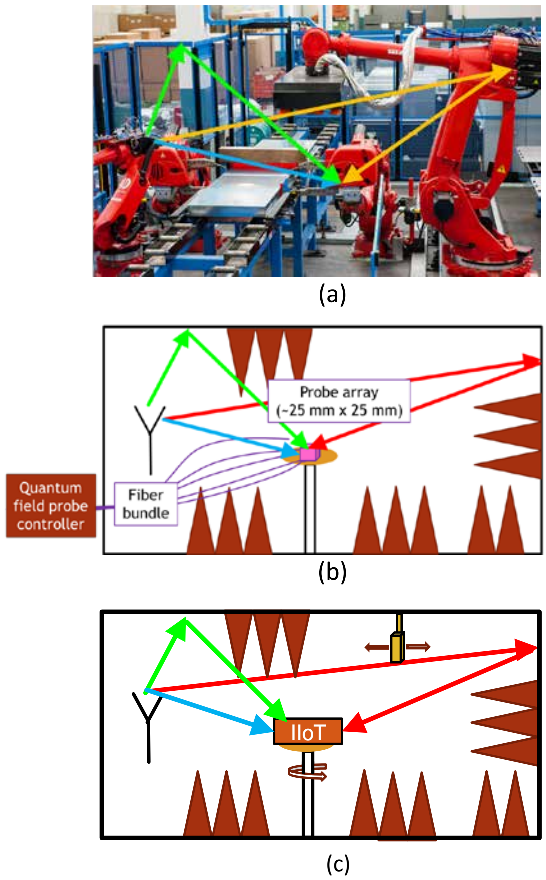

FIGURE 4 (a) The factory floor workcell contains static and dynamic wireless channel conditions that are emulated in the IIoT over-the-air testbed shown in (b). A noninvasive quantum probe array verifies the channel characteristics. In (c), an IIoT device is placed on the rotating platform and exposed to the known channel conditions.

power and receiver sensitivity limits in nonreflective, "isotropic" environments, where signals are incident on the device from all angles equally. Newly released standards focus on creating specific channel conditions to test multiple antenna devices, such as cell phones with multiple antennas (3GPP[4]).

To support the millisecond timescales needed for adaptive mmWave IIoT, OTA tests must evolve to emulate 3D spatial channel characteristics such as the timing and AoA of reflected signals. As such, NIST is applying a wide range of expertise in wireless communications, manufacturing, and artificial intelligence to create a repeatable, noninvasive dynamic OTA testbed utilizing innovative quantum field probes.

The NIST OTA testbed will expose an IIoT device to a repeatable, dynamically changing environment to assess its ability to reconfigure adaptively to changing channel conditions by use of machine learning (Kashef et al. 2021). As an additional benefit for IIoT designers, our measured datasets and models of the dynamically changing channels will be made available for users to design and train their AI-based adaptive network hardware.

The concept is illustrated in figure 4. The measured static and dynamic reflective characteristics of the factory floor environment (figure 4a) are extracted, as described above. The channel conditions are then replicated in a lab-based test chamber by placing reflective and electromagnetic wave–absorbing material in the appropriate locations. This process is facilitated by machine learning. Once configured, the chamber characteristics are verified through measurement.

The large, metallic bodies of conventional channel sounders perturb the environment in which they operate and are their most important and fundamental accuracy limitation in physically small environments. To address this limitation, NIST is creating minimally reflective quantum field probes to characterize the time-evolving channels in the chamber, leveraging the NOAC Rydberg atom–based probe. An array of the NOAC probes is needed to accurately measure the timing and AoA of signals incident on an IIoT device by sampling the ambient fields at multiple spatial locations in the test chamber through the use of synthetic aperture techniques.

The important features of this test setup include the accuracy of the workcell channels that it recreates, including the traceable characterization of these channels with the use of a low-invasiveness probe, and the wide range of channels that can be created.

Challenges

There are many technical challenges remaining to mature the technologies needed for a reliable, scalable factory infrastructure. Along with those in communications and sensing, outlined above, other challenges to achieving digital transformation include security, culture, and competition.

Security

IoT and IIoT security is complex, with vulnerabilities in the middle layers of the technology stack, between

[4] 3rd Generation Partnership Project, Technical Specification Group Radio Access Network. Study on channel model for frequencies from 0.5 to 100 GHz (Release 16), 3GPP TR 38.901 V16.1.0 (2019-12). Available at https://www.3gpp.org/.

applications and hardware, across communication channels, and in communication protocols (Friedman and Goldstein 2019). The security challenge is one of risk management, and the following factors need to be considered and are active areas of NIST research (Lee et al. 2020):

- identification and authentication control
- use control
- system integrity
- data confidentiality
- restricted data flow
- timely response to events
- resource availability.

Culture

Embracing new technology—such as self-calibrating quantum-based sensors—requires a cultural shift. Measurement assurance is based on an international system of intercomparisons, accreditation, and assessment. Quantum-based sensors can short-circuit this labor-intensive foundation, but only if the global community trusts it.

Competition

The United States has been slow to realize Industry 4.0. Despite the potential offered by digital transformation, initiatives fail with alarming frequency—a 2016 study by McKinsey showed that 70 percent fail outright (Bucy et al. 2016), and Forbes placed this number as high as 84 percent (Rogers 2016). These false starts may be explained as the tribulations of early adopters. They may also reflect a market failure to institutionalize the infrastructure needed to realize the benefits of digital transformation.

While US industry is grappling with its slow climb to success, other countries are investing. According to the Information Technology and Innovation Foundation, other countries are making Industry 4.0 policies a priority by launching "pilot fabs" for smart manufacturing, documenting digitalization use cases (Germany has identified over 300), and providing financial support to industry (Atkinson 2020).

Conclusion

In this brief overview, we have highlighted ways NIST is working to facilitate a cultural shift in the use of new technology to increase competitive activities in the industrial sector. By addressing some of the measurement-related gaps and supporting standards development for new wireless technology, industry can move forward with greater confidence as new technology becomes available.

Through measurements and standards, NIST's goal is to facilitate the postpandemic adoption of efficient, secure, and decentralized technology for the industrial sector.

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Academic makerspaces can quickly create holistic complementary teams and execute complicated projects under significant time pressure.

University Makerspaces and Manufacturing Collaboration: Lessons from the Pandemic

James D. McGuffin-Cawley and Vincent Wilczynski

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The role of universities in addressing the needs of the manufacturing sector has been substantially evolving in the past decade because of macro trends and associated policy changes. Notably, the classic combination of lecture and laboratory courses has been augmented by open-ended exploration and hands-on skill development in university makerspaces.

Disruptions associated with the covid-19 pandemic have required new adaptations. The pandemic not only suspended existing practices but demanded that institutions assume new roles. University makerspace staff and resources were directed to support efforts related to research, design, manufacturing, and testing solutions. Such responses were possible because of the availability of academic talent in the technical operations required to make precise and complex articles and devices.

There is broad, if informal, recognition that things will not return to the state that existed before the pandemic, so reflecting on lessons learned and considering appropriate actions for the future is warranted.

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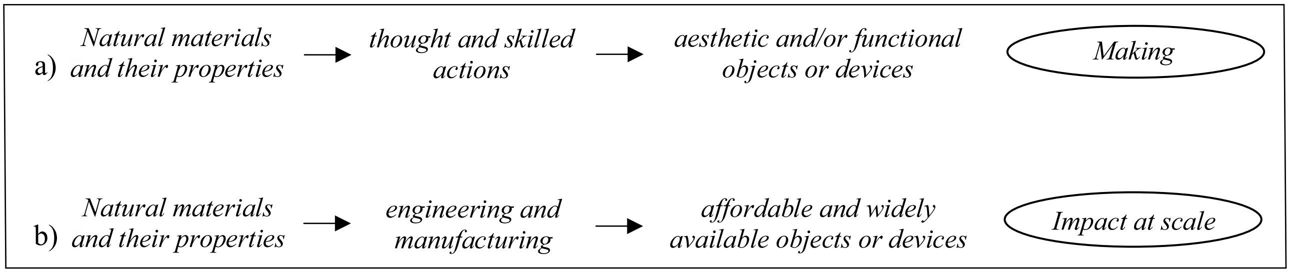

FIGURE 1 Expressions of making (a) and engineering (b).

Academic makerspaces can be leveraged and modified to strengthen the relationship between manufacturers and higher education in new ways. Experience suggests rich opportunities to guide universities in preparing students for a manufacturing career and, through research and technology transfer, to assist manufacturers in making effective use of newer technologies and scientific results.

Differences between Making and Manufacturing

Making and manufacturing are distinct but complementary and involve similar skills. Both are advanced by creativity and inventiveness. Making advances an idea into a prototype and manufacturing advances a prototype into a product.

The technical unit operations are the same, but making typically involves small production volumes, whereas manufacturing spans production volumes from single digits to millions of parts (Kalpakjian and Schmid 2020). And making as an enterprise is distinct from manufacturing as a profession. Fully half of Americans self-identify as makers (Lou and Peek 2016); less than 10 percent have manufacturing employment (Helper et al. 2012).

Academic makerspaces are conceptually connected to the long-recognized value of both experimentation and experience in learning (Kolb 2015). As a well-defined entity, they are traced to the MIT Fab Lab program that grew out of Neil Gershenfeld's course "How to Make (Almost) Anything" (Gershenfeld 2005). They now involve a network of alumni, regional manufacturers, material suppliers, and a broad array of users, with established processes to accept external inquiries. During the last decade (Barrett et al. 2015; Lou and Peek 2016) they have moved from being unusual to expected, and there has been serious study of the role and impact of academic and other makerspaces (Hilton et al. 2018; Rosenbaum and Hartmann 2017; Wilczynski et al. 2017).

The purpose of academic makerspaces is not specifically aligned with that of manufacturing. Manufacturing engineering represents only half of the discipline-specific skill development in typical academic makerspaces (Wigner et al. 2016), where exploration of design is a key facet (Wilczynski et al. 2017) and the reintroduction of prototyping and fabricating has been identified as an opportunity to link engineering skills to the humanities (Nieusma and Malazita 2016). In makerspaces participants learn and refine skills (such as design, fabrication, testing) to develop prototypes and single-user artifacts. Makerspaces also provide a comfortable and safe environment and a support system for the complete novice to acquire confidence while developing manufacturing-relevant technical skills.

To illustrate the distinction between making and manufacturing, it is helpful to consider two expressions inspired by those developed by Harms and colleagues (2004) in their analysis of the field of engineering (figure 1).

The first expression (figure 1a) represents the general process of transforming raw materials to effect a goal—that is, making something. It includes invention, prototyping, design of experiments, and artistic expression, as well as manufacturing. From this perspective, making is a form of thinking and creativity that complements abstract conceptualization and reflective observation, while demonstrating both how to work within constraints and how to leverage and synthesize knowledge.

In addition, as a general practice, the making community facilitates people working together and communicating so that needs and desires get translated into designs that can be realized. All of these facets help develop attributes sought by employers, including critical thinking and problem solving, communication skills, teamwork, and collaborative skills.

In making, the focus is on the characteristics of the product. Cost, time, and reproducibility are factors, but not prime considerations. In contrast, implicit in manufacturing is an awareness of the primacy of economics, the need for documentation to ensure repeatability, scalability, tolerances, risk management, conformance to standards, throughput, and capitalization of facilities, among other factors. Manufacturing supported by comprehensive engineering (figure 1b) offers societal benefit through widely available affordable devices that offer high performance and highly reliable operation.

The scale of mass manufacturing is not remotely approached in the context of making. For example, annual light vehicle production is more than 90 million worldwide (with a single popular model approaching or exceeding 0.75M units). Similarly, smartphone production exceeds 1.4 billion per year, and an astonishing 200 billion aluminum cans are produced each year.

Furthermore, the extremely low tolerance of risk associated with manufactured goods is generally not a guiding criterion in the context of making. Even with small production volumes, compliance with design specifications and industry standards is paramount with manufacturing, but typically not in the context of making, which is often done on a best-effort basis. Scaling up to production levels safely is a challenge for all industries (e.g., Fernandes et al. 2019; Reisman 1993; Ward et al. 2012), and the fact that it is so frequently accomplished is a testament to the professionalism and dedication of those involved.

Manufacturing enterprises that connect with universities have much to offer academic makerspaces in terms of reliability testing methods, case studies of solutions to seemingly intractable problems, dealing with constraints, strategies for decision making, and prioritization methods.

International Support for Academic-Industry Collaboration

The World Manufacturing Forum was established in 2018 as a collaboration of commercial enterprises, the academic sector, and associations with the mission of generating and diffusing a manufacturing culture around the world and goals of economic equity and sustainable development. Its report on the future of manufacturing includes ten short- and long-term recommendations, many of them relevant to university-based initiatives (Taisch et al. 2018):

1. Cultivate a positive perception of manufacturing
2. Promote education and skills development for societal wellbeing
3. Develop effective policies to support global business initiatives
4. Strengthen and expand infrastructures to enable future-oriented manufacturing
5. Encourage ecosystems for manufacturing innovation worldwide
6. Create attractive workplaces for all
7. Design and produce socially oriented products
8. Assist small and medium-sized enterprises with digital transformation
9. Explore the real value of data-driven cognitive manufacturing
10. Promote resource efficiency and country-specific environmental policies

One important response to the need for manufacturing-relevant research is a network of 15 institutes designated Manufacturing USA[1] (Molnar 2018). Its goals include facilitation of the transition of innovative technologies into scalable, cost-effective, and high-performing domestic manufacturing capabilities, and acceleration of the development of an advanced manufacturing workforce. In 2018 Manufacturing USA supported nearly 500 research and development projects and more than 200,000 students in associated STEM activities. In addition to its 244 government, government lab, and not-for-profit members, the public-private partnership includes 474 universities, colleges, and community colleges, and 1129 companies (371 large and 858 small manufacturers). Manufacturing USA has also been singled out for NSF support (Wang 2016).

Making advances an idea into a prototype and manufacturing advances a prototype into a product.

These developments set the stage for covid-19-motivated collaborations between manufacturers and academic makerspaces.

[1] https://www.manufacturingusa.com/institutes

Covid-19 and Important Contributions of Academic Makerspaces

In March 2020 most US institutions of higher education abruptly shifted from in-person on-campus instruction to remote learning, affecting as many as 14 million students (Hess 2020). One consequence was that user facilities such as academic makerspaces suddenly had excess capacity and assumed new roles. A number of them reconfigured to support their institutional mission, producing parts to support distance learning—such as classroom models and demonstration components—and projects, courses, and laboratories. Even while responding to these new demands, there was still often excess capacity.

The pandemic required leveraging existing and new relationships among makerspaces, regional healthcare providers, and manufacturers.

They were also able to respond to the pandemic directly, in partnership with the manufacturing community, by addressing needs, challenges, and opportunities related to the following realities:

- The existing supply chain was unable to meet the dramatic increase in demand for personal protective equipment (PPE).
- Traditional demand for many manufactured goods suffered a sudden drop, creating excess capacity.
- Supply chains, particularly those that drew on international suppliers, became rapidly depleted in raw materials.
- Standard operating procedures for entities that rely on close-proximity interactions with broad swaths of the population (e.g., health care, hospitality, and education) changed fundamentally—and these changes appear to be becoming institutionalized.

The early stages of the pandemic placed makerspaces in a surrogate manufacturing position, suddenly faced with challenges associated with inventory, supply chain, testing/certification, packaging, and distribution—all areas beyond their normal expertise. The distinction between making and manufacturing became immediately apparent. The PPE need, for example, was simply too large for makerspaces to address (e.g., Westervelt 2020). Impact required leveraging existing and new relationships among makerspaces, regional healthcare providers, and manufacturers.

Often, makerspaces served as a conduit to medical professionals, with industry, making, and manufacturing professionals working together in ad hoc teams to create solutions. Makerspace employees served as liaison or interpreter between clinical engineers and professional peers in manufacturing. This role illustrates a potentially important and transformative partnership that could be continued after the pandemic.

In other cases, makerspaces (and university research labs) fulfilled a quality assurance function in the manufacturing process when medical technology or PPE required performance verification. Makerspaces pivoted to create tests, evaluation systems, and processes to validate material that lacked external certification, such as respirators, surgical masks, and ventilator components. However, while these are standard operations for manufacturing industries, they are not commonly a component of makerspace operations, and the role of regulatory agency oversight for PPE and medical technology was perhaps underrecognized early on. Nevertheless, makerspace staff took care to ensure that potentially unsafe equipment was not introduced into the community. This represents another opportunity for manufacturers to work together with universities.

Illustrative Case Studies

To illustrate makerspace responses to the pandemic, we briefly review three case studies.

Academic Makers Collaborate to Produce Face Shields

At Case Western Reserve University (CWRU), the limited availability of face shields was an early priority in the pandemic. The shields have three components: headband, clear face shield, and rubber strap. An open-source design for a 3D-printed face shield was available (Prusa 2020), but the cycle time for production in the maker community was daunting.

The components can be produced in a makerspace using a combination of fused deposition for the headband and laser cutting for the clear face shield and rubber strap, but the cycle times are long relative to manufacturing operations: The cycle time to make 48 rubber straps using a laser cutter was about 48 minutes (60 sec each), whereas the same quantity could be manufactured by die cutting on a sheet-fed clicker die in about 1.5 minutes total (1.9 sec each). And to make two clear face shields using a laser cutter would take about 1 minute (30 sec each), whereas they could be manufactured by die cutting on a roll-fed clicker die in about 5 seconds total (2.5 sec each).

The largest time sink was for producing the headband. Making two headbands on an industrial 3D printer would take about 40 minutes (20 min each), whereas they could be manufactured by injection molding on a 2-cavity mold in about 8 seconds (4 sec each). In this example, making entailed a production rate of 3 units per hour whereas manufacturing yielded 900 units per hour. Multiple cavities and other standard techniques enabled more than a doubling of throughput using common manufacturing methods.

A team was formed with two universities, three manufacturers, and an industrial design firm (CWRU 2020).[2] A faculty member at one university designed injection molding tooling. The academic makerspace staff at the second university prototyped and validated adjustments to the original designs for molding and die cutting in consultation with the industrial designer and academics with relevant expertise. Manufacturing and logistics were handled by the companies.

It took less than 2 weeks to progress from idea to the start of production. The collaboration resulted in 150,000 face shields manufactured and delivered within 30 days—where no supply chain had existed. Collaboration with a local manufacturing extension partnership extended the impact to the scale of mass manufacturing (MAGNET 2020).

The critical takeaway is that if CWRU had tried to make face shields using only its own prototyping equipment it would have failed. The fact that the university's technically trained people reached out and formed partnerships allowed a nontraditional set of small manufacturing firms to produce face shields at rates comparable to those of large vertically integrated firms (e.g., 100,000/week by Ford in Troy, MI). The CWRU example shows that universities are gaining experience in real manufacturing and thereby developing experience that can foster better university-industry partnerships.

[2] White Label Face Shields, https://whitelabelfaceshields.com/

There are many other examples at CWRU and other universities. The lesson here is that the academic makerspace community quickly created holistic complementary teams and executed complicated projects under significant time pressure.

It will be valuable to incorporate this type of rapid response into standard operating procedures for academic makerspaces. Successfully confronting the challenge of true manufacturing, rather than prototyping, creates an experience base for universities to leverage in future partnerships with industrial firms.

Creation of Rapid Testing Capacity for Respirators

In another example, quality assurance principles commonly associated with manufacturing were applied at a university makerspace to ensure that PPE met specified standards.

The pandemic rapidly stressed the PPE supply chain in the Northeast United States, prompting hospitals to reach out beyond their normal vendors. For respirators, donated supplies and material from potential vendors were not always certified (by the National Institute for Occupational Safety and Health, NIOSH) as N95 respirators. In the absence of this certification, hospitals needed methods to evaluate respirator quality.

> *Makerspace staff designed and implemented a local respirator testing station based on NIOSH testing guidelines.*

At Yale University a team was formed in late March 2020 to address this issue, with physicians and supply chain logisticians from the hospital, researchers and design staff at the university's makerspace (Yale Center for Engineering Innovation and Design), and faculty. With expertise in design, electronics, fabrication, and testing, makerspace staff served as the conduit between the medical and research communities to quickly design and implement a local respirator testing station based on NIOSH testing guidelines. Components for the testing station were manufactured on site.

The team created a test station to evaluate the efficiency and flow impedance of uncertified respirators. Performance tests documented the system's accuracy and precision, and the results were verified using independent measurement devices.

Many university makerspaces have space to jointly host outreach events with manufacturing firms.

At the height of the pandemic's spring wave, respirators arrived daily for testing, and the results on each mask's fit, efficiency, and flow impedance were provided within 24 hours. The method was published to enable others to develop local respirator testing platforms (Schilling et al. 2020).

An Academic-Industry-Federal Lab Collaboration

Another collaboration that included production of face shields underscores the distinction of making versus manufacturing in terms of production rates and raises other important points as well. This was a three-way partnership of the federal Manufacturing Demonstration Facility at Oak Ridge National Laboratory; the University of Tennessee, Knoxville, involving a faculty member in advanced composites and manufacturing innovation; and a global manufacturer of medical supplies (ORNL 2020).

The manufacturer, seeking to produce face shields, recognized the need for a new type of mold to increase production rates but did not have the time to fully research potential solutions. It collaborated with the university for design knowledge and the federal laboratory for unique additive manufacturing technology to produce the new mold. The manufacturer began production with a manual approach, then added automation technology to increase production rates—more than 40,000/day—and reduce unit cost.

This example demonstrates the value of federal investment, state investment, and the establishment and maintenance of public-private and academic-private sector relationships to synthesize their complementary knowledge to achieve rapid high-impact redeployment.

However, there is a serious gap in manufacturing-relevant higher education. A technical staff member of the national laboratory subsequently argued that "those capabilities should have existed outside a national laboratory."[3] Academic makerspaces can—and should—be used to build the bridge between making and manufacturing, developing the capacity to quickly get to a prototype while considering safety, the role of design on ease of production, cost-effective decision making, and other factors and constraints.

Opportunities

The large number and broad distribution of academic makerspaces create opportunities for collaborative work to support manufacturing and benefit society, consistent with the recommendations of the World Manufacturing Forum. Aspects of university infrastructure are also well aligned with the mission and goals of the Manufacturing USA institutes and their supporting federal agencies, the needs and desires of manufacturing firms and companies, and priorities of regional, state, and federal government. And the pandemic reemphasized both the benefits of and need for collaboration in a highly visible and compelling way.

Many university makerspaces serve the public and may have space that can be used for outreach events held jointly with manufacturing firms. Doing so avoids challenges associated with an industrial setting, such as safety or noise concerns, the need to disrupt regular production, and the possibility of technology leakage.

University-hosted events can also show both what types of educational programs lead to different career options and clever and impactful work that can inspire a wider community. A well-run makerspace reflects an attractive and appealing workplace that welcomes the involvement of others. By cultivating entrepreneurial activities, academic makerspaces become natural hosts or cosponsors of events and may inspire collaboration and even curricular reforms that introduce engineering and other students to policy, supply chain (including resource efficiency), financing, and risk analysis.

Finally, university makerspaces and engineering programs are in a very strong position to explore design for manufacturing. This can be fostered by engaging and collaborating with students and community groups focused on socially oriented products.

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[3] Scott Smith, group leader, Machining and Machine Tool Research, Oak Ridge National Laboratory, in personal conversation with JDMC, Feb 4, 2021.

Academic makerspaces are inherently collaborative spaces that can demonstrate the action of business, in this case manufacturing, as an agent of world benefit. As evidenced by covid-19 partnerships, collaborations between the manufacturing and making communities accelerate progress in both domains.

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Considerations for designing manufacturing supply chains to be resilient in the face of likely future disruptions.

Designing the Global Supply Chain in the New Normal

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The year 2020 was one of turbulence and unprecedented challenges. Global companies had already been redesigning their supply chains in response to escalating trade frictions, threats of higher tariffs, and increasing protectionism from governments in many countries, but the covid-19 pandemic presented even more complex issues as disruptions resulted in major shifts in both demand and supply.

The need for shifts will persist as the new normal is likely to involve increasingly frequent disruptions—other pandemics, earthquakes, floods, hurricanes, trade disputes, perhaps even human-made disasters. In addition, globalization is expected to yield highly unpredictable opportunities that will require prompt action to meet customer needs and demands. This article focuses on the design of the supply chain in this new environment.

Supply Chain Weaknesses Exposed by the Pandemic

When the pandemic hit different parts of the world, there were soon shortages of products because of offshored production, primarily to China ("the world's factory"). The pandemic exposed the risk of having a single source: when that source was disrupted, the company's supply chain quickly broke.

The massive breakdown in supply chains has also been attributed to excessively lean processes in practice: "just-in-time" operational processes hold very little buffer inventory to protect against unexpected disturbances.

Cost considerations also reduced capacity levels to the minimum.

A number of remedies have been suggested. In the United States the most common is to address the risk of overreliance on China as the manufacturing base. Companies have been advised to diversify their supply bases, either instead of or in addition to China (the latter is referred to as the "China Plus One" strategy).

Coupled with the diversification strategy is the push for more domestic or regional supply chains to safeguard against future shocks, as managing a disruption at a faraway site is much more difficult than at a nearby one.

Because being too lean in the supply chain is risky, some redundancies in the form of buffer inventory or capacity are appropriate. Of course, greater lead time and flexibility in production processes through automation and labor upskilling are always helpful.

Implementation of these recommendations could lead to increased investments in digital technologies, reshoring, dual sourcing, more inventory stockpiling, and extra idle capacity. Shih (2020) provides an excellent overview of the risks and potential ways forward.

Factors to Consider in Supply Chain Design

Protecting supply chains against disruptions by adding redundancies such as increased buffer inventory and additional capacity can be costly. The inefficiencies introduced could lead to the loss of competitiveness. Companies that once maintained ample inventory and extra capacity were pressured to reduce the buffers for cost efficiency when no major disruption occurred and they were left with excess inventory. Such oscillation creates nervousness in the system and hurts the long-term health of the supply chain.

For security reasons, a certain level of domestic supply chain with redundancy for essential products is desirable. But it may not be feasible or it may be too costly to develop a complete, domestic, vertical supply chain for some products, even in resource-rich countries. And a disaster in the home country may completely disrupt the domestic supply chain. So a diversified global supply chain is likely to be more resilient than a totally domestic one.

A survey of executives of global companies found that supply chain design requires more than simply following one best practice principle (Cohen et al. 2018). It is a balancing act among multiple objectives and risks and requires careful consideration of the following questions:

- What is the role of total (landed) and other costs in changing a supply chain design?
- To what extent are trade agreements and customs duties a determining factor in the design of a supply chain?
- What are the factors to consider in reshoring production or pursuing a combination strategy, with both off- and reshoring? And how should diversified supply bases be used differently?
- What is the best way to balance the trade-off between cost efficiency and redundancy to ensure flexibility in the face of supply chain disruptions?

Assessment of Total Landed Costs

One of the pitfalls in redesigning the supply chain either by moving a factory to a new location—domestic or offshored—or diversifying to multiple locations is an incomplete landed-cost analysis.

The total landed cost is the end-to-end cost from sourcing point to product delivery, covering transport of the raw materials for production through multiple intermediate points to reach the demand destination. The cost should also account for the riskiness of disruptions and other vulnerabilities throughout the process.

Every supply chain redesign involves potential changes in sourcing costs, processing costs, and logistics costs.

Every supply chain redesign involves potential changes in the sourcing costs of the raw materials, processing costs at the site, and logistics costs to get products to the destination points. The logistics costs include customs duties and freight. These are the obvious components of the total landed costs, but there are many other components (e.g., inventory, border delays, quality, and risks of regulatory or code of conduct violations) that require consideration. Careful evaluation may reveal that a new supply source is not as attractive as it first appeared.

Operations research models have been developed for such evaluation. For example, one analysis of network design based on landed-cost components considered taxes, local government incentives, customs duties, local content requirements, and transfer prices (shown in the mathematical programming model described in Cohen and Lee 1989).

Less obvious, but critically important, are the costs associated with crossing borders—what the World Bank calls "cross-border logistics frictions" (Hausman et al. 2005, p. 1). In addition to customs duties, these are the costs and time involved in getting products through borders, such as loading and unloading from shipping vessels, documentation requirements, waiting for inspections, and delays incurred at port facilities. One item singled out by the World Bank as a significant source of delay is the number of signatures—ranging from a few to 48—required by the receiving government. Such logistics frictions can be a major impediment to the attractiveness of trade between countries (Hausman et al. 2014) and are part of the total landed cost.

The costs of noncompliance and breaches—and of monitoring to reduce or prevent them—are part of the total landed cost.

When setting up supply sources in emerging and developing economies—for example, for Central America to serve the North American markets, North Africa or Eastern Europe to serve the European Union, or Southeast Asia to be part of a diversified strategy to reduce reliance on China—it is important to account for the risk of problems or violations in sustainability in new supply sources. The costs of noncompliance and breaches—and of monitoring to reduce or prevent them—are part of the total landed cost.

Finally, another component often missed is the cost of exit. A new production site may turn out not to be a permanent one. Changes in market demands, technologies, economic or geopolitical conditions, or trade relationships may result in the need to redesign the network and to close a site or abandon the supply source. The cost of such a closure or discontinuation of a relationship should be factored into the total landed cost. One may have to think twice if that cost is prohibitive.

Customs Duties, Trade Agreements, and "Product DNA"

The calculation of customs duties as part of the total landed cost may not be simple. It depends on the bill of material for the product (i.e., the components and subassembly of the product) and the location of the manufacture of the components, subassemblies, and final assembly, all of which are often governed by various bilateral and regional trade agreements. Whether a final product can be labeled as made in a particular country depends on its content, or "DNA"—its structure and the origins of its components. All of these factors determine the customs rate for products entering a country.

There has been a proliferation of trade agreements in the past few decades—from three in 1970 to more than 300 in 2020[1]—that specify rules, including customs duty rates, for trade in specific products between two or more countries. The rules may allow duty-free treatment or reduced duties if certain requirements are met. The agreements may have expiration dates, with options to renew or modify rates and terms.

For these reasons trade agreements may affect supply chain design decisions. For example, the US shoe company Crocs retained its manufacturing plant in Canada to make products for export to Israel, taking advantage of the zero duty rate stipulated in the trade agreement between Canada and Israel (Hoyt 2007).

The Logan car made by Renault also illustrates the impact of trade agreements on supply chain decisions (Lee and Silverman 2008). Intended primarily for markets in Eastern Europe, the Middle East, and North Africa, the Logan was originally built entirely in Romania. But the country quickly ran out of capacity when the car became unexpectedly popular in Western Europe. After Romania's EU accession in 2007, parts produced there qualified as European parts, so, to get duty-free shipping, Renault took advantage of the complex set of trade agreements between Romania and Morocco and between Morocco and the European Union. Instead of investing in the facility and manufacturing processes for the whole car in Morocco, Renault arranged to ship the core kit of parts from Romania to Morocco and used the factory in Morocco for the final assembly of the vehicle. With enough of the value of the parts imported, the

[1] World Trade Organization, http://rtais.wto.org/UI/charts.aspx#

Logan assembled in Morocco could satisfy the rules of origin to achieve a duty-free rate for the finished vehicle shipped to Europe, saving 10 percent duty.

In the United States in 2019, as import tariffs on bicycles made in China increased and threatened to go up even higher, some bicycle companies were able to switch to make bike frames in Cambodia while continuing to buy about half the components from producers in China (Singh 2019). The finished bicycles from Cambodia could enter the US tariff-free, designated as made in Cambodia as long as 35 percent of the costs were derived from that country.

Optimizing Mixed Sourcing for Cost Efficiency and Flexibility

When companies use a dual or multisourcing strategy, they need to take into account the characteristics, strengths, and weaknesses of each site.

Broadly speaking, sites can be classified as "cost-efficient" or "flexible" (this is a crude classification but is used here to illustrate the idea). Cost-efficient sites provide a low cost for production or procurement, but may be less flexible and require longer lead times. Flexible sites tend to have better engineering support and capabilities to enable quick responses, but higher costs. Offshored manufacturing sites in very low cost countries may be viewed as cost-efficient sites, and onshore (domestic) or nearshore (regional) sites as flexible sites. A combination of these types may be effective.

As an example of mixed sourcing, Hewlett-Packard used a cost-efficient site to produce at a fixed volume and a flexible site to produce variable volume in response to fluctuating and uncertain market demands (Olavson et al. 2010). The company thus enjoyed the benefits of both.

There are other ways to use multiple sites based on the characteristics of the sites and the products. Within a company, the needs of multiple products at various stages of the lifecycle and the manufacturing processes involved are different. The different product needs and manufacturing processes must be matched with the sites that have the right characteristics. This is the basis of supply chain strategy alignment (Lee 2002). Different strategies are shown in table 1.

TABLE 1 Mixed sourcing strategies

	Flexible source	Cost-efficient source
Volume-based	Variable volume	Stable volume
Product-based	Risky, essential	Stable, nonessential
Time-based	Ramp-up & end of life	Mature phase
Process-based	Critical, postponement	Generic

- A volume-based mixed strategy addresses the need to accommodate both fixed and variable volume.
- A product-based strategy depends on the nature of demand for the product: stable demand (e.g., for basic apparel or standard consumer electronics, or noncritical products); or risky, uncertain demand (e.g., for fashion apparel or advanced electronics, or essential products such as those critical for national security).
- With a time-based strategy the cost-efficient source is used for products at their mature phase, when demand tends to be more stable and predictable; the flexible source is used in the ramp-up or end-of-life phase, when demand is more volatile.
- Finally, a process-based strategy recognizes that the initial stage of the production process tends to be more standardized, for building generic core engines, for example; later, in the customization or postponement stage, products are customized or differentiated into options or distinct products. The earlier standardization stage has more stable, predictable demand, while the customization stage involves greater demand uncertainties. Hence, the cost-efficient source is better suited for the initial stage, and the flexible source better for the customization or postponement stage.

Balancing Cost Efficiency and Redundancy: Capacity Building and Agility

Besides a resilient supply chain design, best practice calls for reexamining the need for buffer inventory and buffer capacity. With the increasing uncertainties of the new normal, two additional capabilities are needed: quick capacity building and agile configuration of the supply network.

When the pandemic hit in early 2020, Taiwan was able to respond quickly to make personal protective equipment (PPE) not because it had domestic vertical supply chains of PPE or a large buffer inventory of the products. Instead, Taiwan has the know-how of the machining industry, which was leveraged to make PPE production equipment (Fang and Li 2020). This highlights the importance of having the knowledge and capability to build capacity when needed, instead

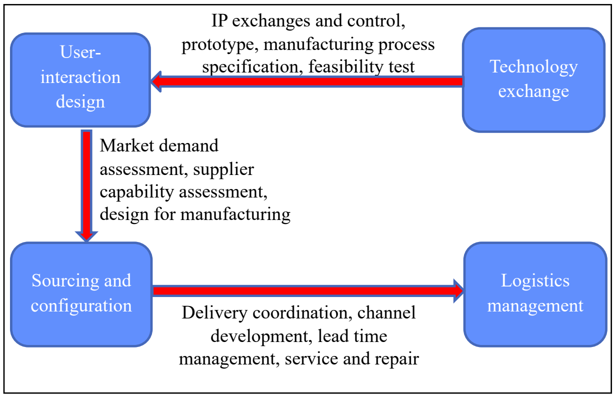

FIGURE 1 Agile configuration platform for new products. IP = intellectual property.

of maintaining costly extra capacity or inventory just in case.

Companies must strengthen their ability to create new capacities as needed. The know-how involved in manufacturing process technologies is critical and should not be outsourced or offshored. When companies diversify their manufacturing footprint, they should locate some sites in a region with a capacity-building ecosystem. This was the machine-building ecosystem that Taiwan used.

A disruption like covid-19 could lead to an instant need for products that did not even exist before. Social media and fast-changing fashion trends can also rapidly create opportunities for new products. Companies need to have the capability to configure a new supply network on the fly. Such a network is not just about suppliers of materials and final assembly, but about quickly connecting designers, intellectual property (IP) owners, prototype builders, market testers, and new sales and logistics channels.

A digitally connected platform is effective for agile configuration. Haier, which owns GE Appliances, has achieved such agility with a digital platform, COSMOplat (Xie and Li 2020), that connects the entities involved in design, market test, and production of industrial appliances for new product generation and launch. This is how the company was able to create a mobile isolation ward for hospitals in China during the worst of the pandemic. The country was in lockdown at the time of the Chinese New Year, and there was a need for mobile isolation wards that could be moved from hospital to hospital as patient loads shifted. This was not an existing product, and so the supply network did not exist. Haier's digital platform made it possible to design and build the product in 2 weeks.

An agile configuration platform requires a network of multiple modules (figure 1). The technology exchange module allows designers and IP holders to collaborate on new product design, do rapid prototyping, perform feasibility tests, and design for manufacturability. With the user-interaction design module, potential users test the product, provide feedback, and give an early indication of market acceptance. The sourcing and configuration module facilitates identification of the component, subassembly, and final assembly partners in the supply network for building the product, and the logistics management module engages the right players for channel development, order fulfillment, and after-sales service and repair.

Conclusion

Global supply chain design in the new, postpandemic normal requires a full understanding of total landed costs, integration of product design, alignment of the characteristics of production sites with product DNA and trade restrictions, and, finally, the ability to build capacity and reconfigure supply networks quickly.

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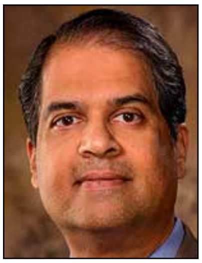
Urgent and continued work in frugal engineering and manufacturing is essential for addressing technosocioeconomic inequity in the United States.

A Case for Frugal Engineering and Related Manufacturing for Social Equity

Ajay P. Malshe, Dereje Agonafer, Salil Bapat, and Jian Cao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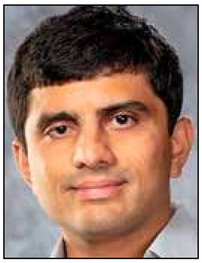
Dereje Agonafer


Salil Bapat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Traditionally, problems arising from lack of access to basic human needs such as food insecurity, affordable health care are thought of as global problems only pertinent to developing and underdeveloped countries. However, these problems silently exist and are growing in developed countries such as the United States. These problems are driven by the equity gaps put to

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the forefront and further magnified by the covid-19 pandemic. This paper is presented in two parts. The first part unfolds the clear equity gaps in access to basic human needs in America. In the second part, we propose and illustrate the potential of frugal engineering and manufacturing approaches to address these equity gaps. Further, the paper also highlights the importance of convergence among science, engineering, education, policy, economics, community engagement, and businesses for understanding and developing affordable and accessible solutions for the complex problem of inequity in urban and rural deserts in the United States. Through the review of successful and representative frugal social innovations around the world, we identify key attributes of frugal engineering and manufacturing approach to guide social innovation for equity.

BOX 1 Disparities in access to basic human needs in urban and rural areas of the United States

22.5% of African-American households are food insecure in urban areas, double the national average[a]

Rural communities (15-20% of US population) have worse healthcare facilities than their urban and suburban counterparts, have fewer doctors, are uninsured, and travel long distances for health care[b]

Native American communities are 19 times more likely than white households to lack indoor plumbing[c]

79% of urbanites have access to home broadband, only 63% of Americans in rural areas have access to broadband[d]

[a] https://www.healthypeople.gov/2020/topics-objectives/topic/social-determinants-health/interventions-resources/food-insecurity
[b] https://www.aamc.org/news-insights/health-disparities-affect-millions-rural-us-communities
[c] http://uswateralliance.org/sites/uswateralliance.org/files/Closing the Water Access Gap in the United States_DIGITAL.pdf
[d] https://www.pewresearch.org/fact-tank/2019/05/31/digital-gap-between-rural-and-nonrural-america-persists/

A recent study shows that since 1975 over $47 trillion in wealth in the United States has been transferred from the poor and middle classes to the top 1 percent (Hanauer and Rolf 2020). Especially, during 10 months of the pandemic, "America's billionaires have grown $1.1 trillion richer when 8 million Americans fell into the poverty of the final six months of 2020. The poverty rate climbed 2.4% in the second half, nearly double the largest annual increase in poverty since 1960, when some groups have suffered more than others" (Egan 2021). Concurrently, since 1975 the population in urban and rural areas has increased significantly in America and other industrialized nations. Historically disadvantaged groups in these regions are disproportionately affected by equity gaps, lacking in basic needs such as access to nutritious food, clean water, internet connectivity for education, and basic health care (box 1). Technological advances remain unaffordable and inaccessible to many, given average US earnings of $34,000/capita in 2019.[1] Inaccessibility to basic needs has been further exposed and exacerbated by the covid-19 pandemic (Malshe and Bapat 2020). The US technosocioeconomic divide obstructs upward social mobility necessary for eradicating, for example, generational poverty (Malshe and Bapat 2020; Peterson and Mann 2020).

Traditionally, the question of inequity is largely addressed by social scientists, lawyers, and economists and seldom by those in science, technology, engineering, and math (STEM) fields, despite the potential for technological innovations to address this problem. Beyond the need for more uniform digital connectivity (Tsatsou 2011), the broader role of scientific and technological innovations in addressing the problem of inequity in basic human needs has not been sufficiently explored, especially via working with communities in need.

As evident, the complex problem of inequity is at the intersection of multiple disciplines and could be understood effectively as a convergent problem. According to the recent report of the Academies convergence of the life sciences with fields including physical, chemical, mathematical, computational, engineering, and social sciences is a key strategy to tackle complex challenges and achieve new and innovative solutions (NRC 2014). What is needed is a convergent approach that leverages the work of all stakeholders connected to this inequity gap including, for example, STEM scientists and engineers, social scientists, and policymakers.

[1] US Census Bureau QuickFacts: United States (https://www.census.gov/quickfacts/fact/table/US/INC910219#INC910218)

At the same time, there are examples of effectively implemented social innovations across the world addressing basic human needs, and they can enhance social equity through conscious and convergent efforts by scientists, engineers, social scientists, and policy researchers. "Social innovations (SIs) are defined as new solutions (products, services, models, markets, processes, etc.) that simultaneously meet a social need (more effectively than existing solutions) and lead to new or improved capabilities and relationships and better use of assets and resources" (Caulier-Grice et al. 2012, p. 42).

Technosocioeconomically constrained communities can benefit significantly from frugal scientific and technological innovations.

Frugal engineering is characterized by at least an order of magnitude reduction in the use of resources—time, capital, space—for invention, innovation, and implementation to address a specific problem. For example, a prestigious Rolex Award–winning innovation, the Zeer pot-in-a-pot, provides refrigeration without electricity in the very hot climate of Nigeria (Rolex.org 2000). Without proper refrigeration, fresh produce spoils quickly and hampers the earning ability of farmers. The innovator, Mohammed Bah Abba, a potter by profession, realized evaporative cooling through porous clay pots for refrigeration. The solution benefited the local community by helping farmers extend the shelf life of their produce, using local know-how (pottery) to create jobs, and providing fresh produce for consumers. The following sections present the equity gaps present in the United States, a review of successful social innovations around the world followed by the proposed frugal engineering and manufacturing model that could be applied for social equity.

Traditional Viewpoint: Looking Outward in the World for Gaps

For decades, the United States STEM community has been engaged in addressing inequity across the globe, as challenges rooted in inequity are unfortunately commonplace throughout the world. Although fundamental STEM knowledge and technology are available to address challenges rooted in inequity, numerous barriers prevent this know-how from benefiting those in need.

To identify hidden gaps that impede development, the Purdue Innovation Science Laboratory conducted a comprehensive success factor analysis (Sinfield et al. 2020), comprising a systematic literature review and automated data mining of sources (peer-reviewed articles, grey literature, case studies, and social media content). Analysis of over a dozen complex challenges around the world—from potable water availability in the Dominican Republic to food security in Uganda and small business opportunities in Southeast Asia—revealed common barriers that drive inequity.

The analysis showed that populations around the globe are consistently marginalized by barriers associated with skill, wealth, physical/social access, time, behavior, attitude, and/or belief; in many cases, several of these barriers are present simultaneously (Sinfield et al. 2020). Additional large-scale literature and perspective mining, focused *within* the United States, performed to examine, for example, means to address poverty in urban settings, and drive adoption of new energy solutions, reinforced the very same patterns. Thus, the barriers that isolate and disenfranchise populations are not unique—and are present in the United States as much as outside the nation. Overcoming these systemic barriers that break the cause-effect chain of social equity will be a critical focus of any effort to achieve equal access to the resources that address fundamental needs.

Looking Inward: Gaps in Affordability and Access to Meet Basic Human Needs in the United States

Table 1 lists illustrative facts to highlight the inequities and challenges across urban and rural desert communities in the United States with representative examples from Atlanta, Chicago, rural Indiana, and Navajo Nation. Such information is critical for identifying ways to achieve equity through accessible and affordable frugal innovations discussed later in this article.

Health Inequity in Urban Atlanta

There is considerable evidence across different US population groups (see table 1A) of health disparities, many stemming from factors related to social, economic, and physical conditions prevalent in these groups (NASEM 2017; ODPHP 2020).

TABLE 1 Health, water, food, and connectivity for education in United States urban and rural areas: Existing inequities and impacts of the covid-19 pandemic

(A) Health	**Urban - Atlanta** • Racial and ethnic minorities are affected disproportionately by obesity and associated chronic diseases such as hypertension, diabetes, and coronary heart disease (CDC 2020). • The prevalence of chronic health risk factors among nonwhite and Hispanic Americans may be a contributing factor to the higher covid-19 death rates in these groups, especially for those under 65 years of age, although further studies are needed to establish a definitive correlation (Wortham et al. 2020).
(B) Water	**Urban - Chicago** • In Ford Heights (25 miles south of downtown Chicago), nearly half of the households fall below the federal poverty line, and more than 90% of residents are Black. • Structural inequities and floods cause financial loss ($2B, 2007–14), psychosocial damage, and impaired health (CNT 2014, 2015; Winters et al. 2015). • Drinking water in those low-income areas costs 3x more than in lakeside affluent communities (Gregory et al. 2017). Families often need to choose between essential needs (e.g., water, food, electricity) and cannot afford flood protection.
(C) Food	**Rural - Indiana** • Residents of rural Indiana experience food insecurity at rates similar to those in urban centers. • Before the covid-19 pandemic, "child food insecurity rates ranged from 21.0% in Grant County [rural/mixed] to 11.9% in Hamilton County [urban]," despite downward trends in rural counties over the last several years (Silverman 2020). • As of 2017, 20.3% of children in rural Switzerland County, Indiana, were food insecure (Feeding America 2017) and 13% of the food insecure children were likely ineligible for federal nutrition programs because of their household incomes. Because of covid-19, analysts warn that Switzerland County could go from 15.6% to 21.5% of the overall food insecure population (Feeding America 2020).
(D) Connectivity for education	**Tribal land - Navajo Nation** • Significant disparities in educational outcomes existed for Native American students before the covid-19 pandemic—only 61% of New Mexico's Native American students graduated with a high school diploma within 4 years (Kena et al. 2015). • Public school systems experienced a decline in reading scores among 11th grade Native American students (McFarland et al. 2019) before covid-19 school closures. • School closures and the lack of access to online educational resources have the potential to widen the gap and exacerbate educational disparities between Native American students and their peers.

A characteristic attribute of affected population groups is that they are technosocioeconomically constrained and lack access to affordable and quality health care. Consequently, these communities can benefit significantly from frugal scientific and technological innovations. For example, noninvasive wearable internet of things (IoT)–enabled wireless sensors manufactured at scale and at low cost can help bridge healthcare access gaps in these communities. Recent advances in printed flexible electronics and nanomanufacturing are making such low-cost innovations possible (Kwon et al. 2020).

Water Inequity in Urban Chicago

Chicago, commonly considered a fortunate city, a city by the American Great Lakes accounting for 21 percent of the Earth's surface freshwater,[2] shows significant equity gaps as evidenced by the data presented in table 1(B). In Chicago, undersized infrastructure creates flooding vulnerability in many low-income communities on the South Side, like Ford Heights.

In July 2019 Northwestern University, Argonne National Laboratory, the University of Chicago, and

[2] The World's Fresh Water Sources | The 71 Percent (https://www.the71percent.org/the-worlds-fresh-water-sources)

the Illinois Center for Urban Resilience and Environmental Sustainability hosted a workshop on Sustainable Urban Systems with an emphasis on the Chicago region with support from the National Science Foundation. A major challenge identified at the workshop is to enable community groups to benefit directly from research projects (Miller and Dunn 2019), a challenge that we believe can be met through social innovation and frugal engineering and manufacturing, and by working with the community in need.

Food Inequity in Rural Indiana

Food insecurity is a complex issue, intricately tied to multiple, interdependent factors, including socioeconomic status and race. Its impacts may be particularly significant for children. And as the covid-19 pandemic has revealed, public health crises and accompanying jolts to the ecosystem (e.g., sudden unemployment) can augment food insecurity even more as depicted by the data presented in table 1(C). When schools closed because of the pandemic, a primary source of food-insecure children's healthy meals was also closed, compounding the existing challenge.

A key to envisioning effective technological SIs is to first understand the particular problem and its complexities relevant to a specific community.

Those who are food insecure in rural Indiana often live in a food desert—meaning they lack access to healthful and affordable food because they don't have adequate transportation or enough money (or both)—and/or are in lower socioeconomic strata. Adding to these complications, the food insecure in food deserts rely on volunteers who are aging to bring them food (Carriere and Ayres 2013). Now is the time to design and conduct sound, convergent research on the complex, interconnected relationships among technosocioeconomic, cultural, geographic (urban/rural), public health, and other variables related to food insecurity. As Hindi (2019) argues, food insecurity needs to be thought of as a systemic problem. Communities, health policy experts, and scientists/engineers must work together to advance technological and data-driven recommendations designed to address this pressing social issue.

Inequity in Connectivity for Education on Tribal Lands

The covid-19 pandemic has posed a serious threat to educational outcomes for Native American students, who already struggled with inequality in internet connectivity (table 1D). This is particularly problematic as the country gears up for the 5G network, while many parts of the United States have little or no internet connectivity for basic education.

Distance learning requires internet availability for students to stream online classes or download suggested material. The lack of internet to stream online classes or download suggested material leaves Native American students at a major deficit, exacerbating preexisting disparities in educational attainment. This also means that students lack hands-on learning accompanied by real-time student-teacher interaction, a crucial component to effective learning. Activities to augment distance learning such as virtual visits to zoos, museums, aquariums, NASA education resources, and other STEM centers are also not accessible to students.

The frugal innovation approach, as presented in the next section, is thus critical to ensure that the technological advances remain affordable and accessible to the communities in need. Instead of modifying the existing technology for higher performance, converging the available expertise and infrastructure to ensure its accessibility to deserts such as Navajo Nation will be a crucial social innovation step.

Social Innovations, Frugal Engineering, and Manufacturing

In contrast to the tech innovations average citizens cannot access and/or afford (Malshe and Bapat 2020), SIs can address basic human needs using frugal technologies and provide affordable access and equity to underprivileged people. Frugal engineering and manufacturing methods and innovations enable simplicity, affordability, effectiveness, accessibility, sustainability, and scalability of timely societal interventions to address challenges such as those described above. We review seven representative SIs (summarized in table 2) from across the world to understand key attributes of frugal engineering and manufacturing relevant for their

TABLE 2 Representative international examples of frugally engineered social innovation and their attributes

Innovation and innovator-servant leader	Water filters (Hussam et al. 2008); Abul Hussam	Energy for lighting: "Liter-of-light" (https://literoflight.org/); Illac Diaz	Zeer, Pot-in-pot (Rolex.org 2000); Mohammed Bah Abba	Grameen Bank (NobelPrize.org); Muhammad Yunus	Fog harvesting nets (Trevino 2020); Abel Cruz	Purdue Improved Crop Storage (https://picsnetwork.org)	Low-cost sanitary pads (Venema 2014); A. Muruganantham
Location-specific targeted problem/ area of basic human need	Water purification to address arsenic contamination in rural Bangladesh	Provide energy (lighting) to electricity-scarce community in the urban Philippines	Refrigeration to keep food fresh in the desert heat in Nigeria	Access to capital for women, for job creation in rural Bangladesh	Address water scarcity in arid regions of Peru	Food storage to prevent damage due to insects in Western and Central Africa	Sanitation awareness and personal hygiene in rural India
Science and engineering solution: approach and integration	Composite-iron matrix and sand filters arsenic, charcoal/sand filters residual iron and other impurities	Water-filled recycled plastic soda bottles mounted on roofs to collect/refract sunlight for indoor lighting	Evaporative cooling achieved without electricity through porous clay pots	Cooperative community-owned banking, with financing via microloans without requiring collateral	Maximization of surface area to promote condensation and water capture by design	Insecticide-free, hermetic sealing through multilayered plastic bags	Development of easy-to-use manufacturing setup for cost-effective sanitary pad production
Community engagement	Point-of-use water filtration system reduces the need for women to travel long distances to collect water	Communities taught how to use locally sourced recyclable material to create a plastic light bulb	Created jobs for potters, taking advantage of local know-how	Household entrepreneurs increased access and employment by supporting local businesses	Synergy between community and local government; minimal carbon footprint	A farmer community-research partnership enables point-of-need use and continuous improvement of the product	Self-help groups for women's employment through local microproduction factories
Price of integrated solution for effectiveness	$40 per filter usable for up to 5 years	$1 per bottle	$1–2 per pot	N/A, no-profit/no-loss model	About $100 per net	$150 annual saving per household	<$0.20 per sanitary pad; $1000 for machine
Effective impact of the innovation on population	Scalable and sustainable solution impacting about 1 million people	Integrated plastic waste management to over half a million people	Reduced food waste by extending the shelf life of produce for farmers and families	Avoided exploitation from loan sharks	Access to water for domestic and agricultural use	Low-cost method of storing grains; >1.75 mil PICS bags have been sold in West and Central Africa	Better hygiene practices adopted by many women in rural India
World-class recognition	NAE Grainger award (2007)	Asia Pacific Social Innovation and more	Rolex Award (2000)	Nobel Peace Prize (2006)	Multiple awards	APLU award for exemplary design (2020)	Govt. of India Padma Shri award (2016)

successful implementation and analyze the potential of an SI frugal engineering and manufacturing model to address inequities in the United States.

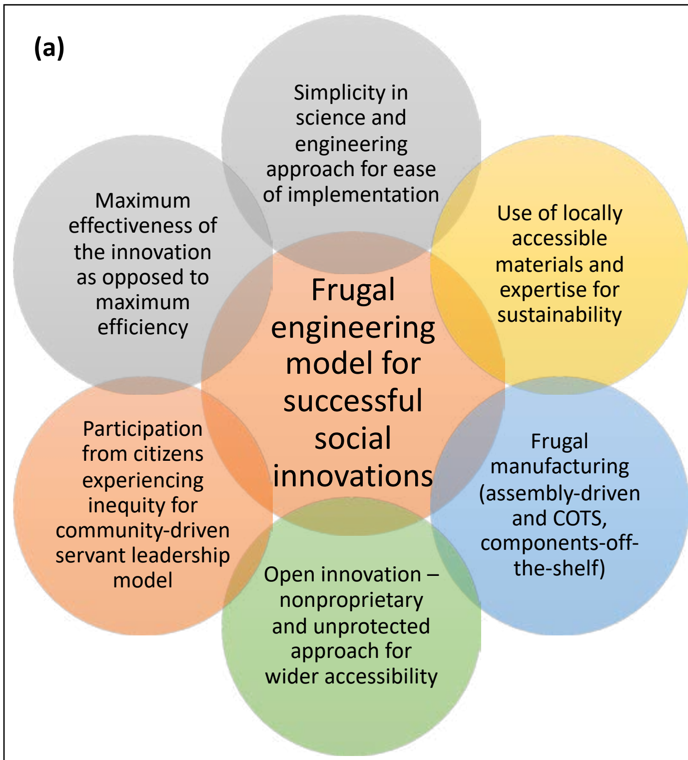
A key to envisioning effective technological SIs is to first understand the particular problem and its complexities relevant to a specific community and then to address it using simple yet effective science and engineering solutions that can be readily adopted and implemented in the community. It is also important for community members who experience inequity to be actively involved in the SI process to help develop the solution and ensure its dissemination and continuous improvement.

Unlike traditional academic STEM research for exploring and publishing new frontiers of science and engineering, the emphasis of SI is on cost effectiveness, which can be achieved through frugal engineering and manufacturing approaches such as components-off-the-shelf and assembly-based manufacturing. Also, open innovation methods (not proprietary and/or patent-protected) ensure wider social effectiveness of the solution instead of the highest technological efficiency.

The examples in table 2 highlight specific areas of basic human need in resource-constrained communities and are well recognized for their success and are presented through the lens of the above-discussed factors of emphasis. They also benefit from an innovator's approach to servant leadership as discussed by James Hunter (1998). In most cases, the innovators are immersed in the community and have experienced the problem first-hand while understanding the value of a simple solution. They have a better understanding of a solution that is "implementable" and "acceptable" to the community in need through a compassionate approach to bring the necessary change. Based on this understanding, the frugal social innovations as proposed in this paper must be developed with the community as opposed to forcing them on the community. The proposed convergent approach must also include the community itself to ensure that an effective and acceptable solution is developed.

Critical analysis of the representative SIs reported in table 2 provides a sound foundation to develop a frugal engineering and manufacturing model for social equity in the United States. The key metrics and attributes of the model are shown in figure 1.

In the United States, SIs using frugal innovation and manufacturing approaches are essential to address



(b) Attributes of social innovations

- Frugal innovation under resource constraints (reduction by 100X in cost of innovation to achieve intended purpose)
- Open source intellectual property for wide access
- Innovation led by social innovator and entrepreneur as "servant" leaders immersed in the community
- Impact is on more than 10,000 people in disadvantaged communities across the world, providing means for equity
- Impacts are in the areas of food, water, employment, shelter, education, and energy
- Negligible carbon footprint
- Innovations driven by communities for communities
- Participation in innovation process science and engineering, policy, economics, and other STEM and non-STEM fields
- Rapidly scalable (reduction by 10X in time to accomplish intended purpose)
- Simple, elegant, and robust
- Accessible to "haves" and "have-nots"

FIGURE 1 Attributes of frugal engineering and manufacturing model for social innovation.

a variety of problems concerning the equity gaps. For example, in Los Angeles, rapid covid-19 test strips were developed with participation from scientists and engineers and the support of the political system. The strips could be manufactured at a fraction (5–10 percent) of the standard PCR test cost and could dramatically increase virus detection, according to the LA mayor (LAist 2020). Similar efforts are also used in developing low-cost ventilators and personal protective equipment. This solution relies on a components-off-the-shelf and assembly approach which utilizes components that can be locally manufactured and readily available (Parmelee 2020). This aspect is especially pertinent in light of the covid-19 pandemic, where relying on large manufacturers and global supply chains caused significant challenges.

Urgent and continued work in frugal engineering and manufacturing is essential for addressing technosocioeconomic inequity in the United States.

Summary and Convergence

Technosocioeconomic inequity is technology-driven at the convergence of basic human needs including water, food, internet connectivity for education, and affordable health care. This inequity exists across growing urban and rural deserts in the United States. As a convergent problem, the potential solutions must involve a convergence of talents from science, engineering, education, economics, policy, community engagement, businesses, and more.

The model of frugal innovations along with manufacturing is executed using key characteristics including implementation of simple science and engineering fundamentals for easy and speedy implementation, use of locally accessible materials and expertise for development and sustainability, frugal manufacturing processes largely driven by the assembly of components-off-the-shelf, an open innovation platform for broad societal participation including members of underprivileged communities, and innovations driven by maximum effectiveness rather than perfect efficiency. Frugal innovations have been effectively implemented by innovators working with and for communities following the attributes of the servant leadership approach. These technosocial innovations are shown to bridge social inequity gaps globally and could be a potent model for addressing technosocioeconomic inequity in the United States.

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In the postpandemic environment, corporations should prioritize elements of social responsibility that are naturally aligned with corporate profitability.

Engineering and Social Responsibility

What the Digital-Industrial Revolution Means for Manufacturing Companies' Social Responsibility

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Marco Annunziata

The digital-industrial revolution, called Industry 4.0, has begun to effect a major transformation of work and daily life: how production is organized; new skills required in the workforce; the interaction between humans and machines, as robotics and artificial intelligence (AI) make continuous strides; and what new products are possible and what they can do (e.g., self-driving vehicles, delivery drones), including their impacts on the environment.

The influences of Industry 4.0 on society promise to be at least as profound as those of the original Industrial Revolution. It is therefore not surprising that this technological revolution has triggered calls to reassess the ethical and social responsibility aspects of manufacturing and other industries.

It also compounds concerns about issues such as climate change and income inequality. Many of these issues have been exacerbated by a confluence of factors in addition to accelerating technological change: deepening globalization, a growing world population, and the push by emerging markets to achieve higher living standards. Studies have assessed the impacts of these factors on employment and wages in specific industries or geographical areas. Some have focused on the effects of innovation such as robotics (Acemoglu and Restrepo 2020); others have documented adverse impacts of globalization, especially competition from China (Autor et al. 2016).

The covid-19 pandemic has exacerbated many of these trends and created a greater sense of urgency. Across the world, lockdowns to contain contagion caused sharp recessions and major job losses, with the attendant economic stress. They also exacerbated inequalities, as some jobs could be performed remotely while others could not, the sectors most severely affected (e.g., hospitality) tend to employ a larger share of lower-skill workers, and the shift to home schooling has proved much more challenging for children from lower-income households and for some groups of adults, especially women (Rothwell and Desai 2020 find that "labor force participation rates are 12 percentage points lower for adults with children in distance learning compared to in-person schooling").

Better alignment of skill supply and demand could help reduce income inequality.

Manufacturing companies have been accused of contributing to these problems by focusing exclusively on short-term shareholder-value maximization, and they face mounting pressure to rethink their social responsibility. How can manufacturing companies best help society surmount these challenges?

Social Responsibility Priorities for Manufacturing Companies

Profitability

Profitability is a necessary precondition for survival in the market economy. A corporation's most basic social responsibility, therefore, is to remain profitable and viable so that it can continue to contribute to economic growth and job creation. Corporate bankruptcies can cause recessions and unemployment and in extreme cases impair the stability of the financial system and/or require governments to come to companies' rescue, putting taxpayer money at stake. Manufacturing companies should therefore aim first and foremost to remain profitable.

In the postpandemic environment, corporations should prioritize specific elements of social responsibility that are naturally aligned with corporate profitability and where their actions can have the greatest impact.

Human Capital

The first priority is to invest in human capital, stepping up company efforts to maintain and upgrade the skills of their workforce and investing in technologies that can augment workers' capabilities and allow them to learn faster on the job.

Studies have shown for some time that innovation is having a very asymmetric impact on the demand for different job skills (Autor et al. 2003), and debate on the skills gap has gained increasing prominence, although the academic literature has not yet produced convincing evidence of such a gap (Cappelli 2015 argues against it, for example). The difficulty in settling the issue lies partly in the challenge of agreeing on clear definitions of skills and in the tendency to confuse skills with academic credentials.

But the anecdotal evidence emerging from industry is clear: more and more industries are struggling to find qualified workers, especially as large cohorts of experienced employees retire. Many industrial companies need to replenish their pool of traditional factory-floor skills, while augmenting it with digital skills that can help workers become conversant with the new digital-industrial technologies. Portable and wearable skill-augmenting technologies can help accelerate upskilling and productivity (Abraham and Annunziata 2017), as can connected-worker technology platforms (Annunziata 2020).

Accelerating innovation drives faster change in the mix of skills required to succeed in the labor market. This change has exposed the inadequacies of traditional education systems, and requires a shift to lifelong learning that calls for a much greater involvement by corporations—providing more in-house training opportunities, allowing workers greater flexibility to pursue upskilling and retraining outside the workplace, and collaborating more closely with education institutions in the design of curricula and internships (see, e.g., Mathó et al. 2019).

Providing the right skills and helping people maintain and upgrade them throughout their careers will play a crucial role in securing high employment levels and providing more people access to better job opportunities and faster increases in incomes; and by better aligning skill supply and demand it could help reduce income inequality. This represents an extremely important social responsibility that industrial corporations de facto shoulder; tackling it would also help them raise efficiency, productivity, and profitability.

Cybersecurity

As digital-industrial technologies become more widespread with the advancement of smart electricity grids, smart homes, smart cities, and smart factories, cybersecurity risks will increase commensurately. Attacks on critical infrastructure could cripple cities and entire economic systems, undermine human safety in workplaces, in urban environments, and on roads, and cause environmental disasters.

Governments are developing extensive cybersecurity policies, but the responsibility for ensuring the security of new technologies starts with the manufacturing corporations that produce and deploy them. By ensuring the cybersecurity of their products, services, and systems, manufacturing corporations can protect economic resilience as well as human and environmental safety. At the same time, cybersecurity is crucial to the reliability and attractiveness of the products and solutions that manufacturers sell, as well as the resilience of their own operations. This is an important social responsibility that corporations are well positioned to take on and that is naturally aligned with their economic interests.

AI and Robotics

AI and robotics play increasingly important roles in manufacturing companies, a trend that is destined to continue and deepen. Yet these technologies carry new risks and potential unintended consequences. This is especially evident in the case of AI, which in some cases operates like a black box, in the sense that its own developers are unable to fully explain why it reaches certain conclusions or decisions.

One of the key advantages of AI is its speed of reaction. This can be extremely valuable in the industrial context and will enable massive efficiency gains in contexts such as smart factories and smart cities, particularly with more extensive recourse to machine-to-machine interactions and transactions.

But to take full advantage of it, humans will be left out of the loop. Powered by AI, robots will act with an increasing degree of autonomy. Manufacturing companies must understand and anticipate the risks and potential undesired outcomes. These could include worker injuries, product and system failures, economic disruptions, and consequent damage to the public's confidence in these technologies, which in turn would slow adoption and limit benefits.

At a high level the issue of risks and potential unintended consequences of AI and robotics deployment encompasses the current debate on ethical AI and dystopian fears of AI eventually developing an agenda of its own. Of more immediate importance are risks related to the physical interaction of workers and robots in the workplace or the possible malfunction of AI algorithms. Manufacturing companies have a primary social responsibility to anticipate, monitor, and minimize these risks as they deploy new technologies both in their own operations and in their relations with customers.

Principles for Establishing a Purpose beyond Profit

It is legitimate and may be desirable for manufacturing and other companies to take on additional social responsibilities beyond investing in human capital and cybersecurity. The choice could be guided by the specific sector that the company operates in (e.g., environmental responsibility for companies in the plastics industry) or by sensitivity to broader social issues such as opportunities for women and minorities, or immigration.

The responsibility for ensuring the security of new technologies starts with the manufacturing corporations that produce and deploy them.

A properly defined purpose beyond profit can benefit companies' performance and bottom lines through several channels: it can improve their ability to attract and retain talent, bolster employees' motivation and productivity, and in some cases underpin customer loyalty and sales. A recent analysis finds that "firms exhibiting both high purpose and clarity have systematically higher future accounting and stock market performance" (Gartenberg et al. 2019).

To adopt a corporate purpose beyond profit maximization, manufacturing companies should follow three basic principles that can help them define their corporate social responsibility in ways that are transparent, actionable, measurable, and accountable—including in terms of profitability. This in turn would provide better information for consumers, employees, and institutional and individual investors to base their decisions on whether to invest in a company, buy its products, or join its workforce.

Transparency

This principle calls for the company to articulate what additional goal(s) it wants to pursue and why, spelling out whether and under what conditions the pursuit of these goals might conflict with profitability and how the conflict will be resolved. All of this should be clearly formulated in a purpose statement or "governing objective" (Mauboussin and Rappaport 2015) formally approved by the company's board of directors and transparently communicated to the entire workforce.

Measurability

Well-specified metrics must be established to assess how well the stated goals are being met. This is an extremely important part of the exercise. The metrics should be objectively verifiable, preferably validated by a third party (in much the same way that financial accounts of publicly listed corporations are audited by external agencies). And it should be made explicit why they are considered the right metrics to assess the company's impact on the stated goals.

Accountability

To make sure that all managers and employees act in pursuit of the stated goals, the company needs to put in place the appropriate incentives and ensure internal accountability. Performance evaluations, promotion criteria, and compensation policies should reflect, among other factors, the extent to which managers and employees pursue the stated goals and how well they succeed. The board of directors should hold the CEO and the rest of the executive team similarly accountable. The company should also establish external accountability by regularly publishing selected metrics that demonstrate its progress toward achievement of the stated goals.

Conclusion

The digital-industrial revolution is changing the role of manufacturing companies in the economy and in society. This change provides an opportunity for companies to rethink their social responsibility and respond proactively to societal concerns. Any broadening of corporate social responsibility should be undertaken in a rigorous, pragmatic, and transparent manner.

It likely makes sense for manufacturing companies to primarily focus on the areas where they can have the greatest impact and that are most closely aligned with their profitability—investment in human capital, cybersecurity, safe deployment of cutting-edge technologies. They can then choose to take on additional goals; these will vary depending on a company's industry, location, and the particular sensitivities and priorities of its board, management, and workforce. All goals should be transparently identified and communicated, mapped to objective metrics for tracking and disclosing progress, and accompanied by incentive mechanisms that make management, employees, and the company itself accountable for advancing the goals.

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Op-ed

Undergraduate Engineering Education: How Can We Do Better?

Hanchen Huang

Jim Williams

Hanchen Huang is dean of the College of Engineering and the Lupe Murchison Foundation Chair at the University of North Texas, where Jim Williams (NAE) is a distinguished research professor in the Materials Science and Engineering Department.

As research assumes an increasingly central role in the research-active engineering schools across the country, we argue for an alternate and complementary curriculum pathway for students who plan to work as practicing engineers with a bachelor's degree in engineering. The research-active path is important not only for students but also for faculty because it helps keep them technically current.

The closest thing to such a pathway is available at four schools that have a formal cooperative education program: Drexel University, University of Cincinnati, Rochester Institute of Technology, and Northeastern University. These schools do an excellent job of educating "job-ready" graduates, but out-of-state public school tuition or private school tuition can be a deterrent for prospective students. Students at these institutions earn money during their cooperative education, and this helps, but the "coop" periods also require the use of summer time for full curriculum coverage. Against this background the following question seems appropriate: "Is it time for some innovation in undergraduate engineering education?" We say "Yes!"

The reality today is that changes in educating students in the post-covid-19 era have introduced possibilities for innovation in engineering education—and the following three areas are ripe for innovation:

1. reduction of on-campus time to earn a bachelor's degree in engineering,
2. reduction of the net cost to earn this degree, and
3. inclusion of a significant amount of experiential coursework in the curriculum to better prepare graduates for the workforce.

Creating an additional educational pathway that accomplishes these things represents a significant deviation from the traditional curricula in place today. What we propose is intended to *complement* the traditional research-active curriculum, not supplant it, and would still be consistent with accreditation (ABET) requirements.

We believe that the second pathway not only is possible but also would be beneficial and therefore of interest to a significant fraction of undergraduate students. The following points summarize our thoughts on how the proposed approach would address the three areas above.

1. The freshman engineering curricula at all schools are more similar than different, essentially providing the tools—calculus, physics, chemistry, economics, and, for some majors, biology—to grasp the concepts central to engineering. Online teaching is appropriate for these subjects, its effectiveness is constantly improving, and, because of the pandemic, it has become pervasive. Why, then, can't these subjects be taught this way *while students also work as technicians*? Learn-

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ing some of these subjects online, on their own time, while working full-time will enable students to spend less time on campus to complete a degree program. After all, many technicians are hired straight out of high school; why not hire high school graduates who also are academically strong enough to go to college? Some of these students opt out of college for financial reasons that are unrelated to their ability to succeed academically. Those who work as technicians become "known quantities" as potential future coop interns for the companies that initially hired them.

2. A second benefit of this approach is that first-year students hired as technicians will be paid while working and taking their virtual courses. These earnings will help cover the cost of their tuition and course materials during on-campus time. Not only do these students benefit directly but the hiring companies have a larger pool of qualified potential employees to choose from, since it includes those who otherwise might not have gone to college because of financial concerns. Taking some courses virtually during work will further cut costs, since online courses cost less.
3. After students spend their first year working as technicians and taking classes virtually, they will be more attractive candidates as interns, positioning them to gain relevant work experience, learn what engineering work is like, and contribute in the workplace. And the companies will have an idea of how the interns would perform as full-time employees. This translates into higher retention numbers, which is good for both parties.

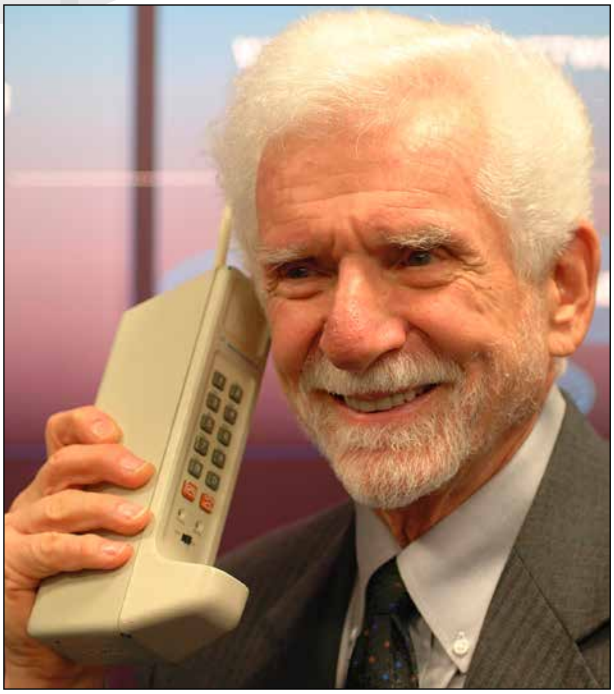
We have briefly described an alternate approach to undergraduate engineering education. Clearly the first year as technicians and virtual students would not be easy, but it is already true that a not insignificant fraction of highly qualified high school graduates who enroll in a traditional engineering program find it too challenging and transfer out of engineering in the second or third year. Those hopeful, capable students are thus lost to the engineering workforce. Such losses are not helpful to the country's technically intensive industrial sector.

Finally, we do not propose a complete transformation of engineering education to this new model. Rather, we suggest that this new pathway may be attractive to students who are interested in engineering because of its role in successful product-making companies.

This path will not be for everyone, but neither is the current, traditional path, especially those who enter college thinking that they will go on to graduate school. We believe a two-track system will create better opportunities and better outcomes for young folks who like the idea of engineering but have little basis for understanding it in any detail.

An Interview with . . .

Martin Cooper, "Father of the Cell Phone"



NAE member Martin Cooper is widely celebrated as the "father of the cell phone." He was an inaugural member of the Wireless Hall of Fame (2000) and is a recipient of the IEEE Centennial Medal (1984), the Marconi Prize (2013), and the NAE's Draper Prize (2013), among others.

In a special virtual event on February 3, 2021, he was interviewed by Guru Madhavan, Norman R. Augustine Senior Scholar and senior director of NAE programs. An edited version of the conversation follows.

GURU MADHAVAN (GM): It's an honor to share this virtual stage with the wizard of the wireless, Marty Cooper. Living through the coronavirus pandemic, thanks to Marty's invention we find connectivity and meaning. I am tempted to compare Marty's work, which has in a large part enabled the information revolution, to that of James Watt, whose engines powered the Industrial Revolution.

We are really honored to have you with us, Marty. Let's start briefly with why and how you became an engineer.

MARTY COOPER: From my earliest memories, I knew I was going to be an engineer. As a child, whenever I saw a gadget, say an alarm clock, I took it apart—and of course was unsuccessful in putting it back together. But you can't win everything. Even today I take things apart, and my track record has improved since the alarm clock!

I went to a technical high school where every semester they had me assigned to a different shop—wood shop, print shop, forge, foundry.... Having that practical experience turned out to be invaluable in my career.

GM: I enjoyed reading the advance copy of your recently published memoir, *Cutting the Cord: The Cell Phone Has Transformed Humanity* (Rosetta Books). There's treasured history in it but there's also philosophy, commerce, economics, and globalization. You're tackling at least 10 or 15 different threads about the "brick" you originally invented. Could you take us through some historical aspects of the wireless communications industry, and touch on what was the thinking behind the engineering of mobility and portability as chief design attributes?

MR. COOPER: The essence of the creation of a portable phone was stimulated by the Bell System. Claude Shannon established the basis of data transmission and Bell Labs proposed a system where communications among large numbers of people could be achieved with a limited amount of radio spectrum without the hindrance of the copper wire. It was an excellent idea. The flaw in their proposal was that their solution was the car telephone as an extension to the wired network. We had been trapped in our homes or our offices by that copper wire, and we're now going to be trapped in our cars? That didn't make any sense to us at Motorola because we had already observed in our portable two-way radio business that a true portable device gives people the freedom to communicate everywhere, not just when they're in a car. That freedom ended up being extraordinarily valuable. It allowed people to collaborate. And that understanding drove Motorola to take on Bell, the biggest company in the world by every measure at the time.

Marty Cooper holds up an exact model of the original cell phone.

The Bell System, of course, was proposing that the wireless approach be a monopoly. They wanted to be the only provider. Had they prevailed, they would have built a system that would work for car telephones but *not* handheld phones. Their study even predicted that the worldwide demand would be a million car telephones. Fortunately, they did not prevail.

Motorola spent $100 million—which for a company of Motorola's size was a ton of money—fighting the Bell System. And that was the genesis of the portable telephone vision. I decided that the only way we were going to really persuade people that this was the right way to go was to show them what a real portable phone looked like and let them hold it in their hands. I have one here. This is an exact model of the original phone. You can see it wasn't exactly small.

The model that we built in 1973 was huge by modern standards, but it was "handheld." And then, because in those primitive times there were no large-scale integrated circuits, the engineers had to put about a thousand parts into it. And all one could do was talk—the internet, the computer, and the digital camera did not exist. The phone ended up weighing about a kilo, 2½ pounds. A battery life for 25 minutes of talking was not a problem since holding up 2½ pounds for 25 minutes is not a very easy thing to do. That was the genesis of the portable phone.

Fortunately, the FCC made the right decisions. The United States ended up with a competitive industry, and from the beginning, cell systems were built to accommodate portables. Today, most of the people in the world use portable phones.

GM: One can imagine an individual lifting 2000 pounds and ending up in the *Guinness Book of World Records*, but you did so with your 2½-pound prototype.

These days, a phone is more than a phone. How do you look at the transformation into a smartphone culture, not merely as an engineer who laid the foundation for this work but also as a consumer yourself?

MR. COOPER: Well, the flaw in the Bell System thinking was to think that this was a phone. They had a vision of this thing as an extension of what they'd been doing for 100 years since Alexander Graham Bell. They didn't realize the broader potential. The traditional landline phone was a device that people used to talk from one place to another. The portable phone was an entirely different concept allowing person-to-person communications. People had the freedom to be truly mobile. People are naturally mobile. The telephone wire was a constraint, and eliminating that constraint required portability.

But calling this a phone and using the word "cell" is a misfit—clearly a bunch of techies came up with that name, not marketing people. The Germans and Japanese and other countries have it right. In Japan and in Germany, they call this the "handy," which is a lot more appropriate than a "cell" phone.

GM: I was born in India. There's been so much written about how cell phones have transformed the economy of the subcontinent and many other emerging nations. Even the concept of nations "leapfrogging" has been made possible by your work, more than any other technology that I'm familiar with. How do you process this extraordinary growth?

MR. COOPER: Well, first, we could never have anticipated the idea of putting a supercomputer in a handheld device, because there weren't even large-scale integrated circuits then. But it didn't take a genius to figure out that when we gave people—whether they were police officers or airline people—when we gave them this portable, they could manage their resources better. They were more efficient. And once they had this device, they couldn't run their businesses without it.

A United Nations study showed that over a billion people moved out of severe poverty in the past 20 years or so, mostly because the cell phone provided them with the resources to improve their productivity. That makes me very proud.

GM: Let's talk about the day when you made the first cellular phone call.

MR. COOPER: Although that ended up being a historic moment, the only thing on my mind that day was Murphy's law.

It was a demonstration day. I was scheduled to be on a TV broadcast the morning of April 3rd, 1973, and we got bumped for some other development. So, our PR people set up an interview with a local radio station, and I said, "You know, if we're going to do that kind of interview, we're going to do it out on the streets, moving around so we can show the freedom that you get from a portable."

I met with this reporter outside the Hilton on 6th Avenue in New York. At that moment I wondered who I should call for the demo. And I reached in my back pocket and pulled out my phone book (as we did in the ancient, primitive times) and I looked up the number for Joel Engel, who was my counterpart in developing cellular technology at AT&T. I called him and, miraculously, Joel himself directly answered. I said, "Hi, Joel. It's Marty Cooper. I'm calling you from a cell phone. A real cell phone. A personal, portable, handheld cell phone!" There was silence on the other end of the line. I think he got the message. To this day, Joel doesn't recall that phone call and I guess I don't blame him!

Marty Cooper demonstrating the new portable phone on 6th Avenue in New York, April 3, 1973.

GM: Can you talk about the Motorola culture and leadership during that time?

MR. COOPER: Joining Motorola in 1954, after I got out of the Navy, was the luckiest thing in my life. Motorola's founder, Paul Galvin, left a strong culture. His statement I have lived by is "Do not fear failure. Reach out." Sure enough, I had my share of failures. His son Bob Galvin carried on that message and tolerated me! I didn't fit into the standard corporate pattern, but I must have had compensatory attributes.

The most important thing I learned at Motorola was the idea of objectivity—removing your personality, your desires, from decision making and looking at things dispassionately. That's the hardest thing for people to do. It's so easy for an engineer to fall in love with something that he or she created and forget about the fact that the technology must make people's lives better.

Without the *people* part, technology is just a curiosity. It doesn't mean anything. People are what it's all about.

GM: Let's talk about the infrastructure around the phone, specifically the myth of spectrum scarcity.

MR. COOPER: When Marconi made his first radio transmissions, which were point-to-point transmissions around 1900, there was essentially one radio channel. And the capacity on that radio channel—I hope you find this amusing—was one bit every 6 seconds. We now flip literally billions of bits per second, and we have tens of thousands of radio channels. And we repeat that capacity geographically.

The interesting observation is that anytime anybody has come up with a new idea—broadcast radio, two-way radio, television, satellites, Wi-Fi—there's always been enough spectrum. So how could you have a myth that spectrum is like beach prime property? that once you use it up, it's gone?

> *It's easy for engineers to fall in love with something they created and forget that the technology must make people's lives better.*

We have managed with technology to increase the capacity. My observation, what's informally called "Cooper's law," is that we have doubled the capacity of the radio spectrum for communications every 30 months or so for over a century. For the first 50 years, we increased the capacity a million times. You carry that on for another 50 years and it's a trillion times. And it turns out all of that is done by technology. And we can see how we can do this for at least another 50 years. So how could anybody say that there is a limit to the capacity of the spectrum? And yet that is the basis of how the FCC allocates spectrum today. We've got to fix that.

GM: Marty, I now wish to turn our attention to your wife and fellow engineer, Arlene Harris, to explore her thoughts on simplicity and complexity in smart phones.

ARLENE HARRIS: Well, the beginning of my work on simplifying technology, some 20 or so years ago, came because the user experience that cell phones and computers delivered was beginning to overwhelm their users. The more options we have, the more tools we have, the more we have that can become unintegrated. The idea of a simple technology that can be used intuitively continues to escape the people who design products.

In the creation of a simple interface or a simple service, the issue is to eliminate the unnecessary. That's what makes people's lives better. And if you can start with that notion and create a platform for that, we are in much better shape. Otherwise, every year, it will be tougher and tougher for new technologies to be adopted. Cell phone development has focused on the attributes *smaller, lighter, faster*. We need to focus on simplicity, on customizing, personalizing, and reducing friction.

MR. COOPER: Arlene expresses these things very well. The essence of her genius is she has observational abilities that are amazing and troublesome at times, because she could look at anything and instantly find the flaws. She looks around at the world and sees a whole bunch of opportunities to fix things. Occasionally it applies to me, which I don't care for very much, but when it comes to a technology, she is wonderful.

GM: Thank you, Arlene. Marty, let's conclude by talking about your book. Anyone preparing a memoir must invariably engage in the act of reflection, reappraisal, and revision. As you wrote this book, what did you learn that possibly surprised you or led to a revised understanding of yourself?

MR. COOPER: Reflecting on Marty Cooper as a person, I am so different than I was 50 years ago, and 20 years ago, and 10 years ago. I have an open mind. Everybody that I talk to, it doesn't matter whether I like the person or not, has something to teach me. The essence of my life is learning and thinking, having an idea that at least for me is original. These ideas have almost always been thought of by other people, but the thrill of my life is to come up with a new way of looking at something and thinking about it differently. In that regard, I'm like a sponge. I love to learn new things.

GM: Thank you, Marty for this insight, and importantly, for your book. It was our honor to talk with you.

NAE News and Notes

Class of 2021 Elected

The NAE has elected 106 new members and 23 international members. This brings the total US membership to 2355 and the number of international members to 298.

Election to the National Academy of Engineering is among the highest professional distinctions accorded an engineer. Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature" and to "the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education." Election of new NAE members is the culmination of a yearlong process. The ballot is set in December and the final vote for membership occurs during January.

Individuals in the newly elected class will be formally inducted during the NAE's annual meeting on October 3, 2021. A list of the new members and international members follows, with their primary affiliations at the time of election and a brief statement of their principal engineering accomplishments.

New Members

Russell Allgor, chief scientist, Worldwide Operations and Amazon Logistics, Amazon, Bellevue, WA. For application of operations engineering to design and improve logistics and fulfillment systems for e-commerce.

Barry Arkles, chair and CEO, Gelest Inc., Morrisville, PA. For contributions to organosilicon materials and organometallic and biochemical reagents.

James R. Arnold, principal, Taproot Construction LLC, Fort Mill, SC. For commercial application of processes for gold and silver recovery and implementation of advanced environmental controls.

John G. Aunins, senior advisor, Bioprocess and Manufacturing, Seres Therapeutics Inc., Cambridge, MA. For advances in bioprocess engineering, the introduction of new vaccines, and development of microbiome-based products.

Santokh S. Badesha, corporate fellow and manager of open innovation, Xerox Corp., Webster, NY. For developing materials enabling the broad use of laser printing and the creation of color laser printing.

James L. Barnard, global practice and technology leader, Black & Veatch, Kansas City, MO. For the development and implementation of biological nutrient removal in water treatment.

Luiz André Barroso, vice president, Core Systems, Google Inc., Mountain View, CA. For contributions to the architecture, design, and performance of energy-efficient warehouse-scale computing.

James G. Bellingham, director, Consortium for Marine Robotics, Woods Hole Oceanographic Institute, Woods Hole, MA. For design, development, and deployment of autonomous underwater vehicles to advance understanding of the ocean and its resources.

David Bem, chief technology officer and vice president of science and technology, PPG Industries, Pittsburgh. For business leadership and a sustained record of materials discovery to commercialization.

Christopher N. Bowman, James and Catherine Patten Chair, Department of Chemical and Biological Engineering, University of Colorado Boulder. For development of photopolymerization reactions for adaptable polymer networks and their innovative applications.

Julia J. Brown, senior vice president and chief technical officer, Universal Display Corp., Ewing, NJ. For contributions to materials and device technologies for phosphorescent light emitting diode displays, and their commercialization.

Christopher B. Burke, chief executive officer, Christopher B. Burke Engineering Ltd., Rosemont, IL. For leadership in executing complex water resources projects and service to the engineering community.

Carlos A. Cabrera, executive chair, board of directors, Genomatica Inc., Northbrook, IL. For leadership in developing and commercializing widely adopted processes for fuels and intermediate chemicals.

Zoltan J. Cendes, adjunct professor, electrical and computer engineering, Carnegie Mellon University, Naples, FL. For contributions to theory, development, and commercialization of electromagnetics simulation software.

Sebastian Ceria, chief executive officer, Qontigo, New York City. For application of optimization tools to advance integer programming and financial engineering.

Lili Cheng, corporate vice president, Conversation AI, Microsoft Corp., Bellevue, WA. For scientific and industrial leadership in user interface design, social computing, and computing education.

J. Edward Colgate, Breed University Professor of Design, Mechanical Engineering, Northwestern University, Evanston, IL. For development of haptic interface technologies, including surface haptics for touchscreens.

Lance R. Collins, Joseph Silbert Dean of Engineering, College of Engineering, Cornell University, Ithaca, NY. For contributions to understanding turbulent processes, leadership in engineering, and contributions to the diversity of the profession.

Catherine Ford Corrigan, president and chief executive officer, Exponent Inc., Menlo Park, CA. For elucidation of injury mechanisms and mitigation, and leadership in biomechanical engineering and scientific consulting.

Erroll Brown Davis Jr., PBS and Union Pacific (retired), Atlanta. For leadership in research and development of renewable resources integration with the grid, and public education.

Peter J. Delfyett Jr., University Board of Trustee Chair Professor of Optics, ECE, and Physics, University of Central Florida, Orlando. For contributions to development and commercialization of low-noise, high-power ultrafast semiconductor lasers.

Jonathan S. Dordick, professor, Department of Chemical and Biological Engineering, Rensselaer Polytechnic Institute, Troy, NY. For contributions to methods for rapidly screening drug efficacy and toxicity, and biocatalytic technologies for improving human health.

Francis J. Doyle III, John A. and Elizabeth S. Armstrong Professor and dean, Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA. For insights into natural biological control systems and innovative engineering of diabetes control devices.

Frederick Dryer, Educational Foundation Distinguished Research Professor, Mechanical Engineering, University of South Carolina, Columbia. For contributions to understanding of combustion processes for propulsion and transportation applications and for fire safety.

William T. Freeman, principal scientist, Google Inc., Cambridge, MA. For contributions to computer vision and image enhancement.

Andrés José García, Regents' Professor, Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta. For contributions to molecular engineering of biomaterial surfaces and cell adhesion force technology to characterize stem and cancer cells.

Gary J. Goldberg, director, board of directors, BHP Group Limited, Castle Pines, CO. For promoting safety, sustainability, inclusion, value, ethics, and responsibility in the mining industry.

Charles N. Haas, LD Betz Professor of Environmental Engineering and department head, Civil, Architectural, and Environmental Engineering, Drexel University, Philadelphia. For contributions to quantitative microbial risk assessment for drinking water quality and public health.

Craig Hawker, director, California Nanosystems Institute, and director, Dow Materials Institute, Materials Engineering, University of California, Santa Barbara. For contributions to polymer chemistry through synthetic organic chemistry concepts and the advancement of molecular engineering principles.

Wayne W. "Nick" Hazen, president and CEO, Hazen Research Inc., Golden, CO. For leadership in the commercial development of hydrometallurgical processes for recovering metals from ores.

Mary Catherine Hill, professor, Department of Geology, University of Kansas, Lawrence. For contributions to development and application of methods for parameter estimation and sensitivity analysis in hydrologic models.

William Walter Hogan, Raymond Plank Research Professor of Global Energy Policy, Harvard Kennedy School, Harvard University, Cambridge, MA. For contributions to electricity industry restructuring, electricity market design, and energy policy modeling and analysis.

Jonathan Patrick How, Richard Cockburn Maclaurin Professor, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge. For contributions to decision making and control of intelligent autonomous aerospace vehicles.

Hao Huang, technology chief (retired), General Electric Aviation, Dayton, OH. For contributions to advances in electric machines and power electronics technologies for aerospace electrical systems.

Patricia Nell Hurter, chief executive officer and president, Lyndra Therapeutics, Watertown, MA. For leadership in formulation technologies, amorphous dispersions, and continuous processing for hepatitis C and cystic fibrosis treatments.

Marija D. Ilic, senior research scientist, Laboratory for Information and Decision Systems, Massachusetts Institute of Technology, Cambridge. For contributions to electric power system analysis and control.

Donald Elliott Ingber, director, Wyss Institute for Biologically Inspired Engineering; and professor, Paulson School of Engineering and Applied Sciences, Harvard University, Boston. For interdisciplinary contributions to mechanobiology and microsystems engineering, and leadership in biologically inspired engineering.

Kathryn J. Jackson, director, Energy and Technology Consulting, KeySource, Sewickley, PA. For contributions to management of large-scale power system technology, and harmonization of engineering solutions with public policy.

Christopher Tyler Jones, chief of operations, The Leadership Compass, Herndon, VA. For leadership of defense logistics, sustainment, training, and system readiness in support of US national security.

Zakya H. Kafafi, adjunct professor and distinguished research fellow, Center for Photonics and Nanoelectronics, Lehigh University, Bethlehem, PA. For contributions to materials technologies for organic optoelectronics.

David Kaplan, Stern Family Professor in Engineering and Distinguished University Professor, Department of Biomedical Engineering, Tufts University, Medford, MA. For contributions to silk-based materials for tissue engineering and regenerative medicine.

Terri L. Kelly, director, United Rentals, Wilmington, DE. For leadership in product development and commercialization by advancing management practices that foster innovation.

Thomas F. Kelly, founder and CEO, Steam Instruments, Madison, WI. For design and commercialization of the local electrode atom probe to yield 3D atomic-scale analysis of materials.

Anne S. Kiremidjian, professor, Department of Civil and Environmental Engineering, Stanford University, Stanford, CA. For research and dissemination of probabilistic seismic hazard methods and mentoring.

Witold F. Krajewski, Rose and Joseph Summers Chair in Water Resources Engineering, Department of Civil and Environmental Engineering, University of Iowa, Iowa City. For advances in flood prediction and mitigation.

Roger A. Krone, chair and chief executive officer, Leidos Inc., Reston, VA. For technical leadership in industry engineering and advances in aerospace and information technology programs.

Rajiv Laroia, cofounder and CTO, Light, Far Hills, NJ. For contributions to adaptive multi-user orthogonal frequency division multiplexing for cellular voice and data systems.

Shelley K. Lavender, senior vice president, Strike, Surveillance, and Mobility, Boeing Defense, Space, and Security, Program Management, The Boeing Co., St. Louis. For contributions to technological advances of military aircraft platforms and systems.

B. Gentry Lee, chief engineer for solar system exploration, Jet Propulsion Laboratory, California Institute of Technology, Pasadena. For contributions to 20 planetary exploration missions to Mars, Jupiter, asteroids, and comets.

Claire Leon, director, Graduate Systems Engineering, Loyola Marymount University, Rancho Palos Verdes, CA. For technical and engineering management of national security space systems.

Frances E. Lockwood, chief technology officer, research & development, Valvoline (retired), Lexington, KY. For contributions and leadership in the development of sustainable lubricants in automotive and industrial applications.

Azad M. Madni, founder and CEO, Intelligent Systems Technology Inc., Los Angeles. For advances in low-cost simulation-based training using interdisciplinary model-based approaches.

William D. Magwood IV, secretary general, Nuclear Energy Agency, Organization for Economic Cooperation and Development, Paris. For leadership and contributions to research programs that drive innovation in global nuclear energy enterprises.

Hani S. Mahmassani, William A. Patterson Distinguished Chair in Transportation, and director, Transportation Center, Civil and Environmental Engineering, Northwestern University, Evanston, IL. For contributions to modeling of intelligent transportation networks and to interdisciplinary collaboration in transportation engineering.

Josh Makower, general partner, New Enterprise Associates, Los Altos Hills, CA. For inventing balloon sinuplasty, and for leading the commercialization of this and multiple other innovations.

James O. Malley, group director and senior principal, Structural

Engineering, Degenkolb Engineers, San Francisco. For leadership in improving seismic design.

Louis A. Martin-Vega, professor and dean, College of Engineering, North Carolina State University, Raleigh. For support of engineering and engineering education through industry-academic collaboration and opportunities for underrepresented groups.

Margaret R. Martonosi, Hugh Trumbull Adams '35 Professor, Department of Computer Science, Princeton University, Princeton, NJ. For contributions to power-aware and power-efficient computer architectures and mobile systems.

Marcia Kemper McNutt, president, National Academy of Sciences, Washington. For elucidation of lithosphere geomechanics and leadership in earth resources engineering.

Pamela A. Melroy, chief executive officer, Melroy & Hollett Technology Partners, Arlington, VA. For contributions to human space flight, space access, space situation awareness, and military aeronautics systems.

Danielle W. Merfeld, vice president and chief technology officer, GE Renewable Energy, General Electric Co., Charlotte, NC. For leadership and development of products for large wind turbines and solar photovoltaic systems.

Julie B. Miller, senior fellow, Technology Office, Lockheed Martin, Sunnyvale, CA. For contributions to space electronic communication systems and system of system designs.

Sumita B. Mitra, founder and partner, Mitra Chemical Consulting LLC, St. Pete Beach, FL. For designing and engineering nanomaterials that have revolutionized dental care worldwide.

Michael C. Mountz, principal, Kacchip LLC, Lincoln, MA. For advancing industrial mobile robotic material handling systems for order fulfillment.

Julio A. Navarro, senior technical fellow, Boeing Research and Technology, The Boeing Co., Renton, WA. For development and implementation of phased array sensors and communication systems for aerospace applications.

Oyekunle Olukotun, professor of electrical engineering and computer science, Stanford University, Stanford, CA. For contributions to on-chip multiprocessor architectures and advancement to commercial realization.

Mari Ostendorf, professor, Department of Electrical and Computer Engineering, University of Washington, Seattle. For contributions to statistical and prosodic models for speech and natural language processing and for advances in conversational dialogue systems.

Maria Palasis, president and CEO, Lyra Therapeutics, Watertown, MA. For outstanding contributions to the design of medical devices and drug delivery systems.

Jong-Shi Pang, Epstein Family Chair of Industrial and Systems Engineering, Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles. For the development of methods to advance the theory and applications of optimization and operations research.

Mario Paniccia, CEO, Anello Photonics, Santa Clara, CA. For contributions to integrated silicon photonic devices and their commercialization.

Glaucio H. Paulino, Raymond Allen Jones Chair and professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta. For contributions to topology optimization and its applications to medicine and engineering.

Fernando C.N. Pereira, vice president and engineering fellow, Google Inc., Palo Alto, CA. For contributions to speech, natural language, and machine learning.

David J. Perreault, Joseph F. and Nancy P. Keithley Professor of Electrical Engineering, Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge. For contributions to power electronics technology and design techniques for very high frequency energy conversion.

Mark T. Peters, laboratory director, Idaho National Laboratory, and president, Battelle Energy Alliance LLC, Idaho Falls. For leadership and contributions in advancing US nuclear energy capabilities and infrastructure.

Joseph B. Powell, chief scientist – chemical engineering (retired), Chemicals and New Energies Technology, Shell International Exploration and Production Inc., Houston. For contributions to process developments in energy, chemicals, and biofuels technologies.

Laura J. Pyrak-Nolte, distinguished professor, Department of Physics and Astronomy, Purdue University, West Lafayette, IN. For advances in understanding of the processes that link the mechanical, hydraulic, and seismic properties in discontinuities.

William J. Radasky, president and managing engineer, Metatech Corp., Goleta, CA. For leadership in the development and application of electromagnetic transient disturbance and protection standards for national security and commercial systems.

Theodore S. Rappaport, David Lee/Ernst Weber Chaired Professor, Electrical and Computer Engineering, Tandon School of Engineering, New York University, Brooklyn. For contributions to the characterization of radio frequency propagation in millimeter wave bands for cellular communication networks.

Lutgarde Raskin, Altarum/ERM Russell O'Neal Professor of Engineering, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor. For application of genetic tools to improve anaerobic biological water treatment.

Peter Bernard Roemer, GE Healthcare (retired), Tampa, FL. For contributions to performance improvement and widespread availability of MRI technology.

Jeanne M. Rosario, former vice president and general manager, Engineering Division, General Electric Aviation, Lexington, SC. For leadership in advancing aircraft engine design, global engineering, and support for women in engineering.

Krishan K. Sabnani, research VP emeritus and ambassador-at-large (retired), Bell Labs/Nokia, Westfield, NJ. For contributions to software-defined routing and networks.

Kamal Sarabandi, Rufus S. Teesdale Professor of Electrical Engineering, Electrical Engineering and Computer Science, University of Michigan, Ann Arbor. For contributions to the science and technology of radar remote sensing.

Mark Peter Sarkisian, partner, Structural and Seismic Engineering, Skidmore Owings and Merrill LLP, San Francisco. For innovation in efficient and aesthetic design of tall buildings and structures.

Rachel A. Segalman, department chair and Edward Noble Kramer Professor, Department of Chemical Engineering, University of California, Santa Barbara. For contributions to semiconducting block polymers, polymeric ionic liquids, and hybrid thermoelectric materials.

J. Marshall Shepherd, Georgia Athletic Association Distinguished Professor, and director, Atmospheric Sciences Program, Department of Geography, University of Georgia, Athens. For development of methods to understand the Earth's hydrometeorological and hydroclimate system, and for climate science public communication and outreach.

John B. Simpson, staff cardiologist, Cardiology, Sequoia Hospital, Woodside, CA. For contributions to coronary angioplasty and atherectomy, and their widespread application.

Winston Oluwole Soboyejo, senior vice president and provost, Worcester Polytechnic Institute, Northborough, MA. For contributions to understanding dynamic behavior of materials and for leadership in STEM outreach in Africa.

Sidlgata (S.V.) Sreenivasan, Joe C. Walter Endowed Chair in Engineering, Walker Department of Mechanical Engineering, University of Texas, Austin. For research, innovation, and entrepreneurship in industrial deployment of nanoimprint lithography equipment.

Kathleen J. Stebe, Goodwin Professor of Applied Sciences and Engineering, Department of Chemical and Biomolecular Engineering, University of Pennsylvania, Philadelphia. For contributions to understanding of nonequilibrium processes at soft matter interfaces and its impact on new technologies.

Yu-Chong Tai, Anna L. Rosen Professor of Electrical Engineering and Medical Engineering, Department of Medical Engineering, California Institute of Technology, Pasadena. For contributions to microelectromechanical system technologies and parylene-based biomedical microdevices.

Juming Tang, Regents Professor and Distinguished Chair of Food Engineering, Department of Biological Systems Engineering, Washington State University, Pullman. For invention and commercialization of electromagnetic spectrum wave–based food processes.

Jefferson W. Tester, Croll Professor of Sustainable Energy Systems, School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY. For leadership in development of novel renewable energy systems.

Michael Makepeace Thackeray, distinguished fellow and senior scientist, Energy Storage Department, Chemical Science and Engineering Department, Argonne National Laboratory, IL. For invention of cathode materials that dominate in Li-ion batteries for electric vehicles and grid storage.

Levi Theodore Thompson, dean, College of Engineering, and Elizabeth Inez Kelley Professor, Department of Chemical and Biomolecular Engineering, University of Delaware, Newark. For advances in catalysis and energy storage, entrepreneurship, and academic leadership.

Arthur J. Tipton, founder and CEO, Vulcan Gray, Birmingham, AL. For the development and commercialization of drug delivery systems, business leadership, and fostering STEM education of disadvantaged students.

Nikhil C. Trivedi, senior partner, Idekin International, Easton, PA. For development of minerals processing technologies and mineral products for the paper, polymer, and building industries.

Hongtei Eric Tseng, senior technical leader, Ford Research and Innovation Center, Ford Motor Co., Dearborn, MI. For contributions to control systems for enhancing vehicle safety.

Vickie A. VanZandt, president, VanZandt Electric Transmission Consulting Inc., Battle Ground, WA. For contributions to advanced transmission, protection, and wide area monitoring systems.

Yurii A. Vlasov, GEBI Founder Professor of Engineering, Department of Electrical and Computer Engineering, University of Illinois, Urbana-Champaign. For contributions to development and commercialization of silicon photonics for optical data communications.

Cindy L. Wallis-Lage, executive director and president, Water Business, Black & Veatch, Kansas City, MO. For applying innovative technology to complex large-scale water infrastructure systems.

Christopher J. Wiernicki, chair, president, and CEO, ABS Group of Companies, Spring, TX. For innovations in the design, engineering, and operation of ships and offshore structures.

Donald R. Wilton, professor emeritus, Department of Electrical and Computer Engineering, University of Houston. For contributions to computational electromagnetics of highly complex structures.

Murty V. Yalla, president, Management, Beckwith Electric Co. Inc., Largo, FL. For contributions to digital protection and control devices for the grid.

Jackie Y. Ying, executive director, Institute of Bioengineering and Nanotechnology, Singapore. For contributions at the interface of nanostructured materials, nanomedicine, and diagnostic devices to improve human health.

Matthew J. Zaluzec, director and senior technical advisor (retired), Global Materials and Manufacturing Research, Ford Motor Co., The Villages, FL. For innovation of lightweight materials and manufacturing technologies to improve automotive fuel economy and safety and reduce the carbon footprint.

New International Members

Takuzo Aida, professor, Department of Chemistry and Biotechnology, University of Tokyo, Japan. For contributions to the engineering of smart and adaptive molecular materials using physical perturbation of multivalent interactions.

AbdulHameed AlHashem, principal research scientist, Petroleum Research Center, Kuwait Institute for Scientific Research (KISR), Salmiya. For research in support of improved materials for the energy sector, and establishment of atmospheric corrosion maps for Kuwait.

Paula Alves, CEO, Instituto de Biologia Experimental e Tecnológica (iBET), Oeiras, Portugal. For leadership in biomanufacturing, advanced biotherapeutics, and bridging the gap between academia and industry.

Giuseppe Bellussi, senior vice president (retired), Development, Operations and Technology Division, Eni S.p.A, Piacenza, Italy. For development and commercialization of environmentally beneficial chemical processes.

Peter Fratzl, director, Department of Biomaterials, Max Planck Institute of Colloids and Interfaces, Potsdam, Germany. For studies of structure and physical properties of biological materials and their application in materials science and medicine.

Xiaobing Fu, professor and director, College of Life Sciences, General Hospital of PLA, Beijing, China. For achievements in elucidating wound healing mechanisms and sweat gland regeneration, and national leadership in clinical management of trauma.

Luis Enrique García, professor, Civil Engineering, Universidad de los Andes, Colombia. For contributions to the earthquake-resistant design, construction, and building code development of concrete structures.

Elisabeth Guazzelli, distinguished senior researcher, Matière et Systèmes Complexes, Centre National de la Recherche Scientifique (CNRS), Paris, France. For experiments and theory that enhance understanding of dispersed particulate systems.

Sudhir K. Jain, director, Indian Institute of Technology, Gandhinagar, Gujarat. For leadership in earthquake engineering in developing countries.

Jyeshtharaj Bhalchandra Joshi, Emeritus Professor of Eminence, University Institute of Chemical Technology (UICT), Mumbai, India. For contributions in rational design of multiphase chemical process equipment and leadership in shaping the Indian chemical industry.

Johann W. Kolar, professor, Information Technology and Electrical Engineering, ETH Zürich (Swiss Federal Institute of Technology), Switzerland. For contributions to power-electronic technologies, multiobjective design optimization, education, and technology transfer to industry.

Khaled Ben Letaief, New Bright Professor, Electrical and Computer Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon. For contributions to adaptive resource allocation in multiuser orthogonal frequency-division multiplexing wireless systems and for academic leadership.

Yoelle Maarek, vice president of research, Alexa Shopping, Amazon, Haifa, Israel. For contributions to online information retrieval and data management, and leadership in applied industrial research.

Mario Veiga Ferraz Pereira, president and chief innovation officer, PSR Energy Consulting and Analytics, Rio de Janeiro, Brazil. For contributions to methodology and implementation of multistage stochastic optimization in hydroelectric scheduling, energy planning, and policy.

Barbara Sherwood Lollar, professor, Earth Sciences, University of Toronto, Canada. For contributions to understanding of the evolution of Earth's groundwater and atmosphere.

Pierre Suquet, distinguished senior scientist, Laboratoire de mécanique et d'acoustique, Centre National de la Recherche Scientifique (CNRS), Paris, France. For contributions to the mechanics of nonlinear behavior of heterogeneous viscoplastic solids.

Christofer Toumazou, Winston Wong Chair, Biomedical Circuits, Department of Electrical and Electronic Engineering, Imperial College London, United Kingdom. For innovations in electronics for medicine, including rapid diagnostics.

Alejandro López Valdivieso, profesor investigador, Area de Ingeniería de Minerales, Universidad Autónoma de San Luis Potosí, Mexico. For contributions to the processing of complex sulfide ores and educational leadership.

Marinus Aart Van den Brink, president and chief technology officer, ASML, Veldhoven, Netherlands. For driving advances in optical and extreme ultraviolet lithography that enable smaller, faster, and more energy-efficient semiconductor devices.

Luc Van den hove, president and CEO, Interuniversity Microelectronics Center (IMEC), Leuven, Belgium. For leadership in major international industry-university collaborations for the semiconductor industry.

Yangsheng Xu, president, Chinese University of Hong Kong, Shenzhen, Guangdong, China. For contributions in space robotics and autonomous systems.

Wanming Zhai, dean of faculty, Transportation Engineering, Southwest Jiaotong University, Chengdu, China. For contributions to the design and operation of high-speed rail transportation networks.

Xiaoxin Zhou, honorary president, China Electric Power Research Institute (CEPRI), Beijing. For contributions to the development and implementation of power systems technology in China.

NAE Newsmakers

Frances H. Arnold, Linus Pauling Professor of Chemical Engineering, Bioengineering, and Biochemistry, California Institute of Technology, has been appointed by President Biden to **cochair the President's Council of Advisors on Science and Technology** with NAS member Maria Zuber, vice president of research and E.A. Griswold Professor of Geophysics at MIT.

Peter J. Basser, senior investigator, Section on Quantitative Imaging & Tissue Sciences, National Institutes of Health, is one of two recipients of the **2021 Eduard Rhein Stiftung Technology Awards**. The award is being conferred "for the development of MRI diffusion tensor imaging, which is used for surgery and radiation planning, for research into neurological diseases associated with white matter changes, and for reconstruction of neural pathways in the brain (tractography)."

The Optical Society (OSA), the leading global professional association in optics and photonics, has announced that the **2021 Frederic Ives Medal/Jarus W. Quinn Prize** will be presented to **Federico Capasso**, Robert Wallace Professor of Applied Physics and Vinton Hayes Senior Research Fellow in Electrical Engineering, Harvard University. Professor Capasso is honored for seminal and wide-ranging contributions to optical physics, quantum electronics, and nanophotonics. The Frederic Ives Medal recognizes overall distinction in optics and is the OSA's highest award.

Joseph M. DeSimone, Sanjiv Sam Gambhir Professor in Translational Medicine and professor of chemical engineering, Department of Radiology and the Molecular Imaging Program, Stanford University, is the recipient of the **2019–2020 Harvey Prize** in science and technology. The Harvey Prize, the most prestigious prize awarded by the Technion–Israel Institute of Technology, is awarded each year for outstanding achievements in science and technology, human health, and significant contributions to humanity. Professor DeSimone is being recognized for his contributions to materials science, chemistry, polymer science and technology, nanomedicine, and 3D printing; prize administrators said his work is "a model for combining basic scientific discoveries with developments of industrial technologies that have a significant influence."

Amit Goyal, director of RENEW Institute, SUNY Distinguished Professor, and SUNY Empire Innovation Professor, University of Buffalo, has been elected a **fellow of IEEE**, recognized for "contributions to high-temperature superconducting materials."

Erich P. Ippen, Elihu Thomson Professor of Electrical Engineering Emeritus and emeritus professor of physics, Massachusetts Institute of Technology, has been named an **honorary member of the Optical Society of America** (OSA). Honorary membership, the most distinguished of the OSA member categories, is for individuals who have made seminal contributions to the field of optics. Professor Ippen is recognized "for laying the foundations of ultrafast science and engineering, as well as providing inspiring leadership to the optics community."

At the 2020 annual meeting of the Controlled Release Society, Samyang Biopharm USA Inc. announced the establishment of the **Samyang CRS Award in Honor of Sung Wan Kim**; the Distinguished Professor of Pharmaceutics and Pharmaceutical Chemistry and Bioengineering, University of Utah, died February 24, 2020. The award will be presented annually to a midcareer scientist in biomedical research who shows signs of becoming a leader in drug discovery, has made significant scientific contributions to their area of research, and embodies the scientific discipline and rigor of Professor Kim. The inaugural award will be presented at the Controlled Release Society's 2021 annual meeting.

David C. Larbalestier, Francis Eppes Professor, Applied Superconductivity Center, National High Magnetic Field Laboratory and Department of Mechanical Engineering, Florida State University, was elected a **fellow of the Royal Academy of Engineering**, cited for his "seminal work in high current, high field superconducting materials for over 50 years."

Cato T. Laurencin, University Professor; Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering; professor of materials science and engineering; director, The Raymond and Beverly Sackler Center for Biomedical Biological, Physical and Engineering Sciences; and CEO, The Connecticut Convergence Institute for Translation in Regenerative Engineering, University of Connecticut, was named the **2021 Kappa Delta Ann Doner Vaughn Award** recipient. The Kappa Delta Awards recognize research in musculoskeletal disease and injury. Dr. Laurencin was chosen for his 30 years of scientific research in musculoskeletal regenerative engineering, the field he founded and brought to the forefront of translational medicine.

Gareth H. McKinley, professor of teaching innovation, Department of Mechanical Engineering, Massachusetts Institute of Technology, was elected **a fellow of the Royal Society** in 2019.

Lelio H. Mejia, senior principal, Geosyntec Consultants, was selected for the **Ralph B. Peck Award** from the Geo-Institute of the American Society of Civil Engineers. He was recognized for international leadership in and contributions to the practice of geotechnical earthquake engineering, for the seismic evaluation and design of embankment dams and foundation systems, and for the refinement and calibration of analytical procedures through the examination of key case histories.

Henry Samueli, chair of the board, Broadcom Inc., is the recipient of the **2021 IEEE Founders Medal**, "For leadership in research, development, and commercialization of broadband communication and networking technology with global impact."

Molly M. Stevens, professor of biomedical materials and regenerative medicine, Imperial College London, has received the **FEBS/EMBO Women in Science Award** in recognition of her outstanding scientific achievements. This award of the Federation of European Biochemical Societies (FEBS) and European Molecular Biology Organisation (EMBO) annually recognizes outstanding scientific achievements of a female life scientist who has worked in Europe in the last 5 years. Recipients are also inspiring role models for future generations of scientists. Professor Stevens was selected for her innovative bioengineering approach that addresses problems in regenerative medicine and biosensing. The award will be presented at the 45th FEBS Congress in Ljubljana, Slovenia, July 5, where Professor Stevens will give a plenary lecture (possibly virtually).

On April 20, the DRI (Desert Research Institute) Foundation will present the **2021 DRI Nevada Medal** to **Kathryn D. Sullivan**, senior fellow, the Potomac Institute, during a special hour-long virtual program titled "Sea, Earth, and Sky: Celebrating the Spirit of Scientific Exploration, Discovery, and Innovation." Dr. Sullivan, Earth explorer and astronaut, is the first American woman to walk in space and the first woman to reach the deepest-known spot in Earth's oceans. The DRI Nevada Medal was established in 1988 to acknowledge outstanding achievement in science and engineering and is the highest scientific honor in the state.

Michael A. Sutton, Carolina Distinguished Professor Emeritus, University of South Carolina, has been awarded the Society of Engineering Science's **Engineering Science Medal**, "For pioneering contributions to experimental solid mechanics and materials characterization by inventing the digital image correlation (DIC) method to access full-field displacement and strain information on deforming bodies." The award highlights the increasing importance of DIC technology, which is now used in nearly every field of engineering.

Sheldon Weinbaum, CUNY Distinguished Professor of Biomedical and Mechanical Engineering Emeritus, City College of the City University of New York, was one of 12 recipients of the **2020 Presidential Award for Excellence in Science, Mathematics, and Engineering Mentoring** (PAESMEM). The awards are America's highest honor for mentors who work with underrepresented groups to develop fully the nation's human resources in STEM. In naming him a recipient the PAESMEM team stated that "Sheldon Weinbaum represents the most outstanding mentors America has to offer and serves as both a model and an inspiration to students and those entering the professional workforce."

Nikolay I. Zheludev, deputy director, Zepler Institute, University of Southampton, and codirector of the Photonics Institute, Nanyang Technological University, has been awarded the Singapore **President's Science Award**, one of the annual President's Science and Technology Awards bestowed on research scientists and engineers in Singapore. He shares the award with NTU colleagues Chong Yidong and Zhang Baile. The award recognizes their global leadership in and fundamental contributions to topological nanophotonics research, underpins the development of a new generation of light-based technologies.

The **2021 Queen Elizabeth Prize for Engineering** is shared by five NAE members: **Isamu Akasaki**, professor, Research Center for Nitride Semiconductors, Meijo University; **M. George Craford**, retired CTO, Lumileds Lighting; **Russell D. Dupuis**, Steve W. Chaddick Endowed Chair in Electro-Optics, Georgia Institute of Technology; **Nick Holonyak Jr.**, John Bardeen Chair Emeritus Professor of Electrical and Computer Engineering and Physics, University of Illinois; and **Shuji Nakamura**, CREE Distinguished Professor, Materials, University of California, Santa Barbara. The prize is given for the creation and commercialization of LED lighting, which forms the basis of all solid state lighting technology. The recipients are recognized not only for the global impact of LED and solid state lighting but also for the technology's tremendous contribution to reducing energy consumption and addressing climate change.

Jingsheng J. Cong, Distinguished Chancellor's Professor and director, Computer Science Department, University of California, Los Angeles; **Eleftherios (Terry) Papoutsakis**, Unidel Eugene DuPont Chair of Chemical and Biomolecular Engineering, University of Delaware; **George Varghese**, Chancellor's Professor, Computer Science Department, UCLA; and **Lihong Wang**, Bren Professor, Medical Engineering and Electrical Engineering, California Institute of Technology, have been named **fellows of the National Academy of Inventors** (NAI). According to the NAI, election as a fellow is the "highest professional distinction accorded to academic inventors who have demonstrated a prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and the welfare of society."

Message from NAE Vice President Corale L. Brierley

The past year was one of the most challenging in recent memory for many reasons; nevertheless, your increased support ensured that the vital work of the National Academy of Engineering did not slow down. In 2020 our members, friends, and partner organizations collectively contributed over $9.7 million in new cash, pledges, and planned gifts. I am so very grateful for the continued generosity shown by the NAE community.

The ongoing covid-19 pandemic illustrates the urgent need for engineering expertise that only the NAE can provide. President **John L. Anderson** noted in the 2019 *Annual Report*, "As a trusted source of advice, the NAE must also be dynamic and proactive to address complex and consequential issues." A healthy foundation of unrestricted support is essential to the NAE's ability to act both proactively and promptly whenever called upon by the nation.

During the exceptional year of 2020, philanthropic support—provided by members and friends—of the Charles M. Vest President's Opportunity Fund during the NAE's 50th Anniversary Campaign (2011–14) was instrumental in launching the NAE's multigenerational Call for Engineering Action on the Covid-19 Crisis. This unrestricted quasi-endowment, established in 2012, was created deliberately to seed new initiatives and support exploratory studies. Since its creation, the Vest Opportunity Fund has supported programs like EngineerGirl, public engagement activities, and core NAE mission funding.

More recently, the Committee on Racial Justice and Equity was made possible in part through unrestricted funds. In addition to building on the NAE's history of working for diversity and equity in the engineering profession, this presidential advisory committee will provide actionable recommendations to address racism, prejudice, and discrimination based on scientific evidence and engineering methods. We cannot predict when or what the next crisis will be, but we can ensure that the NAE is adequately resourced to respond.

In addition to launching timely and necessary initiatives, private support provides sustaining funding for established programs. Our EngineerGirl program introduces girls and young women to the countless learning experiences and career opportunities in engineering. In 2021 EngineerGirl will celebrate 20 years of bringing national attention to the possibilities that engineering represents to all people at any age, but particularly to women and girls. Your support also helps the NAE convene up-and-coming engineering leaders to facilitate cross-disciplinary collaboration through the Frontiers of Engineering (FOE) program. Over the past 27 years, the FOE program has forged a community of more than 4000 alumni who develop lifelong partnerships with each other and have access to online resources to further cultivate their engineering careers. These programs rely completely on private support to carry out their work. Their sustained success is a true testament to the generosity of the NAE community.

Onward

As we close the chapter on 2020 and look ahead to a new year—one hopefully filled with health, happiness, and prosperity—the NAE is prepared to continue its vital work with refreshed vision and drive. Unfortunately, the covid-19 pandemic is still all too much a part of our lives, and there is work to do in addressing and contributing solutions to societal problems related to racial injustice and inequity, as well as climate change.

We are able to continue our work *because of* your generosity as members, friends, and partners. You understand the importance of an authoritative voice to provide evidence-based advice and guidance on major challenges facing the nation and world, and you play a vital role in ensuring a dynamic and proactive NAE. Thank you for your continued support.

Corale L. Brierley

For more information about ways to give, please contact:
Radka Nebesky, Director of Development, 202.334.3417 or RNebesky@nae.edu

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We greatly appreciate the generosity of our donors. Your contributions enhance the impact of the National Academy of Engineering's work and support its vital role as advisor to the nation. The NAE acknowledges contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation.

Lifetime Recognition Societies

We gratefully acknowledge the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of the academies as advisor to the nation on matters of science, engineering, and medicine.

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Calendar of Meetings and Events

Late February–April 26	Call for new nominations for 2022 election cycle (from current members/international members only)
March 1–31	Election of NAE officers and councillors
March 17–19	German-American Frontiers of Engineering Symposium
May 14	NAE Council Meeting
May 24–26	Workshop on Sharing Exemplary Admissions Practices that Promote Diversity in Engineering
June 23–25	Japan-America Frontiers of Engineering Symposium

Meetings are held virtually unless otherwise noted.

In Memoriam

R. Byron Bird, 96, Vilas Professor Emeritus, University of Wisconsin–Madison, died November 13, 2020. Dr. Bird was elected in 1969 for contributions to fundamental chemical engineering in the fields of transport phenomena and rheology.

Ronald Bullough, 89, retired consultant, research director and chief scientist, AEA Technology, Harwell Laboratory, died November 21, 2020. Dr. Bullough was elected a foreign member in 2011 for contributions to understanding irradiation effects in solids and leadership in nuclear technology.

George Dieter, 92, Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park, died December 12, 2020. Dr. Dieter was elected in 1993 for contributions to engineering education in the areas of materials design and processing.

Tony F.W. Embleton, 91, retired head, Acoustics and Mechanical Standards, National Research Council of Canada, died November 13, 2020. Dr. Embleton was elected a foreign member in 1987 for outstanding contributions and international leadership in engineering acoustics.

Robert E. Fenton, 87, professor emeritus, Ohio State University, died December 28, 2020. Dr. Fenton was elected in 2003 for pioneering systems research and engineering on the design and operation of automated highway systems.

Vladimir E. Fortov, 74, academician secretary, Russian Academy of Sciences, died November 29, 2020. Acad. Fortov was elected a foreign member in 2002 for pioneering research of hot, dense matter under extreme conditions and for reforming and energizing engineering in Russia's civilian sector.

Robert A. Frosch, 92, retired guest investigator, Woods Hole Oceanographic Institution, and retired senior research fellow, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, died December 30, 2020. Dr. Frosch was elected in 1971 for contributions toward the improved application of engineering resources to large-scale engineering developments with special emphasis on underwater acoustics.

Roddam Narasimha, 87, DST Year-of-Science Professor, Jawaharlal Nehru Centre for Advanced Scientific Research, died December 14, 2020. Dr. Narasimha was elected a foreign member in 1989 for leadership in the development of aeronautics in India and for many significant contributions to the understanding of fluid flow.

Thomas W. Parks, 81, professor emeritus, School of Electrical and Computer Engineering, Cornell University, died December 24, 2020. Dr. Parks was elected in 2010 for contributions to digital filter design, fast computation of Fourier transforms, and education.

Peter B. Teets, 78, retired president and chief operating officer, Lockheed Martin Corporation, died November 29, 2020. Mr. Teets was elected in 1999 for contributions to the nation's space and launch vehicle programs and for management of aerospace programs.

Daniel M. Tellep, 89, retired chair, Lockheed Martin Corporation, died November 26, 2020. Mr. Tellep was elected in 1979 for pioneering theoretical, experimental, and design contributions in the development of reentry systems for US Fleet Ballistic Missiles.

Invisible Bridges

Tinker, Taylor, Soldiering, Spy: Escaping Efficiency Traps

Guru Madhavan is the Norman R. Augustine Senior Scholar and director of NAE programs.

John le Carré laid espionage traps. They came with honey pots, false flags, and negotiated morals. Just as in these thrillers, one such double agent has infiltrated vast areas of our real lives: the concept of *efficiency*. We created efficiency as a way to think about reducing waste and boosting performance. Now with untold variants, efficiency has become much more insidious. What was once a solution to escape the trap of disorder has now become the trap itself.

In the frosty January of 1912, a perfectly accoutered Frederick Winslow Taylor appeared at a congressional hearing in Washington. Over four days, with formulas and charts, the steely-eyed engineer lectured politicians on process control, capitalism, and work philosophy. A year earlier, he had published *The Principles of Scientific Management*, an accidental bestseller. Taylor sold his theory as the way to elevate efficiency in "every branch of the business to its highest state of excellence, so that the prosperity may be permanent."[1]

Taylor's ideas spread from the oily machine shops of Pennsylvania to the chambers of the US Congress and Sunday sermons in Paris. A father in the Dominican Order preached that the "love of God is the Taylor System of our inner life."[2] But for Taylor, the high priest of efficiency, scientific management was bigger than time and task tracking. It was a "mental revolution."[3] In reality, though, that revolution faced resistance. Consider slacking on the production floor—or "soldiering," as Taylor termed it. When factory workers lollygagged, that meant revenue loss. But when the companies following the Taylor System tried to eliminate these unwanted idle times, pointing to accountability, employee morale and burnout problems increased. Efficiency in practice was not an unalloyed advantage.

In a society with countless efficiencies, no two are alike. In a recent analysis, manufacturing policy scholar Erica Fuchs and colleagues cited a midsize American company that struggled to produce nine million masks during the initial stages of the covid-19 pandemic.[4] The chief hurdle was not in sourcing the core ingredient—melt-blown polymer—but in sourcing the elastic cord for the mask's ear loops: The sole US supplier of the elastic could not quickly scale to produce it in sufficient quantity, and the only product it could provide was coiled, which was incompatible with the assembling equipment. Unspooling dramatically slowed production. Policy wonks "wouldn't classically think we needed to produce elastic," Fuchs points out. "And yet, in this story, that lack of elastic cost our country millions of masks *a week*."[5] The point here is not to make elastic manufacturing a national priority, but to make the manufacturing system itself more elastic. Piecemeal efficiencies (or inefficiencies) like highly specialized production can and do trigger unanticipated systemic crashes.

Efficiency may be portrayed as a paragon of rational thought, but this can be a cover for its more duplicitous

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Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise. This issue's column also simultaneously appears in the Indian Institute of Technology's new global science and technology magazine.

[1] Taylor FW. 1911. The Principles of Scientific Management. New York: Harper & Brothers Publishers [1919 version], p. 9.

[2] Taylor Society. 1920. Frederick Winslow Taylor: A Memorial Volume. Norwood: Plimpton Press, p. 6.

[3] Hearings before Special Committee of the House of Representatives, January 1912, published in the Bulletin of the Taylor Society XI(3–4), June-August, 1926.

[4] Fuchs ERH, Karplus VJ, Kalathil N, Morgan MG. 2020. To respond to the pandemic, the government needs better data on domestic companies that make critical medical supplies. Issues in Science and Technology, Dec 18.

[5] Hearing on trade, manufacturing, and critical supply chains: Lessons from Covid-19. Testimony for Subcommittee on Trade, House Ways & Means Committee, July 23, 2020.

aspects. Understanding four covert identities may help in uncovering this guise.

The first and the most familiar is when efficiency serves as a *toy*. In this aspect, efficiency produces gains that make countless conveniences possible, from livestreaming to frozen lasagnas and express-delivered Nordic socks. Each application is endlessly—and separately—optimized for efficiency, systematically turning individual preferences into parameters. But if greater efficiency merely produces the newest fad rather than a material gain, we are right to question whether a benefit has been achieved.

The second identity emerges when efficiency becomes a general *theory*. Over the past century, the shopfloor concept has been exported to the management of working hours. The typical 40-odd-hour workweek with meetings, emails, calendar invites, teleconferencing, and action items is more or less a scripted show. We buy into the unspoken theory that these optimize billable hours while leaving our work environments increasingly less nurturing, an enemy of productivity and creativity.

The third is when efficiency is viewed as a *tradition*. Efficiency can be a fierce numbers game. A ritual in its own right, efficiency thrives on rigidity, repetition, and rigor A penchant for quick returns unwisely erodes investments in not just maintenance and scientific research but civics and arts as well. Yet we consciously make these choices, which begs the question: Is efficiency a characteristic of simplified systems or oversimplifying minds?

The fourth and final covert identity of efficiency is that of a *trap*, enticing the mark with the idea of unquestioned goodness. How, after all, could being more efficient be anything other than a positive thing? The simple answer is that numerical objectives that are divorced from human concerns are not innately beneficial. Indeed, the world is full of examples where the "efficient" solution had monstrous consequences.

In *Tinker, Tailor, Soldier, Spy*, le Carré wrote, "The more identities a man has, the more they express the person they conceal."[6] The same is true for efficiency. To become nuanced and skilled in questioning the toys, theories, traditions, and traps of efficiency, we need to unmask our risky flirtations with it. That's how we can engineer efficiencies that don't just make us better off, but *better*.

[6] le Carré J. 2000 (1974). Tinker, Tailor, Soldier, Spy. New York: Pocket Books, Simon & Schuster, p. 213.

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