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Infusing Advanced Manufacturing into Undergraduate Engineering Education

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CONTRIBUTORS

Committee on Strengthening the Talent for National Defense: Infusing Advanced Manufacturing in Engineering Education; National Materials and Manufacturing Board; Division on Engineering and Physical Sciences; National Academy of Engineering; National Academies of Sciences, Engineering, and Medicine

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Consultant

ROBERT POOL, Consulting Writer

NATIONAL MATERIALS AND MANUFACTURING BOARD

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Guillermo Aguilar, Texas A&M University
Dianne Chong (NAE), Boeing Research and Technology (retired)
Stephen R. Forrest (NAS/NAE), University of Michigan
Tracee Gilbert, System Innovation
Susannah Howe, Smith College
Anita K. Jones (NAE), University of Virginia
Richard K. Miller (NAE), Franklin W. Olin College of Engineering
Oludare Owolabi, Morgan State University
Tim Shinbara, Association for Manufacturing Technology

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by David E. Crow (NAE), Pratt and Whitney (retired), and Eric H. Ducharme (NAE), General Electric Aviation (retired). They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Preface

The co-chairs thank the committee for their diligent efforts in undertaking the work of the study and preparing this report. We also thank A. Adele Ratcliff, Industrial Base Analysis and Sustainment (IBAS) Program at the Department of Defense, for sponsoring and helping us launch the study and Robert Pool, who assisted in writing this report.

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Maxine L. Savitz and Robert F. Sproull, *Co-Chairs*
Committee on Strengthening the Talent for National Defense:
Infusing Advanced Manufacturing in Engineering Education

Summary

In recent years a variety of technologies have been developed that have the potential to reshape manufacturing in the United States and other countries around the world. They promise to make it possible to manufacture parts that cannot be created—or cannot be easily created—with traditional methods, to dramatically increase the customizability of manufactured products, to decrease the time between design and production, and, in some cases, to lower the cost of production. The approach made possible by this array of new technologies is often referred to as *advanced manufacturing*, and the ongoing transition to and adoption of these new technologies has been referred to as "the fourth industrial revolution." Advanced manufacturing is of particular interest to the Department of Defense (DoD) as it wishes the defense industrial base to employ whatever means are necessary to produce the most effective, cutting-edge defense technologies possible.

There are, however, a variety of obstacles to the nation's industrial base taking full advantage of the potential of advanced manufacturing. The one that is the focus of this report is the nation's system of undergraduate engineering education and, in particular, the fact that US engineering schools do not do a particularly effective job of preparing their students to work in advanced manufacturing. Too few undergraduate engineering students are being exposed to or taught about the use of advanced manufacturing technologies (or manufacturing technologies in general), and of those students who do get some exposure, few are prepared to design for those technologies when they graduate. The result is a shortage of engineering graduates ready to contribute in this area, which in turn slows the uptake and use of advanced manufacturing technologies in the companies that are part of the defense industry.

To understand the issue in greater detail, consider the example of three-dimensional (3D) printing. The technology is already being put to work in a variety of areas. In medicine, 3D printers are creating prosthetics, hearing aids, and dental crowns. Paleontologists use them to create replicas of the bones of dinosaurs and other ancient creatures. Engineering students use them in makerspaces to produce models of their designs.

But the uptake of 3D printing by industry has been more measured. Both the automotive and the aerospace industries have put 3D printing to work to create parts, for instance, but it is typically done in select cases rather than for volume manufacturing. A characteristic example is the 3D-printed rocket engines that have sent a series of rockets into space; the number of these rockets produced to date has been in the hundreds rather than in the tens of thousands or millions.

The potential uses of 3D printing are practically limitless, and although the printers that most people are familiar with produce mainly plastic or polymer objects, it is possible to print with extremely strong and durable materials such as titanium and stainless steel. Thus this is one of the advanced technologies that DoD is interested in being taken up by the defense industrial base. But it is not as simple as a company buying a 3D printer and supplies and using them to realize its engineers' designs. Producing a jet engine, for instance, that does its job reliably and effectively involves a major learning curve, with the engineers and technicians finding many approaches that do not work before they zero in on one that does. Thus an engineering graduate who has never had the chance to work with 3D printing in a realistic manufacturing setting will start off at a major disadvantage compared to one who has had such experience.

More generally, DoD is eager to have a wide array of advanced manufacturing technologies, not just 3D printing, widely adopted by the defense industrial base and supply chain. The defense industrial base has a history of being innovative—introducing approaches such as the use of composites for aircraft and custom production on major contracts—but its adoption of advanced manufacturing will depend on a number of factors. Some of these are technical, such as judgments about whether advanced manufacturing technologies offer enough improvement over existing methods to justify the investment, but many of them are workforce issues, and one of the major workforce issues is the availability of engineers who are competent to design for advanced manufacturing technologies. This is not such a problem for the larger defense contractors, as they have the capacity to invest in training programs that can teach engineers what they need to know about advanced manufacturing, but small and medium-sized companies often cannot afford such an investment and have difficulty finding engineers with the proper skillset.

DoD, which has a history of addressing workforce issues for the defense industrial base, has recognized this as a problem and is interested in finding ways to improve undergraduate engineering education so that graduates of US engineering schools can make a more immediate contribution to advanced manufacturing. Thus this report offers a number of recommendations for actions that universities, the federal government, and industry can take to make training in and about advanced manufacturing a more prominent and effective part of undergraduate engineering education (see Box S-1). This report is the result of a study sponsored by the DoD Industrial Base Analysis and Sustainment (IBAS) Program; the study statement of task and work plan are in Appendix A.

The recommendations fall into two broad categories. The first group of recommendations focus on ways to augment and adjust existing mechanisms in ways that can move undergraduate engineering education in a direction that will make it easier to realize the potential of advanced manufacturing in US industry, particularly the defense industrial base. It makes sense to mainly work on modifying existing practices rather than trying to build new ones from scratch because undergraduate engineering education has a huge installed base and a trajectory that is difficult to alter substantially.

Among the “augment and adjust” recommendations, a key one is to make manufacturing, particularly advanced manufacturing, an integral part of engineering education (Recommendation 2.1). Undergraduate engineering students typically are exposed to manufacturing at some point, but because the essentials of manufacturing have been mostly stable for a couple of decades (e.g., machining as a key component, the use of only a few metals for most applications), most students spend very little time on manufacturing topics, with their exposure generally limited to what they learn in a few labs. But manufacturing’s period of stability is coming to an end, and it will be important for engineering students to spend more time learning about the details of advanced manufacturing.

A further recommendation is that undergraduate engineering programs should offer experiential learning such as project courses and capstone projects that connect to real, not prototype, manufacturing (Recommendation 3.2). Students should be able to take their projects through to real manufacturing, which would typically be done in conjunction with the industrial sponsors of the projects.

The report also acknowledges the many ways that industry contributes to undergraduate engineering education, beyond its role in universities. Industry provides facilities for use by students and sponsors projects and courses, internships, co-ops, and more. The report encourages industry to continue and amplify these efforts, with a particular emphasis on endeavors that increase students’ familiarity with and understanding of advanced manufacturing technologies.

The federal government has a role to play as well. In particular, the report calls for government-sponsored programs such as manufacturing initiatives (e.g., DoD’s manufacturing innovation institutes) and engineering research support programs to engage more with undergraduate engineering students, using remote learning if necessary.

The second group of recommendations go beyond amplifying existing practices and suggest innovations aimed specifically at improving the presentation and teaching of advanced manufacturing in undergraduate engineering education. One recommendation, for instance, calls for engineering schools to develop and deploy advanced manufacturing curricula that are adaptable to different types of delivery, that are scalable, and that will be easy to update as advanced manufacturing evolves (which is happening rapidly; Recommendation 4.9). Another suggests that the federal government support more applied research in advanced manufacturing as a way to engage undergraduates (Recommendation 4.5); the new

Technology, Innovation, and Partnerships directorate at the National Science Foundation is ideally suited for this role. A third recommendation is to develop remote access to (limited forms of) advanced manufacturing so that students in all regions of the United States can experience real manufacturing; such access could be modeled, for instance, on the Metal Oxide Semiconductor Implementation Service (Recommendation 4.8).

In addition to the recommendations and supporting material provided in the report, Appendix B provides a summary of a workshop held in conjunction with the development of this report. The summary contains descriptions of several current best practices in engineering education that can serve as models for other undergraduate engineering programs around the country.

BOX S-1
Recap of Recommendations

Recommendations for undergraduate engineering education:

2.1 Undergraduate education in every engineering discipline should cover realization (e.g., manufacturing)
2.2 Professional engineering societies should advocate for ABET criteria to explicitly include manufacturing (or “realization”)
2.3 Expand optional paths through engineering education, especially for transfers from community colleges
2.4 Strengthen collaboration between academia and industry
3.1 Offer experiential learning, such as capstone courses, that emphasizes advanced manufacturing
3.2 Incorporate experiential learning throughout an engineering program
3.3 Engage undergraduates in applied research to obtain hands-on experience with advanced manufacturing
3.4 Expand extracurricular advanced manufacturing experiences

Recommendations for industry and government:

4.1 Strengthen the many existing methods for supporting undergraduate engineering education to emphasize manufacturing and advanced manufacturing
4.2 Encourage more industry engineers to contribute to education programs, perhaps using remote collaboration tools
4.3 DoD should pilot a Fraunhofer-like program that pairs a single university with a large defense contractor
4.4 The manufacturing institutes should develop a portfolio of “capstone projects” that present students with a range of problems in advanced manufacturing
4.5 NSF’s Directorate for Technology, Innovation and Partnerships should sponsor research programs that engage undergraduates in advanced manufacturing
4.6 Agencies in addition to DoD and NSF should provide opportunities for students and faculty to spend time in small and medium-sized manufacturing companies
4.7 DoD should initiate a pilot program in applied research fellowships for undergraduates
4.8 NSF should facilitate network access by undergraduates to industrial-quality advanced manufacturing services
4.9 NSF should sponsor projects to develop advanced manufacturing curricula

1

Engineering for Advanced Manufacturing

The world is experiencing what has been described as the "fourth industrial revolution," with rapid advances in manufacturing and other technologies that are expected to result in transformational changes in technological capabilities in a wide variety of areas, including defense technologies. However, realizing the full potential of these new technologies will require engineers with skillsets that are significantly different from those required in more traditional engineering

This chapter provides background and context for the remainder of the report. It defines advanced manufacturing and explains its potential for revolutionizing the manufacturing industry. It discusses the challenges to fulfilling that potential associated with the current state of undergraduate engineering education. And it describes what an ideal future might look like, with engineering graduates having the skills and mindset necessary to take full advantage of advanced manufacturing technologies.

WHAT IS ADVANCED MANUFACTURING?

It is difficult to offer a precise definition of advanced manufacturing. In the most general sense, the term refers simply to manufacturing technologies at a given point in time that have been developed most recently, particularly those that have not yet been adopted widely, so the list of manufacturing technologies that are considered advanced will change over time. Often that change happens gradually, with incremental technological improvements resulting in relatively little difference between well-established technologies and those on the cutting edge. But sometimes change comes more rapidly, with major improvements and fundamentally new capabilities appearing in a short period of time, offering tremendous potential but also tremendous challenges.

Those who study technology and manufacturing speak of four industrial revolutions that have taken place over the past three centuries.[1] The first, in the 1800s, was driven by the mechanization of production using water and steam power; the resulting dramatic increase in productivity and sharp decrease in the cost of manufactured objects led to a shift from an agrarian economy to an industrial one. The second industrial revolution, from about 1870 to 1914, was rooted in the development and proliferation of electric power and other technologies, such as railroad networks, the telegraph, and eventually the telephone; one of the hallmarks of this era was the development of mass production via moving assembly lines in factories, which increased productivity and decreased costs even further. The third began in the mid-1900s with computers and other types of information technology being used to automate production; still more increases in productivity and decreases in cost followed.

The term "fourth industrial revolution" was coined by Klaus Schwab, founder of the World Economic Forum, who argued that a number of new technologies are coming together to make possible a type of manufacturing and production that is fundamentally different from anything that has gone before.[2] Most, if not all of these technologies, are dependent on and made possible by the exponential increases in computing power and memory over the past several decades. The technologies that Schwab identified as underpinning the fourth industrial revolution, including artificial intelligence, advanced robotics, gene

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[1] Schwab, K. 2015. The fourth industrial revolution: What it means and how to respond. *Foreign Affairs*, December 12. Available at https://www.foreignaffairs.com/world/fourth-industrial-revolution (accessed September 10, 2022); also available at https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/ (accessed September 10, 2022).

[2] Ibid.

editing, and additive manufacturing (3D printing),[3] tend to blur the lines separating digital and physical (and biological) realms.[4] This cyberphysical information-based industrial revolution is proceeding much more rapidly and with much broader impact than the previous industrial transformations, Schwab argues, and "the breadth and depth of these changes herald the transformation of entire systems of production, management, and governance."[5]

In the context of the fourth industrial revolution, advanced manufacturing can be defined as manufacturing techniques and technologies with a certain suite of characteristics. First, it consists of newly developed approaches that are improvements over traditional methods and are not yet widely adopted. Most advanced manufacturing technologies today are highly digitized, producing products designed using digital tools, often simulated and/or tested digitally, and manufactured with computer-controlled equipment that follows the digital design and incorporates digital feedback. A "digital thread" of data and control information flows through manufacturing processes, created and verified by software tools, interpreted as control information for physical processes such as machining.

As with the first three industrial revolutions, the fourth promises to make it possible to increase productivity and decrease the costs of many products, but its potential goes far beyond cost and efficiency. One result, for instance, will be a dramatic increase in the ability to customize products, with the possibility of producing small batches or even making individual items to a customer's specification at an affordable cost.[6] For example, customized parts made with additive manufacturing are used for orthopedic and dental implants and in prosthetics. Often additive manufacturing dramatically simplifies the manufacturing process and the number of manufacturing steps required to achieve a finished product. RocketLab, for example, has produced over 300 rocket motors with 3D printing of materials that can withstand extreme heat and stress (see Figure 1-1).

Advanced Manufacturing in the Aerospace Industry

The types of techniques and technologies that make up advanced manufacturing will vary from industry to industry. For example, manufacturing of pharmaceuticals, automobiles, aircraft, and integrated circuits use different technologies. Given that this report focuses on advanced manufacturing in the defense industrial base, it is useful to get a sense of some of the specific advanced manufacturing technologies that are important in that sector. This section focuses on one particular example and examines the various roles played by advanced manufacturing in the construction of the F-35 at the Lockheed Martin plant in Fort Worth, Texas.

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[3] Some feel that the terms "3D printing" and "additive manufacturing" are equivalent labels for processes that create objects by adding material. For others, 3D printing refers to a subset of additive manufacturing in which material is added in a sequence of layers, as in stereolithography, where a light beam is steered over a vat of polymer to polymerize (solidify) a 2D region on top of previously solidified material. Other additive manufacturing techniques, such as selective laser sintering and electron-beam melting, can also be viewed as adding material in layers. But some extrude material from a nozzle that is steered to sites to deposit new material on an object; the deposits may or may not occur in layers.

[4] Schwab, K. 2017. *The Fourth Industrial Revolution*. New York: Crown Business.

[5] Schwab, K. Op. cit., 2015.

[6] *The Economist*. 2012. The third industrial revolution (April 21). https://www.economist.com/leaders/2012/04/21/the-third-industrial-revolution.

FIGURE 1-1 3D-printed rocket motor by RocketLab, produced in Long Beach, California. As of September 2022 more than 300 had been produced, most of them flown successfully on RocketLab rockets.
SOURCE: RocketLab—see timeline-2013.png (940×425) (rocketlabusa.com) (accessed September 30, 2022).

For many years through the late 20th century and into the 21st, advanced manufacturing was mainly associated with the extensive automation used in automobile, electronics, and appliance industries. In the aerospace industry, by contrast, manufacturing automation was slow to develop because of the relatively low rates of production and large capital costs. Instead, the one defining technology that spurred advanced manufacturing technology in aerospace was the creation and consumption of three-dimensional models, sometimes called the "digital thread," beginning in the 1980s. The term refers to the creation and use of digital representations of designs on the engineering flow from concept to design, manufacturing, assembly, and other steps throughout the product life cycle (Figure 1-2).

Additive manufacturing (Box 1-1) depends on the digital thread to specify the components to fabricate. For aerospace (and other) products, digital threads involve models that are created in the design process and then used in manufacturing as the digital targets for automation and metrology applications and also for sustainment functions during the product's period of use. The digital thread enables a variety of advanced manufacturing technologies, including robots and automation, additive manufacturing, advanced metrology, augmented reality, robotic application of coatings, equipment specialized for a product (e.g., drilling airframe components for fasteners), and optical projection using augmented reality to guide assembly, as well as robotic delivery systems that pick and deliver materials in aerospace and other factories (Figure 1-2). Its development has led to increased use of modeling and simulation in design and manufacturing, the use of advanced inspection technologies, and the ability to use models for direct numerical-control programming and robotic assembly.

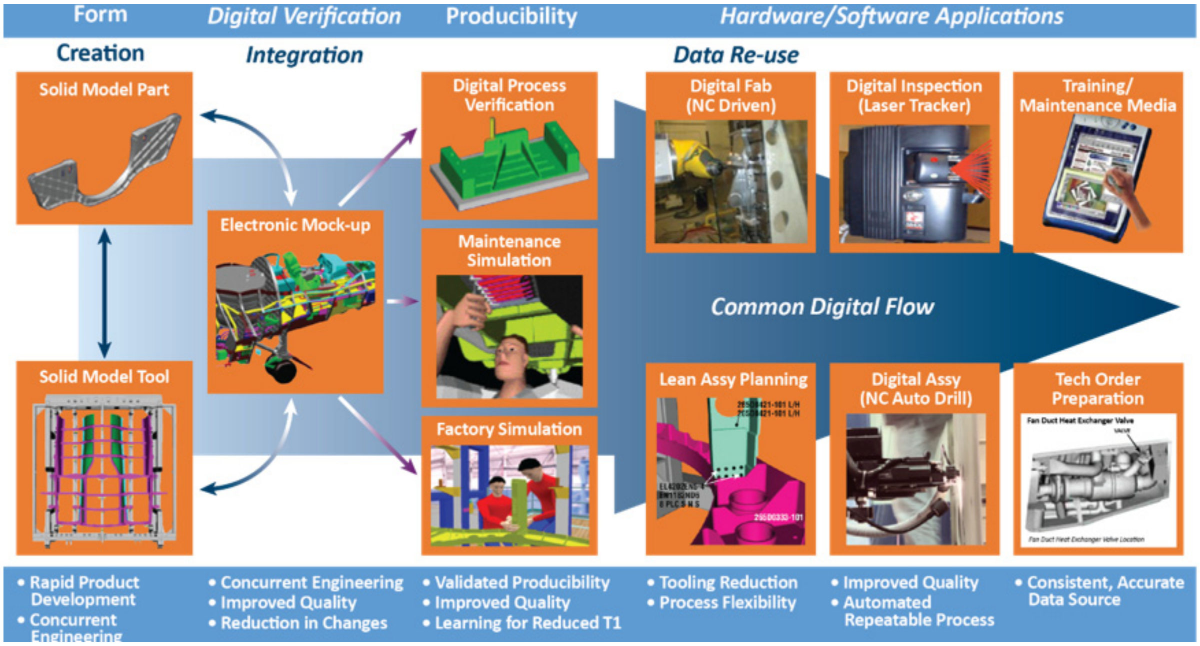

FIGURE 1-2 The digital thread. NOTE: Assy = assembly; NC = numerical control. SOURCE: Kinard, D.A. 2019. F-35 digital thread and advanced manufacturing. In J.W. Hamstra (ed.), *The F-35 Lightning II: From Concept to Cockpit*. Reston, VA: American Institute of Aeronautics and Astronautics. Pp. 161–182.

BOX 1-1
Additive Manufacturing

One of the most promising advanced manufacturing techniques today, used in the aerospace industry and many others, is additive manufacturing. This refers to the building up of an item, often layer by layer. A familiar example is fused-filament 3D printing, where a print head or nozzle lays down extremely thin layers of material on top of one another and they are then fused together to create a solid 3D item in the desired shape. Such processes are referred to as “additive” manufacturing to distinguish them from the traditional “subtractive” manufacturing, where one begins with a solid block of material or a molded piece and then drills holes and cuts off bits of the material to create the finished product.

Additive manufacturing has a variety of advantages over subtractive manufacturing. It is possible, for instance, to create a part much faster and more directly because a digital design can be sent directly to a 3D printer, as opposed to traditional manufacturing, where creating a complex piece may require multiple steps performed by separate machines or vendors. Furthermore, parts created with additive manufacturing can more easily be made out of different materials—say, one material on the inside and another on the outside—which is much more difficult to do with traditional approaches. Similarly, with additive manufacturing it is straightforward to create complex shapes that may be difficult or impossible to achieve with traditional manufacturing methods, such as objects with embedded voids. And additive manufacturing, because items are created one at a time according to a digital model, makes it economically feasible to manufacture small batches or even individual customized pieces.[a]

Additive manufacturing has been in development by US industries for nearly 40 years, starting in 1983 with stereolithography and evolving in many ways, including to laser powder fusion of aluminum, titanium, and polymer substrates. For example, a more recent development is the electron beam welding of titanium wire pioneered by Sciaky, Inc., a US manufacturer of metal 3D printing systems and industrial welding systems; this process may make it possible to deposit pounds of material per hour, which in turn could lower costs. Recent work shows that additive manufacturing of titanium using laser powder bed fusion and simple postheat treatment produces results stronger than conventional methods.[b]

[a] Linke, R. 2017. Additive manufacturing, explained. December 7. MIT Sloan School of Management. https://mitsloan.mit.edu/ideas-made-to-matter/additive-manufacturing-explained (accessed September 5, 2022).
[b] Zhu, Y., K. Zhang, Z. Meng, K. Zhang, P. Hodgson, N. Birbilis, M. Weyland, H. L. Fraser, S.C.V. Lim, H. Peng, R. Yang, H. Wang, and A. Huang. 2022. Ultrastrong nanotwinned titanium alloys through additive manufacturing. *Nature Materials*, 15 September. https://doi.org/10.1038/s41563-022-01359-2.

Many of the advanced manufacturing techniques used in cutting-edge aerospace manufacturing places are enabled by the digital thread. For example, it makes possible the robotic coating systems that provide the accuracy and control necessary for coatings on sophisticated aerospace products like the F-35. Digital design specifications facilitated the creation of a technology called optical projection, whereby engineering data are projected onto parts and assemblies, making it possible to accurately locate such things as fasteners and holes; this is significantly more efficient than using drawings and manually labeling the holes using a pencil. Mixed-reality techniques, a form of virtual reality, are used to help workers route and install wiring harnesses in the aircraft. Digital models are also used in 3D inspection technologies, such as structured light and laser scanning, which can be used to validate that an item has been built to specifications. One particularly convenient use in the construction of the F-35 is to inspect bracket locations prior to the assembly of large bulkheads to prevent downstream issues during system installations. Although it is currently used only intermittently during fabrication and assembly, it will eventually be used to provide real-time inspection monitoring during complex assemblies.

Digital threads play a role in robotics, which is finding its way into aerospace manufacturing even with the industry's typically low rates of production. In one segment of F-35 production, for example, countersinking robots use digital geometry data to roughly locate the desired holes and then use an advanced metrology system to locate the center of the hole and provide a tightly controlled countersink depth.

The digital revolution is also enabling the use of augmented reality in aerospace manufacturing. In one application, augmented reality is used to aid workers in installing wiring harnesses, a challenging task because of complex 3D routing geometries. Other advanced manufacturing technologies used by aerospace companies include automated fiber placement for composites, advanced machining to tightly control part and assembly tolerances and reduce assembly costs, automated material kitting and delivery to the production floor, and modeling and simulation technologies to lay out the factories of the future, simulate product build to reduce issues during actual assembly operations, and accurately develop cost, span, staffing, and manufacturing plans.

The bottom line is that advanced manufacturing technologies hold tremendous potential for revolutionizing industries in the US defense industrial base and, indeed, many others as well. Use of the digital thread opens up many possibilities for rapid development and prototyping, exquisite control of robotic operations, and quality control via comparing measured outcomes with the digital model. And additive manufacturing opens the door to the rapid and cost-effective production of complex parts in small batches as well as making possible the creation of items that would not be feasible to build with traditional methods.

But advanced manufacturing comes with a major challenge as well: Because the technologies are new and rapidly evolving, taking full advantage of them will require engineers with the proper training and mindset, but most US undergraduate engineering education is geared more toward the technologies of the past than to those of the future. The next section examines some of the weaknesses of US undergraduate engineering education in terms of what is required for advanced manufacturing, particularly in the defense industrial base.

CHALLENGES TO FULFILLING THE POTENTIAL OF ADVANCED MANUFACTURING

As Schwab observed in his 2015 article, the complex, rapidly evolving, and customizable nature of the technologies that the fourth industrial revolution is bringing creates great demands on the skills and adaptability of those developing and operating the technologies. "I am convinced of one thing," he wrote: "that in the future, talent, more than capital, will represent the critical factor of production."[7] Unfortunately, an examination of the current state of US undergraduate engineering education indicates that the nation is not producing the engineers necessary to ensure that advanced manufacturing can reach its full potential.

Engineering education has evolved over time, generally in response to changes in technology.[8] Through the 1800s, for instance, the education of engineers in the United States focused mostly on practical skills, such as shop and foundry skills and manufacturing tasks. Then in the first half of the 20th century, as engineering practices became more standardized and scientific knowledge played an increasing role in design, engineering education began placing more emphasis on theory and science and less on practice. The professionalization and standardization of engineering education was driven in large part by the Engineers' Council for Professional Development, established in 1932 and in 1980 renamed the Accreditation Board for Engineering and Technology (now, since 2005, ABET). Over time, the focus on analysis and theory in engineering education was supplemented by more hands-on and project-based learning, along with a change in focus from prescribing required courses to achieving necessary student outcomes.[9]

Many of the changes in engineering education in recent decades have undoubtedly been for the better, and the graduates of US undergraduate engineering programs are highly skilled and competent in many areas. But gaps remain. One of the largest—and the main concern of this report[10]—is that most of today's undergraduate engineering students are provided with very little, if any, knowledge or understanding of manufacturing.[11] Manufacturing topics are offered predominantly as electives, and advanced manufacturing topics are typically not integrated into the curriculum at the undergraduate level.[12] Furthermore, while opportunities exist for undergraduate students to learn about manufacturing through participation in extracurricular activities (e.g., involving racing cars, rockets), these activities are often limited to only a small fraction of students.[13] Similarly, while capstone design projects and certain lab courses introduce students to basic manufacturing, they are limited in scope and rarely extend beyond prototyping. One result of this is that manufacturing has not been presented to undergraduate students as a viable career path; instead, students' impression of manufacturing is often that it is a dirty environment (and may even be perceived as a "low-tech" field).

Many factors have contributed to this general failure to teach undergraduate engineering students about manufacturing, but one underlying factor is particularly important in the context of this report: Mechanical engineering curricula appear to assume slowly changing manufacturing technologies that

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[7] Schwab, K. Op. cit., 2015.

[8] National Academy of Engineering. 2017. *Engineering Technology Education in the United States*. Washington, DC: The National Academies Press. https://doi.org/10.17226/23402.

[9] ABET, "General Criteria for Baccalaureate Level Programs."

[10] This report is the result of a study sponsored by the Industrial Base Analysis and Sustainment (IBAS) Program at the Department of Defense. The statement of task and work plan are in Appendix A.

[11] Harris, G.A. 2021. Engineering education and advanced manufacturing, Presentation to study committee, December 2.

[12] Ward, K. 2022. SME insights: Manufacturing integration into engineering education. Presentation to study committee, January 27.

[13] Ibid.

allow design and realization to be effectively separated: a design engineer's education can focus on the principles and techniques involved in creating effective designs, while on-the-job learning from colleagues will provide local manufacturing know-how. Even "design for manufacturing" is focused more on the economic implications of designs than on the manufacturing technologies used to realize them. Given this perspective, it makes sense to focus undergraduate engineering education on the general principles involved in creating effective designs, with the understanding that, once they go to work for a particular employer, engineering graduates will be able to pick up what they need to know about the specific requirements of that manufacturing setting.

It is arguable that such an assumption may have made sense 10 or 20 years ago. At that point, manufacturing was in a relatively stable phase where although improvements were regularly being made, they were the sorts of incremental improvements that did not change the overall nature of manufacturing. Thus it may have been possible to put forth sets of design principles rooted in how manufacturing was done at the time, teach those principles, and have a reasonable expectation that engineering students using those principles could develop effective designs for manufacture. And, indeed, the ABET standards adhered to by most of the nation's engineering programs assume a mature, stable situation, reflecting the fact that manufacturing has been mostly stable for the past several decades.

That is changing now, however, as advanced manufacturing techniques have the potential to radically change how companies approach the production of manufactured goods. The application of these new techniques will allow for the introduction of new efficiencies in production and manufacture of new designs that are not practical or possible with existing technologies. But taking advantage of this potential requires the development of engineers who are skilled in creating designs tailored to advanced manufacturing techniques as well as traditional manufacturing methods, and the current failure to consistently address advanced manufacturing in undergraduate engineering education is limiting the nation's ability to harness advanced manufacturing to grow the US economy. Note that because advanced manufacturing technologies permit many new kinds of products to be produced, it is not only "manufacturing engineers" who must adapt, but many kinds of engineers who conceive problem solutions, design components, develop materials and structures, invent new materials, and so forth.

Unfortunately, despite the growing importance of introducing undergraduate engineering students to manufacturing—and to advanced manufacturing in particular—there has been little movement in this direction in the US university system. One result is that manufacturing topics are often offered only as electives to undergraduate engineering students, and even those undergraduates who choose to take manufacturing electives typically do not learn about advanced or smart manufacturing, which are normally offered only at the graduate level.

Furthermore, while "realization" is mentioned in the ABET standards under Engineering Education, there is no mention of the associated manufacturing knowledge, skill sets, technologies, processes, or tools that are necessary to actually realize a design. Finally, although engineers going into manufacturing need to be comfortable working with those in other disciplines and jobs, engineering undergraduates have relatively few opportunities to develop such collaborative skills since engineering disciplines are siloed and there are limited cross-program collaborations and learning opportunities.

A request for information by the study committee shows that only 28 percent of the respondents from academia commented positively that the ABET assessment criteria include advanced manufacturing knowledge or skills as objectives or outcomes.[14] While most in academia consider advanced manufacturing to be an important topic, they also express the concern that the engineering curricula are already packed solid, leaving little room for adding new content such as advanced manufacturing. Instead, most schools offer a single manufacturing course as part of their required courses, with advanced manufacturing topics typically offered as electives in a structured way to serve as a link between the BS degree and corresponding 3+2 and 4+1 MS programs. Typical elective courses include smart and intelligent manufacturing, additive manufacturing, manufacturing processes, materials (micro and nano)

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[14] Details of the request for information are in Appendix C.

in manufacturing, design for manufacturing, industry automation (Factory 4.0), and mechatronics and robotics.

Compounding the problems caused by the lack of exposure to manufacturing in undergraduate engineering education is the fact that colleges and universities are generally disconnected from manufacturing (and other) workforce education, as well as disinvestment by government and employers.[15] There is also a lack of fundamental integration between industry, academia, and government in manufacturing. Findings of the National Academies of Sciences, Engineering, and Medicine study also show that US manufacturing productivity is at historically low levels, with the US losing one-third of its manufacturing workforce from 2000 to 2010.[16] The study notes that a new model for workforce development is needed—one that prepares manufacturing engineers as technologists (not just technicians) with the ability to design, operate, maintain, and manage manufacturing systems in order to correct the continued decline in manufacturing jobs, which could otherwise lead to social disruption related to decline in the US middle class.

The current failure to include manufacturing as a regular aspect of undergraduate engineering education hurts the US manufacturing sector in a number of ways. The most obvious is a shortfall in the number of engineering graduates choosing to go into manufacturing.

The shortage of engineering graduates with an understanding of manufacturing—and of advanced manufacturing, in particular—is a particular problem for small and medium-sized manufacturing firms. Because these newly minted engineers did not learn enough about manufacturing during the schooling, they must be provided with significant on-the-job training to bring them to the point where they can make significant contributions in their new careers. This is not a major problem for large manufacturers such as Lockheed Martin, Boeing, or General Dynamics, which have their own in-house training for engineers, but it is a significant challenge for smaller manufacturers. These companies often cannot afford in-house training programs, and while new engineering hires entering these companies can learn from fellow employees about machines that have been around for 20 years, there may be no one to teach them about advanced manufacturing techniques. The result is that many smaller manufacturing firms really struggle to adopt advanced manufacturing approaches.

A separate issue is that engineering graduates who have not been trained in advanced manufacturing techniques are not likely to be able to take full advantage of the potential for new approaches and designs opened up by advanced manufacturing. Because this is an area that is still growing and evolving, there is no "bible" for how to use advanced manufacturing technologies or what sorts of items can be made with them. Instead, it is an area ripe for exploration and innovation. But such exploration and innovation require a fundamentally different mindset from engineers than working with well-established manufacturing technologies whose capabilities and limitations are well understood; instead of focusing simply on design, engineers exploring the potential of advanced manufacturing need to see their jobs as spanning both design and realization. Advanced manufacturing engineers will also need an understanding of the principles underlying advanced manufacturing technologies and the advanced materials that they use and produce. And finally, because these new technologies and materials are too complex for any one person to have a complete understanding, an engineer must be willing and able to collaborate with others, such as the technicians who operate the equipment and know its capabilities intimately. As long as US universities fail to produce engineers with these capabilities, it will be impossible to fully realize the potential of advanced manufacturing.

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[15] National Academies of Sciences, Engineering, and Medicine (NASEM), 2021, *DoD Engagement with Its Manufacturing Innovation Institutes: Phase 2 Study Final Report*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26329.

[16] Since the 2021 NASEM report *DoD Engagement with Its Manufacturing Innovation Institutes*, the manufacturing workforce has recovered somewhat. See Chart 1 in Bureau of Labor Statistics, 2020, "Forty Years of Falling Manufacturing Employment," *Beyond the Numbers*, November 20, https://www.bls.gov/opub/btn/volume-9/forty-years-of-falling-manufacturing-employment.htm.

INDUSTRY PERSPECTIVE

Vital and modern US manufacturing is a national security objective of the US government and especially of the Department of Defense, which has a long history of monitoring and supporting the defense industrial base (DIB). The struggles of US manufacturing, especially with the offshoring of innovative and critical technologies, have prompted study and compensating government investment for more than a decade (see Box 1-2). Although "education and workforce development" are only one aspect of the problem, they have been the target of large investments (e.g., as part of the mission of the Manufacturing USA institutes).[17] While manufacturing workforce concern is usually focused on skilled technicians, the challenge of developing, adopting, and optimizing new technologies such as advanced manufacturing also requires engineers with new skills to capture the innovations' benefits. For this reason, the study committee was charged with recommending ways that undergraduate engineering education could better serve the DIB, its supply chain vendors, and US manufacturing as a whole.[18]

BOX 1-2
Struggles of US Manufacturing

"There are many serious reasons to worry about the fate of manufacturing in the United States. Virtually every week brings a new report diagnosing the state of manufacturing and emphasizing different aspects of its critical significance for the economy…. Today digital technologies and borders open to the flow of ideas, goods, and services make it possible to build international partnerships for bringing innovation into production and into the market. For US innovators there are unprecedented new opportunities to draw on production capabilities that they do not have to create themselves. But there are also long-term risks in these relationships, and they go far beyond the loss of any particular proprietary knowledge or trade secret. The danger is that as US companies shift the commercialization of their technologies abroad, their capacity for initiating future rounds of innovation will be progressively enfeebled. That's because much learning takes place as companies move their ideas beyond prototypes and demonstration and through the stages of commercialization. Learning takes place as engineers and technicians on the factory floor come back with their problems to the design engineers and struggle with them to find better resolutions; learning takes place as users come back with problems."[a]

[a] Report of the MIT Taskforce on Innovation and Production, February 2013. This is a preview of R.M. Locke and R.L. Wellhausen, *Production in the Innovation Economy*, MIT Press, 2015.

At the initiation of the committee's study, John L. Anderson, president of the National Academy of Engineering, said, "This is an opportunity for industry, academia, and government to come together for the purpose of generating and integrating ideas about advanced manufacturing and formulating methods to effectively introduce these ideas into engineering curricula in both the undergraduate and the graduate level."

Adele Ratcliff of DoD's Industrial Base Analysis and Sustainment Program observed that the study was formulated to address a particular question: "Which is the enabler to innovation? Is it the manufacturing process, or is it the precursor of what people call the technology itself?" She went on to argue that today the enabler is likely manufacturing processes and that US engineering programs have not kept pace with them. That was a key question being asked of the workshop attendees, she said: Have

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[17] Manufacturing USA, https://www.manufacturingusa.com, accessed September 25, 2022.

[18] The study's statement of task and work plan are in Appendix A.

engineering programs kept pace with the growing importance of manufacturing processes, and, if not, what should those programs look like? "The gap between an idea for a product and the successful production of that product—that is, the manufacturing step—is often referred to as the 'valley of death,'" she said, because good ideas often fail to be transformed into viable products. However, she continued, "I do not view that as the valley of death. I view that as a valley of opportunity. That is where we convert our ideas to reality—through that manufacturing process. But what will it take to restore the manufacturing capabilities and leadership that the US has lost in recent decades, and how can US engineering programs contribute to that restoration? Those are the questions that the workshop should address."

Because of the nature of defense manufacturing, much of the engineering and manufacturing technology in the DIB Tier 1 original equipment manufacturers (OEMs) such as Lockheed Martin, Boeing, Northrop Grumman, and Raytheon has remained strong. Lockheed Martin developed and applied a plethora of advanced manufacturing technologies for the F-35 production line, including advanced robotics, noncontact metrology, optical projection, augmented reality, and additive manufacturing.[19]

Much of the strength in the DIB is due to the classified nature of DIB products, the DoD requirements for Made in America content, lobbying by states for defense dollars, and generous funding levels for the defense industry for research and development as well as the production of defense articles. However, this engineering development focus is somewhat diluted by the drive for manufacturing cost savings to retain profitability and affordability, which is in turn driven by Congress and the taxpayers. The history of the F-16 program is a good study in this transition. In the early 1980s when the F-16 program was building 25 aircraft per month, manufacturing was vertically integrated and General Dynamics internally produced most of the airframe components (machined parts, tubes, wiring, composites), and designed and assembled most of the fuel, hydraulic, environmental control system, and so on in conjunction with suppliers. In addition, foreign allies such as Israel, Greece, Korea, and Belgium produced components such as wings and center and aft fuselages. Foreign offsets are normal for the defense business where countries expect to receive manufacturing jobs to incentivize purchases of American defense products. However, during declining F-16 production rates in the 1990s, in an effort to maintain profitability and affordability with the decreasing production rates, most detail and subassembly manufacturing was offloaded to suppliers with lower labor and overhead rates while General Dynamics focused on assembly, test, and delivery. In some cases, items were offloaded to low-labor-rate countries such as Mexico in a never-ending drive for cost savings to maintain profitability and keep the cost of the aircraft attractive. This trend, prevalent in the DIB as well as commercial manufacturing, reflects the differing motivations between American industry and that of other Western countries, which typically focus on jobs as part of their social democratic philosophies while US industry focuses on shareholder value.

In spite of the manufacturing offshoring, the capability for the DIB to engineer advanced products has remained strong. Lockheed Martin, for example, employs nearly 60,000 scientists and engineers, a small percentage of whom are involved with manufacturing of advanced products. Large DIB contractors such as Boeing, Lockheed Martin, and Northrop Grumman and other large OEM contractors hire sufficient numbers of engineers (thousands each, annually) from many disciplines and, because of their extensive manufacturing facilities, can also hire or train engineers to support manufacturing operations.

However, lower-tier DIB contractors that supply to the large OEM and Tier 1 suppliers and hire only a few engineers per year may be affected by those engineers' lack of manufacturing knowledge as well as the lack of resources or expertise to train them internally. In addition to being suppliers of parts and components, these lower-tier suppliers are the proving ground for the development of advanced manufacturing technologies used by the Tier 1 companies. Likewise, they are a key focus of the DIB Tier 1s for cost savings because the supply chain constitutes the majority of the cost for the OEMs in their

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[19] D.A. Kinard, 2019, "F-35 Digital Thread and Advanced Manufacturing," in J.W. Hamstra (ed.), *The F-35 Lightning II: From Concept to Cockpit*, Reston, VA: American Institute of Aeronautics and Astronautics, pp. 161–182.

defense products. The lower-tier suppliers are constantly squeezed for cost reductions, leading to offshoring, while their investments are also constricted by short-term profitability considerations.

Large DIB OEMs and Tier 1 suppliers also have specialized advanced manufacturing technology organizations that seek out and develop manufacturing technologies for implementation in current and future products. These organizations serve to develop new technologies and train new engineers for advanced manufacturing careers. But advanced manufacturing technologies such as robotics, automation, additive manufacturing, metrology, and advanced machining equipment, in addition to sophisticated integrated circuits and many other electronic components, are typically sourced from foreign suppliers.

This study issued a request for information from DIB and supply chain companies to sketch the manufacturing problems they face and their expectations for graduates of undergraduate engineering programs (see Appendix C).

ENVISIONING THE FUTURE

What would a future look like in which the potential of advanced manufacturing could be broadly realized? What would engineers be able to do and what would their roles be? A clear picture of that future can help direct today's efforts to prepare the US engineering workforce.

First, the engineers of the ideal future will be familiar with the various technologies used in advanced manufacturing so that they can design for them, improve them, deploy them in factories, integrate them in factory automation systems, and so forth. New manufacturing technologies are being developed at an unprecedented rate, but it does a company little good to have access to them if it does not have engineers capable of designing for it. Again, this may not be a problem for larger manufacturing companies, which have the resources to train their engineers about new capabilities, it can make it impossible for small and medium-sized companies to take advantage of the potential of advanced manufacturing. Thus, in the ideal future engineering graduates will enter the workforce having at least a basic familiarity with the most important advanced manufacturing technologies and know how to keep up to date with new developments.

This familiarity is part of a larger competence that is often overlooked in today's undergraduate engineering education: knowledge about what happens in a manufacturing plant and how that affects engineering decisions. Thus future engineers should be versed in manufacturing in general and familiar with the basic principles underlying design for manufacturing.

Second, future engineers will be comfortable communicating and collaborating with technicians and others in the manufacturing arena. Advanced manufacturing technologies are too complex and changing too rapidly for any one person to be conversant with every aspect of them, so engineers will have to work with not only other engineers but the technicians and others who are responsible for operating the technologies. Traditionally much of engineering education has focused on well-developed technologies with widely accepted best practices where there are clear "right answers" to design problems and a competent engineer can come up with a workable design on his or her own. That will not work with advanced manufacturing technologies, whose complexity and rapid evolution make it essential for engineers to work as part of teams of people who bring different knowledge sets and capabilities to the table.

Finally, the engineers of the ideal future will be explorers and boundary pushers who have the temperament, the knowledge, and the skill sets to expand what is possible to do with advanced manufacturing technologies. Because those technologies are new, powerful, and evolving, they offer boundless possibilities for creating items that are not possible to make with existing technologies or for making existing items in new and more efficient ways. Taking advantage of this potential will make very different demands on engineers than the more traditional tasks of developing designs for creation by well-understood manufacturing methods. To push the boundaries of advanced manufacturing by finding new techniques and approaches, engineers will need an understanding of fundamental engineering principles (including the science behind the technologies), knowledge of modern software tools, familiarity with advanced manufacturing technologies, and willingness to try new things—and sometimes fail—in order to advance the state of the art.

Having a sufficient supply of engineers with these capabilities in the future will go far in ensuring that the country can realize the potential of advanced manufacturing both in the defense industrial base and in the manufacturing sector in general.

The remainder of the report sketches out actions that will need to be taken by academia, industry, and government to ensure that the country's undergraduate engineers programs produce such engineers in the coming years.

2

Revising the Undergraduate Engineering Program

Undergraduate engineering programs must be modified to better prepare graduates for exploiting the benefits of advanced manufacturing. The preceding chapter outlined the state of engineering education and the goal of this study. This and the next two chapters present recommendations for changes that will improve graduates' advanced manufacturing knowledge and skills.

As explained, the term "advanced manufacturing" is applied broadly to new approaches to all aspects of producing output, especially those driven by digital descriptions of the desired result that are converted into instructions for a variety of computer-controlled manufacturing machines. Thus several engineering disciplines are developing and using advanced manufacturing techniques. For this study and report, the committee focused on mechanical engineering and manufacturing engineering programs leading to 4-year undergraduate degrees, and the advanced manufacturing technologies that apply to mechanical engineering. This is consonant with many engineering needs of the defense industrial base and its supply chain.

Advanced manufacturing that produces mechanical articles depends on a range of engineering disciplines and engineers—not on mechanical engineers alone. Since advanced manufacturing can be used to produce new materials and structures, materials engineers may be required to conceive, develop, and test new materials. Software engineers are involved both in creating the software that converts digital design data into formats that control advanced manufacturing equipment and in developing software to operate the equipment. Complex designs will require expertise of many different sorts, from different engineering "disciplines." The integrated rocket motor 3D-printed by RocketLab shown in Chapter 1 involves cryogenic electric pumps, combustion chambers, thrust direction control, and many other parts, and will confront many considerations such as cold and heat tolerance, fluid flow, corrosion, and material compatibility. And the idiosyncrasies of the advanced manufacturing equipment will be a factor; for example, can the optimum shape of the pump impeller blades be produced reliably by the laser beam melting process?

FUSE MANUFACTURING INTO EDUCATION'S CURRENT FOCUS ON DESIGN AND ANALYSIS

Engineering and engineers conceive, design, and build solutions to problems. The "build" element is an essential component of engineering; without it, concepts and designs simply languish on paper or in digital storage. The education, licensing, and professional growth of successful engineers thus must embrace building.[1] It's known by different terms in different fields of engineering—manufacturing, construction, production, fabrication, execution, deployment—but all these terms label the steps essential for a design to have an impact.

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[1] M. Klawe, 2015, "Why Manufacturing Is Vital to Engineering Education," *Forbes*, June 8, https://www.forbes.com/sites/mariaklawe/2015/06/08/why-manufacturing-is-vital-to-engineering-education/?sh=12b6b9993450.

Undergraduate engineering education has long combined principles and practice. Advancing engineering by trial-and-error practice predates Pythagoras, and "principles" have been on the rise ever since. Today's undergraduate engineering education programs are dominated by learning and applying principles, with practice often limited to some laboratory/machine-shop exposure and project courses. The project courses focus on design, often leading to prototypes but rarely including or discussing manufacturing. One-, two-, or three-semester project courses at the end of the degree program are often called "capstone courses." These experiential components of undergraduate engineering education are discussed in Chapter 3.

Undergraduate mechanical engineering has in part been allowed to pay scant attention to manufacturing because for the past several decades most changes to basic manufacturing processes for mechanical objects have not had much influence on design. True, hand-driven machines became numerically controlled, and economics of some processes improved greatly, but the knowledge needed by a designer did not change much. Advanced manufacturing, however, differs greatly from conventional manufacturing and has changed many aspects of product conception, design, and production, thus greatly affecting all aspects of engineering.

Additive manufacturing, with abilities to produce shapes that cannot be produced by traditional subtractive manufacturing processes such as milling, deeply influences problem formulation, solution conception, and design. While the details of additive technologies and the materials they can handle may change rapidly, the principles of the technologies, especially additive manufacturing, are sufficiently stable and likely to endure to be included in undergraduate engineering education.

Therefore, all undergraduate engineering students, and especially those in mechanical engineering, need to learn about manufacturing and advanced manufacturing. The benefits of understanding "realization" as an essential part of engineering are important in all engineering disciplines, as disparate as electrical engineering, materials science, biomedical engineering, civil engineering, chemical engineering, and many more.

> **Recommendation 2.1: Undergraduate engineering education programs should cover the entire engineering process, from concept to design to build—engineering deploys solutions to problems. When the end product is a physical device, fabrication and manufacturing play central roles in the process. Thus the knowledge and practice of advanced manufacturing should be part of the undergraduate engineering education program. Engineering program leaders, such as deans and department heads, should take the lead in ushering in the necessary changes to curriculum and courses.**

Many programs offer elective courses in manufacturing or advanced manufacturing.[2] But the large number of required courses in engineering programs often means only a few students are able to take electives, and the elective material is not integrated into the rest of the engineering curriculum.

Some engineering programs embrace the "build" part of engineering and require coverage of manufacturing technologies in their programs, often via capstone or project courses. For example, California Polytechnic State University, San Luis Obispo has first-year students building air-powered piston engines as an introduction to techniques ranging from reading engineering drawings to press-fitting shafts in flywheels, and hands-on engineering in many courses and every year.[3] Harvey Mudd College has been incorporating manufacturing into its entire curriculum for some time, and for 50 years has required a 3-semester Engineering Clinic capstone that addresses problems posed and sponsored by industry, often leading to production (https://www.hmc.edu/clinic/). These two examples are not unique and they represent major themes of the two institutions' education programs, which are ABET accredited.

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[2] These are not "manufacturing engineering" courses, which concern operating manufacturing processes: scheduling, data collection, factory processes, etc.

[3] Amy Fleischer, dean, College of Engineering, California Polytechnic State University, San Luis Obispo. Presentation at Infusing Advanced Manufacturing in Engineering Education Virtual Workshop, February 25, 2022.

Chapter 3 explores various forms of experiential learning that build manufacturing expertise among undergraduates.

Engineering education leaders and associations are beginning to advocate substantial changes in engineering education, including more emphasis on skills for teamwork, collaboration, and communication. Some schools are rethinking and reorganizing their entire approach to engineering, for example reducing the "silos" of separate engineering disciplines. These redesigns are an opportunity to integrate production into all disciplines and thus to properly address advanced manufacturing. (See Appendix B comments by Kyle Squires on Arizona State University's overhaul of its engineering program.)

Undergraduate engineering programs, though already busy, can be modified to include mandatory coverage of manufacturing and advanced manufacturing. So far, leadership in increasing manufacturing emphasis has not come from ABET, the engineering accreditation body. Its general criteria[4] are proposed and approved by members from 35 professional societies, which represent different kinds of manufacturing and different priorities for its coverage. ABET "Program Criteria," which focus on specific engineering disciplines driven by corresponding professional societies, could be amended to increase coverage of manufacturing. Even without amendment, ABET criteria do not prevent changes, as demonstrated by the above examples of successful integration of manufacturing into accredited programs.

Proper amendments to ABET criteria will encourage academic institutions to build ecosystems for advanced manufacturing education by enabling the integration of engineering design (which is already present throughout engineering curricula) with manufacturing processes, so that students learn to think about design with manufacturing in mind. This will also help to integrate manufacturing-related activities in siloed courses.

Whether or not ABET criteria are changed to mandate coverage of realization, advanced manufacturing, digital infrastructure (such as digital threads and twins), and other topics that are in demand by rapid advances in industry, faculties and professional societies can advocate for emphasizing these topics in the engineering program evaluations that lead to ABET accreditation.

> **Recommendation 2.2: Professional engineering societies such as the American Society for Engineering Education, the American Society of Mechanical Engineers, and SME (previously known as the Society for Manufacturing Engineering), and their members should pursue amendments to ABET requirements to explicitly include manufacturing and advanced manufacturing in accreditation student outcome requirements. For example, current ABET criteria for student outcomes include this statement on engineering design: "an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors." This ABET criterion should be amended to include manufacturing as follows: "an ability to apply engineering design and realization to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors."**

ADVANCED MANUFACTURING CURRICULA

A robust advanced manufacturing curriculum would help spread expertise. Such a development would be especially welcome in academic institutions that wish to grow their advanced manufacturing coverage, perhaps starting from zero. There is an opportunity for institutions and teachers with experience in teaching advanced manufacturing, and for companies that have employed graduates of such teaching,

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[4] See ABET, "Criteria for Accrediting Engineering Programs, 2022–2023," https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2022-2023/, accessed September 25, 2022.

to develop curricula that can be shared widely to support other undergraduate engineering institutions. Stakeholders providing input to advanced manufacturing curriculum development include at least teachers, students, employers, equipment vendors, and service providers.

Advanced manufacturing will evolve, perhaps rapidly, and increase in breadth. Additive manufacturing already allows new materials to be fabricated easily, for example using blown powder directed energy deposition. Curricula need to be developed to be broadly useful for different audiences and settings; for example, they should

- Be modular, with short segments to enable study on varying schedules
- Be flexible as to setting: online, asynchronous, synchronous, in-person
- Comprehensively cover principles and practice
- Offer demonstrations (video) and lab “assignments” to build practice, with access to varying amounts of shop equipment or advanced manufacturing services
- Have a structure that covers basics succinctly, but is expandable for greater depth or for details of specific processes, equipment, materials
- Retain and deliver a curated online repository of open-source materials
- Encourage timely contributions and updates from teachers, students, employers, vendors, service providers

This list is a sketch; detailed curricula design and processes for development and evolution would need to be created. Use cases must be considered: Can such a “curriculum” be used to form an undergraduate required course? an elective? an independent study? a supplement to an existing course? self-study by an undergraduate engineer? a holiday homework assignment? an industry training session to prepare employees for new assignments? an “implementation guide” for a project or capstone course? The rollout of curricula needs to include “teach the teachers” sessions to facilitate adoption. Developing such curricula is an opportunity for academic institutions to partner with other institutions, leading educators, researchers, employers, professional societies, and others to develop an exceptional and effective contribution to the spread of advanced manufacturing.[5]

A stretch target for a curriculum is to serve an engineer in industry starting a project that requires advanced manufacturing in a group where neither she nor her colleagues have experience. Tips for selecting equipment, dealing with vendors, and troubleshooting would be valuable.

Courses and curricula are usually started by one or more faculty members spawning a special topics course and refining it by teaching it several times. The course and associated infrastructure such as labs may grow and become a permanent offering (see Box 2-1). The course developers may invite other collaborators in academia or industry, and plan a nationwide deployment. The growth and development of such a course may attract government funding; options and recommendations are explored in Chapter 4.

BOX 2-1
Education Readiness Levels

Education Readiness Levels (ERLs) could be developed as benchmarks for the development of engineering courses or a sequence of courses, rather than an entire curriculum. ERLs reflect the status of the deployment of a course in a curriculum at a single institution, multiple institutions at a regional level, and at a national level (adopted by multiple institutions across the nation). The following describe a proposed framework of ERLs for a course or set of courses:

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[5] See also “Preferred Approaches to Curriculum and Program Design” and “Preferred Approaches for Program Content” in National Academies of Sciences, Engineering, and Medicine (NASEM), 2021, *DoD Engagement with Its Manufacturing Innovation Institutes: Phase 2 Study Final Report*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26329.

1. Need for new curriculum, educational content identified.
2. Content, syllabus, and delivery method developed.
3. Special topics course taught once.
4. Special topics course refined and taught multiple times.
5. Formal approval and incorporation of the course into curriculum as a permanent course.
6. Multiple faculty teaching the course at the same institution with documented course curriculum.
7. Course taught at multiple regional institutions using documented course curriculum.
8. Supporting material for course prepared and standardized for regional deployment.
9. Course deployment available to and taught at multiple institutions on a national level.
10. Curriculum modified and deployed for various element of the workforce (e.g., 2-year institutions, continuing education programs, professional education programs, and high schools).

FLEXIBLE EDUCATIONAL PATHWAYS

For a variety of reasons many undergraduates choose to veer from the standard 4-year undergraduate degree schedule. Engineering offers a number of reasons and opportunities; for example:

- Start at a 2-year community college, get hooked, transfer to complete a bachelor's degree in a 4-year bachelor's degree engineering program[6]
- Enter a co-op program to get real-world work experience, "social skills" on the job[7]
- Take a year off to continue as research staff on a research project at the university
- Switch from one engineering discipline to another (e.g., from electrical to mechanical engineering)
- Frustrated that required engineering courses preclude other offerings at a university, take an extra year and some engineering electives
- Continue after bachelor's degree for master's

Students want options, with less pressure to "be done in 4 years" and/or to be constrained by specific course sequences. Students get excited at different times for different reasons, to pursue different directions.

Recommendation 2.3: Undergraduate engineering program leaders should expand flexible options that augment advanced manufacturing education or experience. For example:

- **Expand 3+2 and 4+1 programs for MS degrees in advanced manufacturing.**
- **Build a better path from community colleges to 4-year institutions, perhaps allowing transfer credit for some hands-on skills.**
- **Offer manufacturing in modularized formats, blending lectures with hands-on lab experience to allow students to investigate manufacturing within a busy course schedule.**
- **Partner with industry and equipment manufacturers for co-ops (even multiyear), self-paced learning, education, and training in small segments, in partnership with industry and equipment manufacturers.**

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[6] For example, see "Iron Range Engineering Program" in Appendix B.

[7] This was discussed in session 2 of the workshop, which is written up in Appendix B.

INDUSTRY EXPERIENCE IN ACADEMIA

Few engineering faculty members have extensive industrial experience, even fewer manufacturing experience, and fewer yet advanced manufacturing experience. But manufacturing experience is extremely valuable for teaching advanced manufacturing courses, supervising or critiquing hands-on labs and projects, mentoring or supervising independent study, leading a research project in collaboration with an industrial partner, setting up and running advanced manufacturing equipment such as industrial-quality 3D printers, developing or codeveloping teaching materials and curricula, and simply being available to students as role models and authorities on manufacturing. When experienced engineers are invited to join or visit an engineering program, most universities can offer a "professor of the practice" title to recognize their value as a full-fledged faculty member.

Recommendation 2.4: Engineering program leaders should encourage bidirectional collaboration exchanges between academia and industry. For example:

- **Recruit professors of the practice and adjunct professors from industry and alumni (working and retired) with manufacturing experience. Adjunct professors employed in industry can collaborate with undergraduate programs remotely.**
- **Attract engineers to collaborate on research projects, which may also provide some funding.**
- **Encourage faculty to take sabbaticals in industry jobs that will give them deep contact with advanced manufacturing (design and fabrication) and help them return to the classroom or lab with new and useful insights.**

These and other opportunities often already exist, but their small scale and limited contribution to advanced manufacturing, specifically, can be increased. Industry can offer support for faculty to work in year-long industrial assignments,[8] but academic programs need to assure faculty that such experience is valued and will not jeopardize advancement or tenure.

The role of academia in undergraduate engineering education is further explored in the next chapter, which covers practical experiences–experiential education. And the support and collaboration required from industry and government are treated in Chapter 4.

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[8] An example is the Boeing Welliver Faculty Fellowship program, https://boeing.mediaroom.com/2009-04-23-Boeing-Selects-Engineering-Professors-for-2009-Fellowship-Program, accessed November 21, 2022.

3

Experiential Learning for Advanced Manufacturing

A key part of undergraduate engineering education is experiential learning, which takes many forms: lab or shop assignments, project courses, research projects, co-op programs, extracurricular projects—and of course the "capstone course," a required project course in the final one to three semesters of most engineering programs. Experiential learning activities are designed to allow students to gain knowledge or skills by doing. Here, we focus on hands-on activities that enable students to gain *both* knowledge and skills experientially. These learning experiences are often organized to address real-world problems, sometimes suggested by industrial partners or sponsors, and may end by constructing and testing a prototype, or in some cases deploying a solution and observing its impact.

Engineering programs already include experiential elements, but most do not yield experience with manufacturing or advanced manufacturing. Since these elements are already widespread, they represent a mechanism to increase exposure to manufacturing. Some colleges and universities already use these opportunities and are examples of "best practice." This chapter shows some of the best uses of experiential approaches to learn about manufacturing and suggests ways that many more institutions could achieve similar gains.

In the context of undergraduate education, experiential learning activities can be divided into two broad categories: curricular and extracurricular. Curricular experiential learning activities (also loosely known as practicums) are formally woven into the curriculum and may take a variety of forms including:

- Capstone course project: A project that serves as a culminating academic experience for students, aimed at tying together what they have learned throughout their engineering education
- Cooperative education (co-op): A program where students get academic credit for structured on-the-job experience related to their degree
- Work-study: A program that provides students with part-time jobs related to their program as a form of financial assistance while enabling them to acquire on-the-job training
- Labs: Structured hands-on activities, often related to specific courses in an engineering program, aimed at providing students with experiential learning
- Research projects: Credentialed projects that are often performed by students either as independent study courses or as staff on faculty-led translational research efforts

In addition to the above, there are a variety of extracurricular (or cocurricular) activities that students may engage in to bolster their hands-on experiential learning. These include internships, student clubs, design competitions, and engagement with makerspaces, among others.

In response to a request for input issued by the committee, 157 stakeholders from the manufacturing industry (37 percent of the respondents) and academia (63 percent of the respondents) highlighted the importance of practicums and other experiential learning activities in preparing students for careers in advanced manufacturing; 88.9 percent mentioned internships and 80.6 percent mentioned hands-on labs. More observations from this request for input are presented in Appendix B. A report on the

Future of Manufacturing conducted by ASME and Autodesk highlighted a quote from Raju Dandu of Kansas State University, Salina: "One of the major skills the mechanical engineering student is lacking is that manufacturing aspect, which has to be integrated into the design. How will it be manufactured? How will it be handled by the users?"[1]

PROJECT COURSES AND THE CAPSTONE

The most common form of curricular experiential learning activity shared by nearly all US undergraduate engineering programs is the capstone course project. The Capstone Design Survey, initiated by Susannah Howe, the capstone design director at Smith College, provides an excellent source of information about the current state of capstone projects.[2] It has been carried out three times—in 1994, 2005, and 2015—with the next one scheduled for 2025; Howe reported that there were 360 respondents in 1994, 444 in 2005, and 522 in 2015. The greatest number of responses came from those in the mechanical and aerospace engineering fields, followed by electrical and computer engineering, civil and environmental engineering, chemical engineering, and biomedical engineering. Only a few of the respondents were in the manufacturing field. So the survey results are not specific to manufacturing but apply to the engineering field broadly speaking.

Most capstone courses lasted one or two semesters, with more than half of the respondents in 2015 reporting two-semester capstone courses. Furthermore, there was a clear trend toward longer capstone courses, with some now as long as 2 years. The survey results indicate that the number of students taking capstone courses at various institutions has been growing over time.

The most common structure for capstone courses was to have the class and project done in parallel, although a significant minority of the courses were either a class followed by a project or a project only. There were no class-only capstone courses, so the project is clearly a major part of such courses.

In Howe's survey, the objectives for the capstone projects originated from industry, government, faculty research, external competitions, and the students themselves. In 2015, 80 percent of the respondents reported that industry or government was the source for at least some of their students' capstone projects. Much of the funding for the projects came from the colleges and universities, but a significant percentage of it came from the projects' industrial sponsors, and students provided some of the funding as well.

Discussions with various experts from academia, however, revealed that capstone courses and projects do not typically involve manufacturing or advanced manufacturing. Most focus on the problem-solving, analysis, design, and perhaps prototyping phases of engineering, stopping short of any experience in real manufacturing.

However, capstone projects—already operated at large scale—can be adjusted to give students experience with manufacturing. One of the more advanced examples of capstone projects involving manufacturing was from California Polytechnic State University, San Luis Obispo (Cal Poly). Amy Fleischer, dean of engineering at Cal Poly, explained that every engineering student in all 14 of the college's degree programs undertakes a senior capstone project, and most of them incorporate a significant build phase. The mechanical engineering program, in particular, requires all of its students' projects to go to the prototyping phase. The college also offers interdisciplinary senior design projects,

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[1] American Society of Mechanical Engineers and Autodesk, *Future of Manufacturing: New Workflows, Roles and Skills to Achieve Industry 4.0 Business Outcomes: Research Report*, https://www.autodesk.com/campaigns/education/transforming-manufacturing-education-report, accessed September 25, 2022.

[2] S. Howe, L. Rosenbauer, and S. Poulos, 2017, "The 2015 Capstone Design Survey Results: Current Practices and Changes Over Time," Engineering: Faculty Publications, Smith College, https://scholarworks.smith.edu/egr_facpubs/9.

and students in the manufacturing program do blended projects that combine industrial engineering and manufacturing engineering. "As they work through those projects," Fleischer said, "they are building not only the prototypes but also looking at costing and how they would transition to scale manufacturing."[3] Similarly, according to Chris Saldaña, Ring Family Associate Professor at Georgia Tech, mechanical engineering students at Georgia Tech factor manufacturing considerations into their projects through assessing the cost of scaling up and outsourcing production of a single unit.[4] Some schools, like Virginia Tech and Penn State, have so-called "learning factories" that allow students to, as part of their capstone projects, work closely with manufacturing companies to implement advanced manufacturing solutions. And as mentioned in Chapter 2, Harvey Mudd College has been running an Engineering Clinic in its engineering program for 50 years, where "student teams solve real-world problems for industry sponsors."[5]

> **Recommendation 3.1: Engineering program leaders should offer experiential learning opportunities that emphasize advanced manufacturing methods and the interaction between design and manufacturing. They should design and offer some capstone courses that have a goal of designing, prototyping, and manufacturing a solution to the presented problem. They should recruit industrial sponsors and mentors to help supply and guide such projects and connect the students to real-world industrial manufacturing. They should reduce administrative overheads for industry sponsors, offer students an option to select these courses, and provide incentives if necessary.**

EXPERIENTIAL LEARNING THROUGHOUT THE UNDERGRADUATE PROGRAM

While capstone projects provide students with experiential learning at the end of their degree program, it is important to infuse experiential learning throughout the curriculum. A common modality for achieving this in the US education system is hands-on labs and projects attached to engineering and manufacturing courses.

A variety of institutions have incorporated these into their core curricula. For example, Cal Poly has a manufacturing engineering degree program that features a lot of hands-on lab activities every year. First-year students in the manufacturing engineering program are exposed to basic types of manufacturing—electronics fabrication, materials removal, materials joining, casting, and so on—and then in later years the students learn about more advanced types of manufacturing. The manufacturing classrooms combine lecture spaces with laboratory spaces, so students can learn a topic in the classroom and immediately practice it in the lab. The lab spaces have a combination of traditional hand-driven equipment and basic CNC (computer numerical control) machines, and students move to the more complicated machinery as they advance through the program. After the students have mastered different techniques, they combine them to create machines from scratch. Similarly, the University of Michigan has a Design and Manufacturing course sequence progressing from the sophomore to the senior levels, with each course infused with hands-on lab activities involving prototyping using 3D printers and CNC machine tools. A similar sequence is run at Georgia Tech. The University of Texas at Austin (UT Austin) has a hands-on manufacturing lab sequence that includes some scale-up considerations based on injection

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[3] Amy Fleischer, dean, College of Engineering, California Polytechnic State University, San Luis Obispo, presentation at Infusing Advanced Manufacturing in Engineering Education Virtual Workshop, February 25, 2022.

[4] Christopher Saldaña, Ring Family Professor, associate professor, Georgia Institute of Technology, presentation at Infusing Advanced Manufacturing in Engineering Education Virtual Workshop, February 25, 2022.

[5] M. Klawe, 2015, "Why Manufacturing Is Vital to Engineering Education," *Forbes*, June 8, https://www.forbes.com/sites/mariaklawe/2015/06/08/why-manufacturing-is-vital-to-engineering-education/?sh=2f76afac3450.

molding, as well as a senior-level additive manufacturing elective course involving lots of hands-on activities.

Hands-on labs and projects on advanced manufacturing need not only be associated with manufacturing courses. They could be integrated into nonmanufacturing courses as well. For example, a course on strength of materials could include a lab where students 3D print a variety of cantilever beams to help them better understand bending of beams, while giving them a chance to hone their manufacturing skills.

> **Recommendation 3.2: Engineering program leaders should incorporate and expand experiential activities wherever possible in the engineering program, with emphasis on advanced manufacturing technologies. These activities should include hands-on labs, independent study, capstone courses, and cocurricular activities.**

TRANSLATIONAL RESEARCH

Translational (or applied) research, often inspired by problems that arise as a fundamental technology emerges, attacks problems whose solution will have direct impact. Unlike product development, translational research results are applicable more broadly and often lead to further development of a technology. Applied research is a major contributor to the refining and maturing of advanced manufacturing technologies, carried out by universities, industry, and other institutions such as the Manufacturing USA innovation institutes.

Undergraduates participating in advanced manufacturing applied research projects not only learn deeply about advanced manufacturing but also may see their work's impact. A student's engagement may start out as an "independent study" in which a faculty member engages him on her research, but may lead to summer employment, then a year working for the company that is supporting the research, mentored by the company engineer who is also a researcher on the project. The student may encounter state-of-the-art technologies and experiments not generally known. This is not only education and learning, it is contributing, becoming an engineer, and entering the professional culture.

Currently, applied research probably cannot benefit as many undergraduates as the more widespread, and often mandatory, capstone project courses. However, some universities are making concerted efforts to integrate undergraduate research more strongly into their curriculum to increase its access to students. For example, the University of Michigan has a RISE (Research, Innovation, Service and Entrepreneurship) sequence of courses stretching from the sophomore to the senior year that allow students to perform research under the supervision of a faculty member and receive course credit. To facilitate exposure of this course and the resulting projects, a symposium is held at the end of each semester where students present their research projects as poster or oral presentations. Some RISE projects involve advanced manufacturing. For example, a team of students worked on a National Science Foundation (NSF)-sponsored project on automated fault detection in 3D printing as part of their RISE project, which eventually led to a provisional patent application and journal publication.[6] One of the students, a sophomore at the time he completed the project, is now leading the 3D printing club at Michigan and is well positioned for a career in advanced manufacturing. Benefits to undergraduates engaging in applied research are enthusiastically reported.[7]

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[6] S. Aidala, Z. Eichenberger, N. Chan, K. Wilkinson, and C. Okwudire, 2022, "MTouch: An Automatic Fault Detection System for Desktop FFF 3D Printers Using a Contact Sensor," *International Journal of Advanced Manufacturing Technology* 120(11):8211-8224.

[7] See the introduction to R.C. Pearson, K.K. Crandall, K. Dispennette, and J.M. Maples, 2017, "Students' Perceptions of an Applied Research Experience in an Undergraduate Exercise Science Course," *International Journal of Exercise Science* 10(7):926-941.

Another way of expanding the portfolio and access to advanced manufacturing research projects for students is to engage them in projects led by industry or by one of the innovation institutes. These opportunities can be amplified by increasing the support for applied research in advanced manufacturing and adding incentives for undergraduate participation (such as NSF's research experiences for undergraduates, REU[8]). The students who participate are likely to become superb engineers.

Collaborative research and development efforts between industry and academia naturally lend themselves to applied research. Such engagement is beneficial to all parties involved. Most industrial research is targeted toward a shorter timeframe (e.g., 1–3 years) to ensure a reasonable return on investment time horizon. The research is typically applied as it must move a product, process, or capability of the industrial partner toward final deployment. Leveraging universities to conduct applied research is a pragmatic and low-risk approach for industries if executed properly. For example, universities can bring to bear larger teams of engineers (graduate and undergraduate students, as well as faculty and staff) so the industrial partner does not have to hire as an employee. Once the project is complete, the students graduate and secure jobs that may be linked to their research sponsor. By hiring the graduating students, the sponsor can effectively transfer the knowledge base of the applied research project to the company. However, the sponsor does not have a specific or implied responsibility to hire the students. Thus, companies can "spin-up" significant research teams in a very cost-effective manner without longer-term employment implications.

The academia/industry/government roles in supporting applied research in advanced manufacturing are elaborated in Chapter 4.

Recommendation 3.3: Universities and industry should leverage applied research programs in advanced manufacturing to engage undergraduates. They should provide opportunities for students to have significant hands-on experience with advanced manufacturing, to network, to share ideas, and to become familiar with engineering culture.

VARIED EDUCATIONAL PATHWAYS

Students engage in a variety of co- or extracurricular activities to bolster their curricular experiential learning. The most common is internships, which students often perform at will typically during their summer vacation. Internships provide students with a lot of on-the-job experience. However, since they are not formally woven into the curriculum, little or no oversight is provided by the university. Moreover, the internship experience can vary wildly from student to student, depending on the opportunities available to them or the opportunities they elect.

Students can also gain experiential learning through other extracurricular activities like student clubs and competitions (e.g., solar car team, baja racing, etc.) and through engagement with makerspaces that provide them with exposure to advanced manufacturing. For example, Georgia Tech's Flowers Invention Studio and UT Austin's InventionWorks makerspaces provide a variety of advanced manufacturing tools for students to use at will.

There is effort at some universities to incorporate some extracurricular activities into the curriculum, or at least credential them. For example, Penn State has undergraduates build a portfolio, which may include extracurricular activities, as they go through their years in engineering. Texas A&M has a program that requires students to get some sort of experience outside of the classroom. The requirement, called Engineering X, is that a student complete something in addition to what is required in the student's major, and the specifics vary by department. It could be a 48-hour challenge, for instance, or an internship. A very interesting arrangement between Auburn University's mechanical engineering

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[8] Information about the REU program is at National Science Foundation, "Research Experiences for Undergraduates (REU)," published June 7, 2022, https://beta.nsf.gov/funding/opportunities/research-experiences-undergraduates-reu.

program and a neighboring community college requires Auburn students to obtain machine shop certification from Southern Union State Community College.[9]

Co-op and work-study programs are no longer common at US academic institutions. That said, some universities, like the University of Cincinnati (which claims to have invented co-op programs over 100 years ago), continue to run co-op programs. Another example is the America's Cutting Edge (ACE) machining training program offered by the University of Tennessee, Knoxville, which is being scaled up to more universities across the country. However, co-ops are popular in some locations outside the United States. For example, Kathleen Thelen, Ford Professor of Political Science at the Massachusetts Institute of Technology, spoke to the committee about the dual-study program, a type of co-op/work-study program that is growing in popularity in Germany. In the dual-study program, university studies and in-firm training proceed side-by-side. The structure and content of studies are negotiated with the university by individual firms or groups of firms. Students enroll in the program through the participating firms and not through the university directly. The firm pays the apprentice's tuition fees and also pays the apprentice a wage (so they earn money while they study). Often, firms require that apprentices agree to stay with the company after completion for some period of time (usually 3 years). Thelen explained that a major difference between the co-op programs in the United States and the dual-study program in Germany is that the firms are much more involved in the process in Germany. For example, the firms select the students, rather than the US approach where the university selects students and then helps them find placements with firms.[10]

Recommendation 3.4: University engineering programs should provide opportunities for educational pathways that give students practical exposure to advanced manufacturing outside the formal undergraduate curriculum (e.g., through summer classes in machining or advanced manufacturing, certificate programs). Some specific examples include:

- **Government-sponsored advanced manufacturing institutes (e.g., Manufacturing USA, Manufacturing Innovation Institutes, and Manufacturing Extension Partnerships) should broker opportunities for hands-on experiential learning for students by linking the students (or their institutions) with relevant industry partners. (See also Chapter 4.)**
- **Students should receive academic credit or credentials for co- and extracurricular advanced manufacturing activities, like internships, certificate training, and student club activities, given some degree of quality control and standardization.**

FACILITIES AND RESOURCES

The practical aspects of engineering education depend on facilities—hardware and software—that are those of the contemporary professional engineer. Students are poorly served if they have inadequate access to facilities or only to facilities that are obsolete in the profession. Donations and deep discounts by industry are essential for maintaining these facilities, but they are unevenly distributed among educational institutions.

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[9] Gregory A. Harris, director, Interdisciplinary Center for Advanced Manufacturing Systems (ICAMS), Auburn University, presentation to the Committee on Strengthening the Talent for National Defense: Infusing Advanced Manufacturing in Engineering Education, December 2, 2021.

[10] Kathleen Thelen, Ford Professor of Political Science, Massachusetts Institute of Technology, presentation to the Committee on Strengthening the Talent for National Defense: Infusing Advanced Manufacturing in Engineering Education, January 5, 2022.

Software

Many software companies provide their product to universities (and other educational institutions) at no cost or at a highly discounted cost. This provides the students, who will make purchasing decisions over their careers, with some experience with a software product. Examples of companies that have successfully provided discounted software to educational institutions, resulting in substantial industry adoption, include MathWorks (MATLAB), Microsoft (Office), LabVIEW (National Instruments), and Dassault Systèmes (SOLIDWORKS). Such offerings can also be highly beneficial to corporate users as students become familiar with packages and are easily integrated into corporate infrastructures. For example, Google Workspace (formerly G Suite), based on freeware (e.g., Google Gmail, Calendar, Meet, Chat, Drive, Docs, Sheets, Slides), is used heavily by the undergraduate student population. When these students matriculate to companies that use Google Workspace, they are already familiar with its operation and become productive at a more rapid rate.

Nonetheless, partnerships between industry and software companies can be more progressive and beneficial to both parties involved. For example, class engagement can be used to test software capabilities and interfaces for the company. Such testing needs to have an appropriate protocol developed such that input from the academic users is provided directly to the software development team, and updates to the software are rapidly deployed back to the academic test environment. Input from the academic partner not only includes "bugs" but other elements such as workflow, determination of desired options for the project, and an understanding of what product options/capabilities are most heavily used. For the academic institution, the ability to be exposed to, use, and test new software capabilities is of paramount importance in training next-generation manufacturing engineers. Designing for or operating new advanced manufacturing equipment may require device-specific software; again, the ability for the university to operate at the cutting edge of advanced manufacturing is important.

Many CAD/CAM systems are beginning to utilize AI/ML capabilities such as generative design. Working with an industry partner, universities can develop curricula that leverage such capabilities while training students how to use these capabilities in pragmatic ways. For example, generative design is now incorporated in many CAD products. However, there is very little curriculum available that teaches students the best way to leverage such a capability. By working with the CAD system suppliers, a more standardized and proven curriculum using generative design can be developed. Such a development path could easily be documented to provide a methodology for future integration of next-generation technologies. Development of such courses needs to be pursued.

Such academic and industry synergies could easily form the foundation for scaling and deployment of new technologies into the undergraduate manufacturing curricula and eventually directly into the workforce in much the same manner that Google Workspace, Microsoft Office, MATLAB, and LabVIEW have been successful in penetrating the academic marketplace. Furthermore, such collaboration could easily be disseminated beyond a single academic partnership by the industry partner. Finally, development of dissemination materials by the industry partner could be leveraged by the academic partner. For example, many companies have developed web-based training of their systems. Such training is often used as a starting point for student training. Collaborative efforts between academia and industry in this area will result in a constant refresh of training material.

Hardware

A major impediment to having hands-on experiential learning activities that incorporate advanced manufacturing is the capital- and space-intensive nature of advanced manufacturing. With the exception of relatively small programs, like Cal Poly's manufacturing program, which produces about 25 graduates per year, very few schools with large undergraduate student populations have the resources to provide hands-on manufacturing labs to all their students.

A related challenge is that advanced manufacturing is a rapidly evolving field. The equipment needed to provide experiential learning is constantly changing, and it costs a lot to keep replacing equipment to provide students with state-of-the-art training. Another challenge is that, as discussed in Chapter 2, many professors at undergraduate engineering programs do not have industrial experience and therefore are unlikely to have the knowledge, motivation, or skills to provide students with meaningful hands-on experiential learning.

As manufacturing technologies increasingly use digital techniques, access to computing hardware or capacity becomes important. Advanced software for modeling and simulation is not useful without access to substantial computing facilities, perhaps in the cloud. At the other extreme is the hardware of the advanced factory: microcomputers, Internet of Things components, sensors, and the like, not always readily available on the retail market.

A major opportunity—and a challenge—for delivering access to facilities is remote access via the internet. Many aspects of the advanced manufacturing factory could be operated remotely: a designer sends her design for fabrication, expecting a sample part by overnight delivery. Perhaps that works for the experienced, but the learner will need feedback: a critique of the design as it is about to be printed on a powder bed, a critique of the result, counsel about how to improve. Such a “remote factory for the learning designer” is not a distant vision, but nor is it reality. Such a facility, even a modest beginning, would make true advanced manufacturing (as contrasted with desktop 3D printers) available to undergraduate engineering students. To build understanding and adoption of their new products, equipment vendors might offer such online services or add their equipment to the remote factory.

The next chapter deals with the roles of industry and government in advancing undergraduate education, especially in the form of engagement and financial support.

4

Support for Undergraduate Engineering Education

The previous two chapters outlined changes universities can make to undergraduate engineering programs to better equip graduates with advanced manufacturing knowledge and skills. Some of these changes can be aided by support from industry and/or government, both of which have long and important histories of supporting engineering education. We now summarize, in broad strokes, the ways that industry and government currently support engineering education and suggest ways these mechanisms can be adjusted to increase focus on advanced manufacturing. We then discuss options that are either new or distinct from current practice.

CURRENT GOVERNMENT AND INDUSTRY SUPPORT FOR EDUCATION AND ADVANCED MANUFACTURING

Both government and industry have long recognized the value of manufacturing to the health of the economy and of the country as well as the value of undergraduate engineering education to the health of manufacturing, which is why both entities have a history of supporting and improving manufacturing-related engineering education. This section reviews that support in order to offer some background with which to understand the committee's recommendations on ways to expand and extend that support.

Industry Support

Industry depends on university-educated engineers as employees either of a particular company or of the company's vendors and customers who also employ engineers. Companies band together in industry associations to support objectives of their industrial sector, including education and workforce development (EWD). A large employer in a region may support local university and college education to improve the quality of life in the region, especially for its employees.

Industry support of undergraduate education includes student scholarships, fellowships, and summer internship employment; sponsorship of experiential activities such as capstone course projects; competitive design and construction projects, such as solar-powered vehicles; donation of equipment and software for labs; and contribution of the time of company engineers to serve as mentors or advisors to undergraduate programs. Industry builds undergraduate awareness and excitement in engineering through talks, videos, and site visits.[1] Companies often engage in collaborative research projects in which academic faculty and students work on a problem whose solution may directly benefit the sponsor. Undergraduates working on these collaborations derive educational benefit, as outlined in the Translational Research section of Chapter 3.

While these forms of support apply to many different engineering disciplines, they can all be targeted to apply preferentially to advanced manufacturing. Capstone project support can be contingent on

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[1] O.A. Owolabi, 2016, "Effective Learning Activities and Tool Adopted in an Online Engineering Class," *Transactions on Techniques in STEM Education in USA* 2(1):97-106.

pursuing the project through its manufacturing phase, which might use advanced manufacturing technologies. Or a company could negotiate with a faculty member to do research on a new material for additive manufacturing, even involving undergraduates in the research. Engineers from industry who are experienced in advanced manufacturing can serve as valuable advisors to engineering courses, teaching about or using advanced manufacturing. A company could donate industrial-quality additive manufacturing equipment that it uses in its factory so that students can learn to use it and perhaps develop improvements.

Government Support

The US government supports undergraduate engineering education as part of a broad agenda to enhance the country's economic development and competitiveness and to ensure national security. Global competition and offshoring of innovative technologies have, in the last few decades, led to concern about the country's manufacturing capacity. The DoD Manufacturing Technology Program (ManTech) invests on several fronts, including education and workforce development, to strengthen US manufacturing.[2] Government funding of manufacturing research and development (R&D), through the National Science Foundation (NSF), mission agencies (DoD, the Department of Energy [DOE], the National Aeronautics and Space Administration [NASA]), and others (e.g., the National Institute of Standards and Technology [NIST]) supports academic research, which is often an opportunity for undergraduates to engage and learn.

As with industry support, government support can target advanced manufacturing. NSF's Engineering Directorate supports advanced manufacturing research, and a new Directorate for Technology, Innovation and Partnerships (TIP), will emphasize translational (or applied) research; advanced manufacturing is a priority. NSF also supports manufacturing curriculum development, for example in the Division of Undergraduate Education, often supporting collaborations among educational institutions and industry. DoD, through its Manufacturing Innovation Institutes (MIIs), focuses manufacturing investment on advanced manufacturing.

Support through Partnerships

Industry, government, and academia have formed a number of partnerships to work together, acknowledging the linkages that connect the three components and the strengths that each can contribute to manufacturing. Government represents the national mission; industry represents specific innovations, technologies, and challenges; and academia represents the research and education necessary to advance knowledge and talent. Collaborative research is a common form of partnership. DoD, DOE, and NIST collaborate at least 50/50 with industry to support 16 institutes (including MIIs, mentioned above) in the Manufacturing USA public–private partnership. Each institute focuses on a different advanced manufacturing technology, offering technical materials, training, assistance to companies building advanced manufacturing capacity, and applied research projects.

Summary of Current and Augmented Support

The support mechanisms summarized above all contribute to undergraduate engineering education. Some, such as the innovation institutes, emphasize advanced manufacturing. Others, such as

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[2] Department of Defense (DoD) Manufacturing Technology Program, "Education and Workforce Development," https://www.dodmantech.mil/Education-and-Workforce-Development, accessed September 27, 2022.

the numerous programs that fund applied research, could amplify support for advanced manufacturing topics without requiring new funding or support pathways. There are many opportunities in the existing pathways to augment undergraduate engineering education for advanced manufacturing. Tables 4-1 to 4-5 and the short summaries below review the support mechanisms and suggest further augmentations and adjustments by various entities—industry, federal government, state and local governments, and professional societies.

Specific ways in which industry can augment its support include: sponsoring and engaging in collaborative applied research projects on advanced manufacturing topics; employing student interns and offering them assignments in advanced manufacturing; sponsoring advanced manufacturing capstone projects; and providing design and manufacturing assistance.

TABLE 4-1 Industry

Actors	Contributions to undergraduate education
DIB contractors, suppliers, manufacturing equipment vendors, others	Talks/videos about manufacturing innovations
	Equipment and software discounts, donations, grants
	Collaborative applied research
	Cocurricular projects (e.g., competitions)
	Employing student interns
	Co-op degree programs
	Faculty sabbaticals in industry
	Financial and mentoring support for capstone projects, especially those that address advanced manufacturing

The nine DoD MIIs (participants in the 16-member Manufacturing USA[3] network) are designed to spur innovation in manufacturing by providing access to state-of-the art equipment, organizing applied research projects in manufacturing technologies, and implementing "targeted education and workforce development (EWD) training programs."[4] The EWD programs focus on advanced manufacturing for skilled technical workers, but the programs and educational materials developed could also be used in the education of undergraduates. A recent study that reviewed "best practices in education and workforce development" for the MIIs presented a number of findings and suggestions for curriculum design and for scaling up education delivery that apply equally to undergraduate education.[5] The DOE and NIST institutes have similar opportunities.

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[3] DoD Manufacturing Technology Program, "Manufacturing USA," https://www.dodmantech.mil/Manufacturing-Collaborations/Manufacturing-USA, accessed September 27, 2022.

[4] DoD Manufacturing Technology Program, "Manufacturing Innovation Institutes," https://www.dodmantech.mil/Manufacturing-Innovation-Institutes/, accessed September 27, 2022.

[5] NASEM, 2021, *DoD Engagement with Its Manufacturing Innovation Institutes: Phase 2 Study Final Report*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26329.

TABLE 4-2 Federal Government with Industry Collaboration (focused on defense industrial base)

Actors	Contributions to Undergraduate Education
Manufacturing innovation institutes (DoD, DOE, NIST)	Training (mostly for industry) Educational materials Applied research, with industry Advanced manufacturing labs (access to fabrication equipment)

Specific ways in which the manufacturing institutes can augment support include: engaging undergraduates to participate in applied research projects undertaken by the institutes; adapting advanced training materials and courses to serve undergraduate engineering students, including offering online options; using institute-developed training materials to contribute to curriculum development for undergraduate engineering programs; and contributing experience and services of in-house advanced manufacturing equipment and labs to "remote factories" (Recommendation 4.8).

TABLE 4-3 Federal Government

Actors	Contributions to Undergraduate Education
NSF	Individual investigator applied/translational research (may be collaborative with industry) Curriculum development Academic engagement via IPA, peer review Engineering Research Centers (ERC) IUCRCs (Industry-University Cooperative Research Centers) REU (Research Experiences for Undergraduates) GOALI (Grant Opportunities for Academic Liaison with Industry)
Mission agencies (DoD, DOE, NASA, etc.)	Sponsored research, applied and use-inspired Internships, fellowships Small Business Innovation Research (SBIR) and STTR grants
NIST	Manufacturing Extension Partnership (MEP)
DOE Advanced Manufacturing Office	Industrial assessment centers (IACs)

NSF programs are ideal vehicles for supporting academic work; academics are familiar with NSF proposal and grant processes, and NSF has a broad array of programs that already serve undergraduate education.

Specific ways in which NSF can augment support include (1) supplementing applied research grants to include opportunities for undergraduate participation, either with Research Experiences for Undergraduates (REU) funding or research staff support; (2) focusing a new engineering research center (ERC), perhaps hybrid autonomous manufacturing, on advanced manufacturing, with collaboration/partnership with other government agencies and defense industrial base (DIB) manufacturers; and (3) allowing REU student research collaboration with industry, even at an industrial site. The new NSF directorate for Technology, Innovations, and Partnerships has programs in translational/applied research (see below).

The mission agencies sponsor research and development in national labs, industry, and universities. Advanced manufacturing is key to some of this work (e.g., additive manufacturing of aerospace components such as rocket nozzles and motors, turbine rotors, and complex mounting brackets). As with other applied research in advanced manufacturing, these projects might offer research experiences for undergraduates. The laboratories and research centers operated by these agencies provide internship opportunities; some fellowships exist and could be expanded.

Small Business Innovation Research (SBIR) grants go to small companies for focused applied research. SBIR focus areas could be expanded to include advanced manufacturing.[6] Companies with advanced manufacturing projects could seek solutions by working with teams of undergraduate students, perhaps as part of a capstone project. DoD could emphasize this focus in its solicitations and awards.

Both the NIST Manufacturing Extension Partnership and industrial assessment centers support focused R&D programs to enhance manufacturing in small and medium manufacturers. Their programs are opportunities to expand topics into advanced manufacturing, and to reach increased numbers of undergraduate engineering students and faculty. See Recommendations 4.6 and 4.7, below.

TABLE 4-4 State and Local Governments

Actors	Contributions to Undergraduate Education
Economic development offices	Economic development initiatives that bring industrial support for local educational institutions

State initiatives for economic initiatives may include equipment, mock-up manufacturing lines, training, and other mechanisms that can support advanced manufacturing education. Mock-up lines are a perfect opportunity for students at all levels to work on manufacturing equipment, using both established and advanced manufacturing technologies, and to work with industry in identifying new technologies.

State and local initiatives often bring industry to a region, and there are opportunities to engage local academic institutions in many ways. Academics can recruit adjuncts or professors of the practice, sponsorship and real manufacturing mentoring for capstones, and joint advanced development projects, for example. A major new local employer will often sponsor educational initiatives to meet its needs.

Professional societies aggregate academic and industry influence to induce changes that have broad scope, such as government funding, standards development (such as certification), and curriculum objectives, such as those of ABET (see Recommendation 2.2).

Professional societies are also mounting “challenge” competitions to focus modern manufacturing capabilities on problems that resonate with the public. For example, the 2023 Digital Manufacturing Challenge calls on designers and engineers to go beyond the classroom or laboratory and showcase their technical and commercial talents by demonstrating new and creative ways digital manufacturing can add value.[7]

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[6] DoD, 2022, “Small Business Innovation Research (SBIR) Program, SBIR 22.2 Program Broad Agency Announcement (BAA),” issued for pre-release April 20, https://media.defense.gov/2022/Apr/15/2002977654/-1/-1/1/DOD_22.2_FULL.PDF, p. 5.

[7] SME, “Digital Manufacturing Challenge,” https://www.sme.org/aboutsme/awards/digital-manufacturing-challenge, accessed September 25, 2022.

TABLE 4-5 Professional Societies (academic, industry members)

Actors	Contributions to Undergraduate Education
ASEE, SME, ASME, etc.	Curriculum modernization Learning platforms (e.g., SME's Tooling-U, ASME's virtual classrooms)

RECOMMENDATIONS

In light of the above considerations, the committee offers the following recommendations for actions by government and industry, either jointly or separately:

> **Recommendation 4.1: Industry and government should augment and adjust their support for undergraduate engineering education to emphasize both advanced manufacturing (either direct support of degree programs or support to build academic capacity) and benefits for undergraduate engineering education (direct or indirect, e.g., via participation in applied research programs).**

There are many ways these objectives can be met; some augmented support mechanisms are sketched in the tables and text above. Support from industry or government for capstone projects, especially those that involve direct exposure to advanced manufacturing, is a prime example of an existing support path that can be strengthened.

New Opportunities for Industrial Support

Adjunct Roles for Industry Engineers in Academia

Many academic engineering programs would benefit from more manufacturing experience among their faculty, instructors, and advisors. Although industry engineers spending sabbaticals at a university might be ideal, it is rare that their employers will consent. However, employees could be permitted to serve as "remote adjuncts" in limited roles, such as overseeing design projects, critiquing designs, or lecturing about particular additive manufacturing processes. The adjuncts' time commitment could be limited, and almost all their work could avoid absence from their job by using remote collaboration tools. They would get not only thanks but professional credit for the work, and their employers would probably welcome the implicit opportunity to recruit students.

> **Recommendation 4.2: Industry leaders should allow engineers with advanced manufacturing experience to contribute expertise and experience to academic engineering programs as "remote adjuncts." With remote collaboration tools, the burden on the employer and employee should be modest and limited.**

Fraunhofer-Like Programs for Manufacturing

The model of government-industry-academia collaboration practiced by the Fraunhofer institutes in Germany is viewed by many as a successful way to bring technical innovations to market. "Students who choose to work on projects at Fraunhofer Institutes have excellent opportunities to start and develop a career in industry through the practical training and experience they acquire."[8] This is a concrete model of applied research as an educational engine.

Fraunhofer recently launched a cooperative program with the University of South Carolina to stimulate technical and manufacturing resources in the state. This program is not unlike that of the research centers that Google and Microsoft have established attached to major university research departments active in computer and information technologies. The US manufacturing institutes were originally intended as Fraunhofer-like entities.

Recommendation 4.3: DoD should conduct a focused pilot program that pairs a single university and a single large defense contractor to explore Fraunhofer-like structures and practices for applied research, technology transfer, and undergraduate education. The focus should be advanced manufacturing but may be further narrowed to ensure that modest-sized research efforts result in industrial impact.

Develop Capstone Project Portfolios for Advanced Manufacturing

Capstone projects—or other project courses—are an ideal way to introduce advanced manufacturing, usually as 3D printing. Many students will have already done 3D printing as part of makerspace experiences in high school or college or in engineering labs, and will be ready for new challenges, such as trying to make final parts (net shapes) within specific tolerances. Or learning how manufacturing deviations affect certain kinds of assemblies. Or devising experiments to determine the "design rules" that characterize what can be successfully built by a particular machine and material. Or exploring how best to convert a particular "near net shape" produced by additive manufacturing to a final accurate net shape.

A portfolio of project plans that explore different aspects of advanced manufacturing would reduce the uncertainty and course development efforts required for these courses. The plans could also cover a range of advanced manufacturing methods and equipment, and provide links to fabrication services that can support students using them.

Recommendation 4.4: The manufacturing institutes, in conjunction with industry and academic collaborators, should develop a portfolio of "capstone projects" that present students with a range of problems in real advanced manufacturing. The projects should span a range of difficulty and of advanced manufacturing services (and/or equipment) required. (Manufacturing services available in the institutes may be one resource; see also Recommendation 4.8.) The portfolio needs to be actively updated, with feedback as projects are undertaken and with new plans as new ideas or advanced manufacturing equipment become available.

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[8] R. Klinger and L. Behlau, 2012, "Bridging the Gap Between Science and Industry: The Fraunhofer Model," *STI Policy Review* 3(2):130-151, p. 132.

New Opportunities for Government Support

Technology, Innovation, and Partnerships

In March 2022 NSF announced a new Directorate for Technology, Innovation and Partnerships (TIP),[9] which represents a transition from its focus on academic fundamental research to sponsor more applied and translational research, with active participation by industry and nonprofit organizations. The new directorate is to "rapidly bring new technologies to market and address the most pressing societal and economic challenges of our time."

On August 9, 2022, President Biden signed into law the CHIPS and Science Act,[10] which authorizes funding increases for NSF (minus the new directorate) of $1.2 billion in fiscal year 2023, increasing to $13.8 billion in fiscal year 2027. The law authorizes $1.85 billion for the TIP directorate in fiscal year 2023, increasing to $5.1 billion in fiscal year 2027, at which point it will be 27 percent of the total agency budget.[11] Plans for the directorate highlight advanced manufacturing, supplementing support from other NSF directorates.[12] The new directorate is a paradigm shift for NSF (Table 4-6).

In addition to new TIP programs, NSF will move several existing programs to the new directorate: SBIR/STTR small business R&D programs, the Innovation Corps (I-Corps) entrepreneurial education program, Convergence Accelerators, and Partnerships for Innovation (PFI). In September 2022 NSF announced a partnership between the Convergence Accelerator program and DoD (OUSD(R&E) in a $12 million program to advance 5G technologies and communications for US military, government, and critical infrastructure operators.[13]

TABLE 4-6 Directorate for Technology, Innovation and Partnerships: A Paradigm Shift for NSF

Today	Tomorrow
Largely investigator-driven	Users/beneficiaries engaged in shaping, conducting research
Primarily academic research teams	Multisector teams—academia, industry, government, civil society, communities of practice
Stream of discoveries improve prosperity, resilience, quality of life	Important societal and/or economic problems drive research pursuits
"Technology/supply push" +	"Market/demand pull"

SOURCE: Jesús Soriano Molla, Perspectives from National Science Foundation on the Technology Innovation Partnership program. Presentation to the committee on August 10, 2022.

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[9] U.S. Science, 2022, "NSF Establishes New Directorate for Technology, Innovation and Partnerships," News Release 22-002, March 16, https://www.science.us.com/nsf-establishes-new-directorate-for-technology-innovation-and-partnerships/.

[10] See https://science.house.gov/imo/media/doc/chips_and_science_act_section_x_section.pdf. Accessed September 23, 2022.

[11] See https://science.house.gov/imo/media/doc/division_b_sst_fact_sheets.pdf. Accessed September 23, 2022.

[12] See https://beta.nsf.gov/events/intro-nsfs-directorate-technology-innovation-and-partnerships/2022-09-27. Accessed September 27, 2022.

[13] See https://beta.nsf.gov/funding/initiatives/convergence-accelerator/updates/nsfs-convergence-accelerator-dod-partner-12. Accessed September 23, 2022.

Regional Innovation Engines

One of the major new TIP programs is the Regional Innovation Engines (RIE) program, which will fund RIE centers with up to $16 million annually over 10 years.[14] The RIE program supports collaboration between industry and the academic community and provides industry participants the opportunity to help set the agenda and focus applied research efforts on issues that are important to them for economic growth. It is anticipated that the NSF effort will complement other ongoing efforts such as those in other NSF directorates, federal programs at mission agencies such as DoD, DOE, and NASA, and state and private-sector programs. Best practices developed at other large funded centers such as MIIs and innovation hubs such as those at DoD and DOE may apply to the RIE centers as well.

NSF recently initiated a solicitation for concept papers.[15] The program will prioritize geographic regions that do not have well-established innovation ecosystems. The program can be led by universities, for-profit entities, and nonprofit organizations. Funding can be provided to national laboratories, federally funded research and development centers, and state and local governments. In August 2022, NSF announced that 679 concept outlines had been received. They came from all 50 states and four US territories; 407 were submitted by higher education institutions, 168 by nonprofits and government, and 104 from industry, including incubators. Advanced manufacturing, with about 100 concept outlines, was the most popular topic of interest.

It is not clear at this point whether RIE or other TIP programs will have focused topics or open solicitations or a combination of both. ARPA-E has successfully used both approaches.[16] Focused programs would have industry and academia identify specific technologies and education components appropriate for applied research. Open solicitations could be for potentially disruptive technologies along a broad path of applied research.

Translational/Applied Research Program

If TIP is funded as expected, it has an opportunity to initiate an investigator-driven applied research program that may be similar in size and length to programs in other NSF directorates. For example, programs could be funded at a total of $2 million to $10 million over a 3-year period. The portfolio could be developed with industry and universities working collaboratively to identify advanced technologies and educational components including undergraduate engineering student participation (see Recommendation 3.3). These could be open or focused solicitations. In the larger RIE programs, academic applied research will be focused on research applicable to the goal of the sponsoring regional center, but TIP can also support investigator-driven applied research, not related to an engineering program but important for meeting TIP goals of developing new technologies and products to create new jobs, grow the economy, and increase US competitiveness.

In all TIP programs, there are opportunities to support advanced manufacturing in undergraduate engineering education. For example, TIP could support industry internships and work-study programs. Funding could be provided for faculty to spend sabbaticals or summers in industry, and industry employees to work at universities, with faculty and students involved in the project. Translational research programs could favor industry/academic collaborations in which industrially important problems are proposed. There could be funding for advanced manufacturing equipment at the university, and for the centers and practicums in the centers. The RIE centers could use some funds to support regional "learning factories" that can be used by a number of universities to provide students with hands-on learning for advanced manufacturing (see Recommendation 4.8).

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[14] See https://www.nsf.gov/pubs/2022/nsf22082/nsf22082.pdf. Accessed September 23, 2022.

[15] Ibid.

[16] NASEM, 2017, *An Assessment of ARPA-E*, Washington, DC: The National Academies Press, https://doi.org/10.17226/24778.

NSF has a history and culture of funding excellent peer-reviewed use-inspired research at universities and colleges. The new TIP directorate with the planned funding levels offers a major opportunity for academia and the private sector to jointly plan and implement applied research programs that will accelerate development of new technologies and products, involve undergraduate engineering students in applied research programs, and provide industry an opportunity to engage more actively in NSF program management, for example as peer reviewers and through the Intergovernmental Personnel Act (IPA).

> **Recommendation 4.5: NSF's TIP Directorate provides an opportunity for a vigorous translational research program, some of which should be investigator- or industry-initiated. Programs such as RIE should provide support opportunities for undergraduate engineering students. A focused joint DoD-NSF RIE program should be conducted to address an advanced manufacturing technology. The participants should include at least one major defense company in the region, small and medium sized defense supply companies, educational institutions that offer advanced manufacturing courses at the bachelor's level, and community colleges.**

Focusing MEP and IAC on Advanced Manufacturing for the Defense Industrial Base

There are several government programs that provide technical assistance to small and medium manufacturers and an opportunity for undergraduate engineering students to obtain practical experience in an industrial setting.

NIST Hollings Manufacturing Extension Partnership (MEP)

NIST'S MEP has a national network of centers located in all 50 states and Puerto Rico. Pravina Raghavan, MEP Director, gave an update of the MEP at the committee's workshop (see summary of the workshop in Appendix B, "Efforts by Government and Nonprofit Institutes"). The centers work to provide small and medium-sized manufacturers with the resources needed to improve operations, develop new products and customers, adopt new technologies, enhance value within the supply chains, and be competitive in the global marketplace.

The federal government pays half the support for each center, with the balance funded by state/local governments and/or the private sector. Of the 51 centers, 18 are at universities, which provides a direct interaction between industry and academia; 25 centers are nonprofit organizations; and 8 are state based. The nonuniversity members usually have a strong connection with one or more universities. The universities provide access to potential employees as well as to new technologies. MEP centers work directly with university students to support manufacturing projects, through either unofficial internships or cooperative education programs where students are paid. In addition, MEP centers are helpful with capstone projects.

A 2021 study of the Manufacturing Innovation Institutes notes that they should engage with the MEPs.[17] MEPs are shifting from focus on lean manufacturing to the adoption of digital and advanced manufacturing technologies. The report states that the collaboration could be beneficial for technology adoptions, strengthening the manufacturing ecosystem in addition to training a skilled workforce.

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[17] NASEM, 2021, *DoD Engagement with Its Manufacturing Innovation Institutes: Phase 2 Study Final Report*, Washington, DC: The National Academies Press, https://doi.org/10.17226/26329.

DOE Industrial Assessment Centers (IACs)

The Department of Energy (DOE) Advanced Manufacturing Office (AMO) supports R&D projects, R&D consortia, and early-stage technical partnerships with national laboratories, companies (for-profit and not-for-profit), state and local governments, and universities through competitive, merit-reviewed funding opportunities designed to investigate new manufacturing technologies. The major push in AMO is decarbonization.[18]

Becca Jones-Albertus, AMO interim director, DOE Office of Energy Efficiency and Renewable Energy, spoke to the committee about AMO programs including the Industrial Assessment Centers (IACs), which provide no-cost energy assessments for small and medium-sized manufacturers. There are 35 centers at universities across the country. The Infrastructure Investment and Jobs Act (HR 3684, Sec. 40521) appropriates $150 million over 5 years for IACs to help small and medium-sized manufacturing plants identify possible energy-efficient improvements, and a $400 million grant program helps implement the recommendations. The IACs have typically been housed at 4-year institutions with undergraduate engineering programs where students receive hands-on assessment training and knowledge of industrial processes. The funding offers opportunities to reach increased number of undergraduate engineering students and faculty.

Some of the new funding is for expansion to community colleges, union apprenticeships, and other activities to encourage more diverse workforce participation.

Both MEP and IAC support undergraduate engineering students and are expanding. They could provide DoD with collaborative programs involving small and medium-sized companies. Several IACs and MEPs are collocated at the same university center. MEP covers all of the industrial SIC codes; IACs focus on energy assessments.

> **Recommendation 4.6: Agencies in addition to DoD and NSF should provide opportunities for students and faculty to spend time in small and medium sized manufacturing companies. DoD should partner with the NIST MEP to develop and implement a pilot MEP-style program to benefit small and medium sized suppliers to the defense industrial base. Both NIST/MEP and DOE/IAC should grow their support for advanced manufacturing and for undergraduate engineering students and faculty. DoD should provide funding for eight MEP centers hosted by universities for the pilots. Criteria should include advanced manufacturing operations or technologies in the participating small and medium-sized businesses they are working with, and coverage for undergraduate engineering majors and faculty. Each of the MEPs should address a different advanced manufacturing technology. At least two of the centers should be at universities where MEP and IAC are collocated.**

DoD Advanced Manufacturing Fellowships

Most of the individual fellowships awarded by the federal agencies (e.g., NSF, DoD, NASA, DOE) are for graduate or postdoctoral students. Undergraduate support is available through the Reserve Officers' Training Corps, but these target a broad spectrum of disciplinary backgrounds that may or may not be STEM related. The DoD Science, Mathematics, and Research for Transformation (SMART) scholarship program provides funding and training for both graduate and undergraduate in STEM.[19]

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[18] See https://www.energy.gov/eere/amo/advanced-manufacturing-industrial-decarbonization-offices. Accessed September 23, 2022.

[19] See https://www.smartscholarship.org/smart. Accessed September 23, 2022.

Students who participate in the SMART scholarship program are required to spend summers at DoD facilities and then a 12-month period as a full-time staff member at a DoD facility as a civilian staff member.

The Innovation in Buildings (IBUILD) program of the DOE's Building Technology Office offers 3-year graduate research fellowships for PhDs in areas related to the mission of building energy efficiency. "The fellowship provides opportunities for professional development outside the home institution, including mentoring and internships at national laboratories."[20] Students can also stay at their home institution. A fellowship for advanced manufacturing students could be a 2-year program beginning in the student's junior year. It would cover tuition, room and board expenses, and a summer internship doing applied research at the home institution, a service laboratory, military facilities such as arsenals, or a national laboratory.

> **Recommendation 4.7: DoD should initiate a pilot program of undergraduate engineering applied research fellowships, to be administered by the Departments of the Army, Navy, and Air Force. The initial cohorts should be from advanced manufacturing or mechanical engineering departments. The military laboratories, national laboratories at DOE and NASA, and the MIIs should invite these students to participate. If successful, the program should be expanded to all undergraduate engineering students.**

Remote Factories

Most universities can provide "desktop prototype" advanced manufacturing equipment (e.g., 3D printers for polymer materials), but to learn about or pursue applied research in advanced manufacturing, access to industrial-quality equipment is essential.

Access to industrial equipment and processes could be provided in several ways. Commercial vendors provide additive manufacturing services through the internet (e.g., Proto Labs[21] and Quickparts[22]). Several MIIs operate small labs with various advanced manufacturing equipment that could be accessed via the internet. Or one of more entirely new "factories" could be established, operating similar equipment via identical network interfaces. But because advanced manufacturing and its equipment are advancing rapidly, a large commitment to a fixed service is unwise.

NSF offers researchers (and sometimes students) discounted internet access to facilities or services that are not practical for universities to provide themselves or to obtain at full market price. NSF makes commercial cloud computing resources available to computer science researchers through CloudBank[23] and has also enabled Access to Semiconductor Fabrication.[24] In a similar way, NSF could provide access to advanced manufacturing services.

Many users of industrial advanced manufacturing services will need assistance in the form of advice from the services vendor or other knowledgeable engineer. (See Recommendation 4.2.)

> **Recommendation 4.8: NSF should facilitate network access by undergraduate engineering students and faculty to industrial-quality advanced manufacturing services. Advice from users should be used to, for example, select appropriate services and ensure easy access using common software tools.**

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[20] See https://ibuildfellowship.org/. Accessed November 16, 2022.

[21] See https://www.protolabs.com/. Accessed September 25, 2022.

[22] See https://www.cloudbank.org/. Accessed September 25, 2022.

[23] See https://quickparts.com/rapid-prototyping/. Accessed September 25, 2022.

[24] See https://www.nsf.gov/pubs/2022/nsf22113/nsf22113.pdf. Accessed September 25, 2022.

Advanced Manufacturing Curriculum Development

The Advanced Manufacturing Curricula section in Chapter 2 describes the desirable characteristics of an advanced manufacturing curriculum for undergraduate engineering education. Although a single professor can create a superb course, educational materials that meet most or all of the expectations we have described are not likely to emerge spontaneously. Since NSF sponsors curriculum development as well as research to improve pedagogical techniques, it is a good choice to sponsor an advanced manufacturing curriculum.

Recommendation 4.9: NSF should sponsor one or more projects to develop advanced manufacturing curricula with the properties described in the Advanced Manufacturing Curricula section in Chapter 2. Curricula should be open, easily updated, and applicable in multiple educational settings.

Synergies Among Support Recommendations

An objective of this study was to identify mechanisms that could improve the education and supply of engineers for the DIB. Many of the committee's recommendations cannot be implemented rapidly, or are likely to affect only a limited number of undergraduate engineering programs and students. But capstone courses may offer a promising approach, due to several properties:

- Capstone and other hands-on courses are widely implemented in undergraduate engineering programs.
- Course projects often build prototypes, often using desktop additive manufacturing equipment.
- Experimentation in these courses is easier than in other parts of the engineering curriculum.
- Faculty, often collaborating across disciplines, often lead these courses.
- Industry supports many of the courses and/or their projects.

An engineering program could offer one or more sections of these experiential learning courses that have an explicit focus on advanced manufacturing (see Box 4.1).

BOX 4-1
Capstone Course Focused on Advanced Manufacturing

The combined results of several recommendations could bring advanced manufacturing to undergraduate engineering education rapidly, at large scale, and without major impact on existing (often "packed") undergraduate engineering curricula. For example, bring together:

- Capstone project formulations that require industrial-quality advanced manufacturing technologies (Recommendation 4.4)
- Industry engineers serving as adjunct advisors to capstone projects (Recommendation 4.2)
- Advanced manufacturing services, probably offered via internet access to "remote factories" (Recommendation 4.8)

5

Engineering Education for a Changing Future

Engineering and manufacturing are changing rapidly. The impetus for this report, a view that undergraduate engineering education must change to prepare students for new engineering and manufacturing landscapes, will persist and may increase as the fields continue to change.

Many of the technologies represented by "advanced manufacturing" have yet not reached mature roles in the manufacturing industry, but their trajectory, momentum, and promise are palpable. They build on components that have huge markets with expanding scope and declining price: computers, microelectronics, sensors, internet communications and services, artificial intelligence platforms, open-source software, virtual reality visualizations, digital representations of final parts and the processes to produce them, and many more. Advanced manufacturing generates innovations in two ways: in existing manufacturing techniques, equipment, and software, and in novel manufacturing approaches, tools, and processes.

This report makes recommendations for improving undergraduate education in advanced manufacturing given the state of today's advanced manufacturing technologies and their propagation in education and industry. This chapter looks a bit farther ahead to anticipate changes in advanced manufacturing and thus new expectations for undergraduate education.

Undergraduate education programs can prepare graduates in several ways for changes to engineering during their careers. Faculty and professional organizations are discussing ways to meet future needs, and some engineering programs are making changes accordingly. Doubtless the following suggestions developed in this chapter have occurred to many and are being addressed by some:

- Develop an engineering ecosystem for teaching and learning;
- Anticipate likely evolutions of advanced manufacturing; and
- Produce graduates who are sufficiently digitally proficient to function in a complex digital environment.

The chapter concludes with a vision for the engineering ecosystem.

DEVELOP AN ENGINEERING ECOSYSTEM FOR TEACHING AND LEARNING

In pursuing its study, the committee was struck by the speed and excitement of change in manufacturing and the need for those innovations to be diffused rapidly through a large and diverse engineering community. Innovation is outpacing teaching and learning.

Because an undergraduate degree does not cover all a student needs to know to be a practicing engineer, graduates must know how to learn on the job, both because the job requires knowledge and skills that are not covered by an undergraduate program and because the nature of the job will change over time. Most undergraduate programs require students to learn some things on their own. For example, many first-year mechanical engineering students are expected to master an interactive solid-modeling application on their own, using video tutorials and optional assistance from a teaching assistant (admittedly, some students will have achieved mastery in high school or earlier). Problem sets can stretch to require students to learn new mathematics or techniques. And design courses can require learning about new materials or vendor offerings.

A design engineer needs to know the opportunities and limitations of the manufacturing services available to her. Traditional factory machinery is usually introduced in engineering education programs, but new equipment and processes—such as in advanced manufacturing—will require the designer to learn both basics and details. While some of this information will be covered by instruction manuals or online training, ultimately the designer will need to ask questions and take advice from the engineers or technicians in the factory, seeking facts, ideas, and suggestions.

Engineering educators are rightly calling for training students to "learn to learn" or to become "lifelong learners." How can education techniques and the rest of the engineering community help? The committee offers the following suggestions:

- Challenge students with a capstone design that requires materials or techniques that they have not encountered. Assess the manufacturability and cost of a project. Find information on the internet. Better yet, find an expert.
- Recruit engineering alumni to critique student designs one-on-one using online collaboration tool. "Curate" alumni according to their expertise, to make it easy for students to find assistance.
- Would-be employers might also offer online critiquing by their experts. It's a way to evaluate and recruit a student while also helping the student.
- Vendors of advanced manufacturing equipment and software publish tutorials, specifications, manuals, and application notes on the network. By banding together (perhaps through a trade association) they can build a federated, curated database so students can easily find information from different vendors of similar products.
- The various manufacturing institutes (e.g., MIIs, MEP) could play a bigger role in teaching and learning, both for undergraduates and for engineers later in their careers, brokering connections between teachers and learners, especially mixing different types of industries and educational institutions.
- Encourage technical conferences and trade associations to make papers and presentations available for free online. For example, USENIX (the Advanced Computing Systems Association) makes proceedings of all conferences, symposia, and workshops since 1993 freely accessible online.[1] The manufacturing institutes could host and curate repositories of research papers and educational materials.

ANTICIPATE LIKELY EVOLUTIONS OF ADVANCED MANUFACTURING

Advanced manufacturing is not mature: every day brings news of new devices, new materials, new structures, new demonstrations, and new applications. Many of these are not yet ready for routine use; some may be usable only for making prototypes; and only a few are ready for production. Despite rapid developments and improvements, the fundamental techniques emerging in advanced manufacturing, especially in additive manufacturing, digital control, and robotics, and their influence on engineering design, seem certain to endure. A comprehensive undergraduate education that covers these fundamentals will make it easier for an engineer to adapt to evolving changes, such as:

- New additive manufacturing methods, many of which are modest derivatives of those already introduced. Increased emphasis on working volume, speed, and cost.

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[1] See https://www.usenix.org/. Accessed October 4, 2022.

- New materials. Additive manufacturing can combine multiple materials to make a single part. Sintering from powder beds has demonstrated alloys with new combinations or concentrations of materials; some have unequalled strength. And extruded materials can be combined, much the way a resin and its hardener are sprayed for insulation and coatings.
- New composite, multilayer, and multimaterial capabilities. Additive techniques can build multilayer structures or patterned layouts of different materials (e.g., tiling). Composite improvements include affordable out-of-autoclave resin systems and environmentally sustainable layup materials and solvents.
- New structures. Additive manufacturing can build parts with voids or channels, such as used for cooling (e.g., turbine blades, heat exchangers) or for conveying fluids in a network to implement control or mixing systems. New kinds of fixturing or sacrificial support structures for additive manufacturing may emerge.
- Robotic manipulation. Robots large and small have demonstrated additive techniques, such as forming concrete foundations and walls, or welding. Automation improvements include autonomous robotic training and system-of-system coordination.
- Greater dependence on modeling and simulation and the use of artificial intelligence analysis for engineering design, manufacturing process modeling, sequencing, and automation.

Other emerging technologies may not yet be visible on the horizon, but seem inevitable:

- Volume additive manufacturing. Today's additive machines work for low-volume parts; surely some higher-volume designs will emerge. But for what additive technologies and materials? With how much flexibility in part type?
- Factory automation. Build a near-net-shape using laser sintering, remove it, transport it to a CNC mill to create the final shape, then maybe to another machine to measure it. A simple extension of "flexible manufacturing" techniques, extended for example with a robot to grip the sintered part. This is a simple example; more complex and customized configurations are sure to be developed. What machines will be linked in a typical automated "advanced manufacturing factory?" Will small-scale robots be the key to flexibility to handle different part shapes? What about assembly?
- Automated metrology in manufacturing to validate parts and assemblies in real time during processing, perhaps adjusting a manufacturing process accordingly.
- Data integration to connect information in design and manufacturing systems to a complete product life cycle, including engineering, manufacturing, component supply, operation, and sustainment.

Of course, not all of these futures can be covered in undergraduate education, no matter how forward-looking, but some may trigger additional educational coverage. For example, the legacy portfolio of materials (a dozen kinds of aluminum and steel) will be inadequate for additive manufacturing opportunities. Engineers will have to have greater knowledge of, and participation in, the development, characterization, testing, and applications of materials, many of which will be new.

Applied research will be important in evolving advanced manufacturing. US funding and pursuit of applied research in academia appear to be growing. NSF's new Directorate for Technology, Innovation and Partnerships is one recent example (see Recommendation 4.5) and some universities are increasing emphasis on applied research and on the opportunities it offers to engage students and contribute to their education. While US activities are much less fully developed than the German system exemplified by the Fraunhofer Institutes, advanced manufacturing and engineering students will benefit from the growth of applied research.

ENSURE SUFFICIENT DIGITAL PROFICIENCY FOR GRADUATES TO FUNCTION IN A COMPLEX DIGITAL ENVIRONMENT

Engineering design and manufacturing depend on digital representations of designs, processes, and results. Designers use software to create digital models of their designs, which ultimately feed manufacturing processes such as CNC or 3D printing.

The term “digital thread” is apt for describing the passage of digital representations in the paths from design to manufacturing: intervening steps may involve software to analyze and adjust a design for performance properties, manufacturability, cost reduction, and so forth. Software may be able to simulate the design’s operation to determine that it will work correctly as well as extract characteristics of the design such as cost, producibility, weight, and thermal performance. The digital path is also accompanied by additional steps and annotations, for example to incorporate changes, record the results of design or requirements reviews of the project, or develop and check fixtures needed during manufacturing. The path may also lead via digital networks to vendors or customers who perform specialized analyses or check that a design will mate properly to an assembly of parts produced by others.

The digital thread is not new,[2] but the concept and implementations are now being widely adopted and implemented in the DIB and its supply chains. The growth of the digital thread is due in part to design and manufacturing processes and equipment that increasingly create or consume digital specifications, and in part to a growing ecosystem of software and vendors (including system integrators) that offer software products to operationalize the concepts. The availability and widespread use of CAD software were the nuclei of the digital thread. CAD models can be transformed (sometimes requiring human guidance) into digital data to drive manufacturing equipment such as CNC mills and 3D printers. They can also be used to visualize and inspect parts and assemblies, for example to present a virtual reality “walkthrough” of an airplane’s interior.

Digital Twins

A digital twin is a computer model (or “virtual representation”) of a physical asset or process, often encompassing its entire life cycle (see Box 5-1). It is valuable because creative and analytic work on the asset can be done using computers and software tools (the “virtual environment”) before the asset is built. A solid model of an asset created with CAD software may be part of the asset’s digital twin, which may also include test data, simulation scripts, predicted operating parameters, and more. When the asset is realized, as-built measurements may augment the model, as may measurements of operating parameters and their evolution over time as the asset ages. Maintenance events and design upgrades, such as block upgrades of military equipment, can be recorded. A twin can record both real-time measurements of the physical asset and data computed by simulation. It can also include manufacturing twins that can predict build staffing, tool counts, factory space, potential bottlenecks, and capital requirements.

Digital twins to drive modeling and simulation of various product behaviors and capabilities in aerospace or commercial markets are typically created early in product development cycles and validated during product testing and validation. In some aerospace products these cycles can be as long as 20 years because of extensive structural and flight-testing requirements. In the future, modeling and simulation of digital twins are envisioned to eventually reduce product testing and validation requirements, manufacturing risk, and overall product development cost and span.

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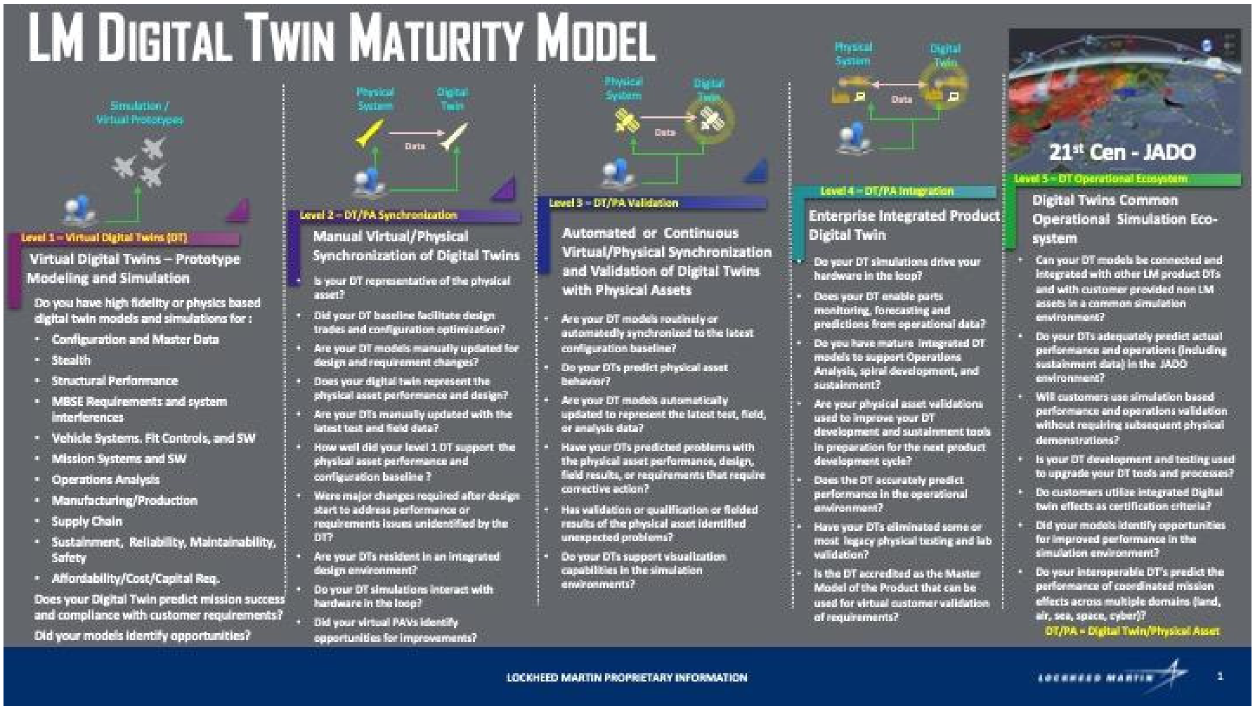
[2] Computers have long been used as digital design aids, for example to record the schematic circuit diagram of a new computer design and simulate the new circuit. In the 1960s it was common for designers to develop ad hoc design and simulation software for these tasks. They also wrote software to transform the circuit diagram into a series of wiring steps to build the circuit. The simulator and the circuit could then be executed step-by-step to ensure that behavior of the circuit (as wired!) matched the simulation. The hardware and the custom software with its data thus represented a limited form of digital twin.

Lockheed Martin sees digital twin models increasing in size and scope as a product is developed, manufactured, and operated (see Figure 5-1). Level 1 digital twins of various product capabilities aim to increase initial product maturity (reduce program risk) prior to engineering release. Levels 2 and 3 use product testing to feed and enhance the digital twins, leading to level 4 digital twins that accurately represent the physical assets and can be used to validate requirements to customers. Level 5 twins are capable of engaging other twins either from Lockheed Martin or provided by the customer in a common digital ecosystem for mission planning and customer accreditation. The more mature the digital twins, the fewer disruptions during the product development cycle, thus reducing manufacturing costs and span times.

Digital twins can be very simple, or complex comprehensive models of large products. In practice, they are often realized as a set of separate but related digital models. For example, at Lockheed Martin, there is no single twin to represent the extraordinarily complex F-35 fighter jet, but subsystems may have their own twins (e.g., for fuel, radar, engine, hydraulics). Models may be simple at the outset, but grow in fidelity and complexity as a design progresses and more accurate analysis is required to ensure that it meets performance targets. Building complex models that are consistent with other, related models and are sufficiently accurate models of reality can be very difficult.



LM DIGITAL TWIN MATURITY MODEL

Level 1 – Virtual Digital Twins (DT)

Virtual Digital Twins – Prototype Modeling and Simulation

Do you have high fidelity or physics based digital twin models and simulations for :
- Configuration and Master Data
- Stealth
- Structural Performance
- MBSE Requirements and system interferences
- Vehicle Systems. Flt Controls, and SW
- Mission Systems and SW
- Operations Analysis
- Manufacturing/Production
- Supply Chain
- Sustainment, Reliability, Maintainability, Safety
- Affordability/Cost/Capital Req.

Does your Digital Twin predict mission success and compliance with customer requirements?

Did your models identify opportunities?

Level 2 – DT/PA Synchronization

Manual Virtual/Physical Synchronization of Digital Twins
- Is your DT representative of the physical asset?
- Did your DT baseline facilitate design trades and configuration optimization?
- Are your DT models manually updated for design and requirement changes?
- Does your digital twin represent the physical asset performance and design?
- Are your DTs manually updated with the latest test and field data?
- How well did your level 1 DT support the physical asset performance and configuration baseline ?
- Were major changes required after design start to address performance or requirements issues unidentified by the DT?
- Are your DTs resident in an integrated design environment?
- Do your DT simulations interact with hardware in the loop?
- Did your virtual PAVs identify opportunities for improvements?

Level 3 – DT/PA Validation

Automated or Continuous Virtual/Physical Synchronization and Validation of Digital Twins with Physical Assets
- Are your DT models routinely or automatedly synchronized to the latest configuration baseline?
- Do your DTs predict physical asset behavior?
- Are your DT models automatically updated to represent the latest test, field, or analysis data?
- Have your DTs predicted problems with the physical asset performance, design, field results, or requirements that require corrective action?
- Has validation or qualification or fielded results of the physical asset identified unexpected problems?
- Do your DTs support visualization capabilities in the simulation environments?

Level 4 – DT/PA Integration

Enterprise Integrated Product Digital Twin
- Do your DT simulations drive your hardware in the loop?
- Does your DT enable parts monitoring, forecasting and predictions from operational data?
- Do you have mature integrated DT models to support Operations Analysis, spiral development, and sustainment?
- Are your physical asset validations used to improve your DT development and sustainment tools in preparation for the next product development cycle?
- Does the DT accurately predict performance in the operational environment?
- Have your DTs eliminated some or most legacy physical testing and lab validation?
- Is the DT accredited as the Master Model of the Product that can be used for virtual customer validation of requirements?

Level 5 – DT Operational Ecosystem

Digital Twins Common Operational Simulation Eco-system
- Can your DT models be connected and integrated with other LM product DTs and with customer provided non LM assets in a common simulation environment?
- Do your DTs adequately predict actual performance and operations (including sustainment data) in the JADO environment?
- Will customers use simulation based performance and operations validation without requiring subsequent physical demonstrations?
- Is your DT development and testing used to upgrade your DT tools and processes?
- Do customers utilize integrated Digital twin effects as certification criteria?
- Did your models identify opportunities for improved performance in the simulation environment?
- Do your interoperable DT's predict the performance of coordinated mission effects across multiple domains (land, air, sea, space, cyber)?

DT/PA = Digital Twin/Physical Asset

LOCKHEED MARTIN PROPRIETARY INFORMATION

LOCKHEED MARTIN

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FIGURE 5-1 Lockheed Martin digital twin models.
SOURCE: https://www.lockheedmartin.com/en-us/news/features/2021/visualizing-the-digital-thread-and-digital-twins.html. Accessed October 4, 2022.

Modeling and Simulation

Most engineering disciplines today are fully engaged with digital methods and the digital threads that link them into engineering processes from design to realization, whether expressed as a collection of related data and tools or as a digital twin. Software tools are available to build and modify models, to run simulations, and to do various kinds of design analysis. An engineering design team may need to use many different software tools, data formats, and vendor services to develop the digital picture of a design.

Modeling and simulation are introduced in undergraduate education, often through simple examples or linkages or crankshafts in MATLAB. Solid models are augmented with models of motion for joints, bearings, and the like. Visualizations of simulations show the results of motion of the moving parts.

Modeling and simulation are the power behind digital twins—and they can become very complex. The fidelity of the virtual models and simulations is what makes the virtual twin valuable to the product's development and deployment. Finite element models using tools such as NASTRAN or Abacus verify structure design loads, which can be validated by testing actual structures. Aircraft designs may involve computational fluid dynamics models to assess loads, flight dynamics, and other performance factors. Custom models might be built, for example, to cover fueling operations or effects of component failures. Models in these separate domains can become very complex, and ensuring that the multiple models are consistent is very challenging.

There are no tools for building comprehensive models; each project or business must decide on an appropriate level of modeling fidelity and on the tools and practices to build, validate, and exploit its models. Different tools are usually needed for different domains, such as hydraulic, electrical, structural, and control. Current lack of sufficiently sophisticated tools and techniques for modeling and simulation are among the principal limitations of the "dream" of digital twins.

Digital Data Management and Infrastructure

For small teams or simple designs, the complexity of the associated digital data files is modest. But as project complexity grows, so do teams, the variety of software tools, and the number of design collaborators, contributing to challenges in the management of the quantity and variety of digital data files. It is easy to lose data, or discover that information saved no longer works with the latest version of a software tool or that a remote collaborator is providing data in a noncompatible format. This situation is commonplace for software engineers, where producing a single software product may require the exact management of several thousand digital files of source code, software tools of varying provenance and version, test data, bug reports, scripts to drive the software "tool chain" that compiles, assembles, and tests the software, and so on. Software tools and practices have evolved to manage project data for large teams.

Every engineer will need to appreciate the challenge of managing dozens of file formats and hundreds or thousands of files. Working for a small company on small projects, a designer may not face data management challenges. Until, that is, a customer returns two years later and asks for a small revision to a product; this is when the designer discovers that he's lost some data or that the data no longer work with current software tools. Larger companies with large projects that may span decades devote considerable engineering and information technology resources to designing, curating, and maintaining the digital infrastructure required for their work. They approach managing digital data as a problem in "systems engineering"—engineering the systems their company uses to do its work.

Undergraduates can begin to glimpse and cope with digital data management in a variety of ways:

- Design courses and practicums to exhibit and use digital techniques, with as much fidelity as possible to those used in manufacturing. Do not overlook the problems of scaling up project size or timeline.
- Practice collaborations that exchange digital information, both off- and online. For example, two metal parts that must mate share an "interface" that can be represented digitally. Another example is a team of design engineers and one of manufacturing experts working collaboratively on a single project, with their respective views and tools.

- Practice using digital data management tools such as Github,[3] even with small teams. To glimpse the challenges posed by large digital datasets, ask a student to make a small change to an existing, large project, represented only by its digital repository.
- Techniques for modeling engineering processes and products, of the sort used in digital twins, could be covered and practiced in engineering programs. MATLAB examples can introduce modeling and simulation, but asking students to make a small modification to a large-scale model can build an appreciation of the difficulty of modeling with the scale and precision required by digital twins.
- Expose all engineers to the cyberphysical techniques used in process automation (including factory automation) involving sensing (the Industrial Internet of Things) and digital control. Small, programmable, flexibly deployed robots are good candidates for practicum projects in this area.
- Encourage engineers to become deeply skilled in computer science or informatics. Skills beyond computer literacy or "computational thinking"[4] are needed. Offerings labeled "CS+X" (where X = engineering) are appropriate.

This report recommends incremental changes to existing undergraduate engineering programs and practice, in the hope that they can be implemented relatively easily and quickly. We have presented a few cases of exemplary practice where such changes have been made; doubtless there are many more examples, and still more engineering schools that are planning or implementing changes.

Many educational institutions are already rolling out changes that will strengthen the treatment of manufacturing and advanced manufacturing. NSF's TIP directorate can develop programs that will also help. And DoD, especially through its Manufacturing Innovation Institutes, has mechanisms to spur action. Government can play large and urgent roles in strengthening undergraduate education of advanced manufacturing.

Harder to predict than changes in engineering and manufacturing are changes in student interest and engagement. Some academics attribute the rise in STEM bachelor's degrees to interest in computer science, inspired by new consumer products and startups. Can national security and defense also attract engineers, to contribute to stability in an increasingly unstable world? Perhaps the challenges of sustainability and of mitigating and adapting to climate change will inspire a new wave of engineers. A major role for industry is to inspire every new wave by showcasing its huge assortment of exciting innovations, including advanced manufacturing.

In the introduction to this report, the committee sketched a vision of a collaborative, interdisciplinary engineering future: a culture of engineers—both academic and industrial—who continuously embrace advanced manufacturing innovations and ramifications, such as in new materials and design opportunities, and who work together to couple design and manufacturing in an engineering ecosystem. The vision is not a monoculture: it must accommodate differences among academic institutions, among businesses, and among engineers. Academic engineering will recognize manufacturing as an integral, essential element of engineering, and will grow its ability to innovate in all aspects of engineering. Students will engage in the real-world engineering ecosystem, where manufacturing is the route to impact.

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[3] See https://github.com/. Accessed October 4, 2022.

[4] P.S. Wang, 2016, *From Computing to Computational Thinking*, CRC Press.

BOX 5-1
Digital Twins

There is no single definition of a digital twin. The American Institute of Aeronautics and Astronautics (AIAA) and the Aerospace Industries Association (AIA) define a digital twin as

> A set of virtual information constructs that mimics the structure, context and behavior of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value.[a]

The objective of a digital twin is to develop a virtual model of a real object or process that records its properties with enough fidelity to use the twin as its substitute for a variety of analyses. The twin might model a design for an object that has not yet been built, but can be analyzed and simulated. At the other extreme, the twin can record the operating history of a mechanism, including data from sensors during operation, maintenance history, engineering upgrades, and other data, throughout its life cycle.

The digital twin permits software to explore or experiment with design adjustments more easily than modifying the real part. Mating of parts can be checked by computations on models. Simulation can show the motion of articulated parts or verify that parts can be joined one by one into a larger assembly. After a part is fabricated, it can be measured accurately and checked against the model; differences can be accommodated by changing the model or the part. Will a part meet its design tolerances when it is heated? If a part of an assembly breaks, will another part fracture? Answers to such questions are computed by software simulating the effect of a change to the model.

Simulation has more direct bearing on models of processes. A model of a factory will describe actions of each of machine, how material moves from machine to machine, the kind and amount of labor needed at various steps, etc. A factory may contain sensors to measure in real time various operating parameters that are reflected in the digital twin, so that software can analyze the factory performance by querying the digital model. Simulating a different job mix, a broken machine, or an absent employee with the digital model helps spot trouble and test workarounds without intruding on the factory floor.

General Electric developed an early digital twin to model the behavior and performance of a jet engine product on the ground and during flight. Data from sensors in the engine are recorded in the twin; software analytics continuously retrieve engine data from the twin to diagnose problems, predict the need for maintenance, and observe opportunities to improve the engine's design or operating regime.[b]

Modeling and simulation are not reality: they do not capture all the properties of the real counterpart. And because building and testing models is hard, the digital twin must be parsimonious, limited to the information essential to enable the analysis and simulation software that uses the model. For example, a model designed to create augmented reality (AR) images to guide a technician installing a wiring harness does not need the precise dimensions of the objects in the harness' environment, but may need their color to be accurate so the technician recognizes them in her AR view. While simple models and applications are already in use, more complex models will need new software tools to construct, verify, and exploit. Only trial, error, and experience will show the trade-offs between model complexity and effectiveness.

Digital threads and twins are the principal themes of Industry 4.0, a collection of innovations that are sometimes characterized as "The Fourth Industrial Revolution."

[a] This definition mentions only physical assets and not processes; there is some variation in definitions, but the principles and objectives are the same. See https://www.aiaa.org/docs/default-source/uploadedfiles/issues-and-advocacy/policy-papers/digital-twin-institute-position-paper-(december-2020).pdf?sfvrsn=b8a6cc93_2. Accessed September 25, 2022.

[b] https://www.ge.com/digital/applications/flight-analytics. Accessed September 25, 2022.

Appendixes

A

Statement of Task and Work Plan

STATEMENT OF TASK

To determine the extent to which advanced manufacturing technologies are treated in undergraduate engineering education and to explore ways to foster the integration of such technologies into undergraduate engineering education to prepare students to enter the workforce carrying knowledge and skills ready to apply to manufacturing or to design-for-manufacturing, the National Academy of Engineering (NAE) proposes to conduct a consensus study, informed by a workshop and expert presentations.

An ad hoc committee will consider advanced manufacturing technologies of most interest to commercial and defense industrial base (DIB) manufacturers and plan and conduct a workshop to explore the needs of the DIB and to highlight exemplary practices of advanced manufacturing treatment in undergraduate engineering education. The committee will consider the workshop discussions, the existing literature base, and other relevant information to develop findings, options, and recommendations. Published output of the activity will be a consensus report with the committee's findings, options, and recommendations.

The goals of the study are to determine:

1. What advanced manufacturing technologies are taught in undergraduate engineering, why are they chosen, and how are they treated? Does the treatment cover the range from design, to prototyping, to manufacturing? How is industrial participation or expertise in manufacturing and advanced manufacturing technologies coupled to undergraduate engineering education?
2. How do capstone courses (and similar) address advanced manufacturing technologies and their transfer to manufacturing? Do some capstone projects treat manufacturing processes as well as design and prototyping? What are best practices and methods for collaboration and experiential learning?
3. What advanced manufacturing technologies are most important to the DIB? What are DIB expectations for engineering graduates with respect to advanced manufacturing technologies and manufacturing processes? Are practicum experiences such as capstone courses, thesis work, industry internships, or co-op programs favored?
4. Highlight, to the extent possible, best practices and exemplary engineering courses that incorporate advanced manufacturing technologies, especially those covering manufacturing considerations.
5. Recommend steps to better integrate advanced manufacturing technologies into undergraduate engineering education and to equip graduates for technology transfer to manufacturing settings.

WORK PLAN

The project will be carried out by an ad hoc committee of about 10 members, appointed by the NAE President, consisting of individuals with current or previous experience in industry, academia, and federal and state governments.

This 18-month project will be conducted in two phases.

Phase I

Workshop and information gathering: A committee of researchers will prepare for and conduct a workshop to frame the scope of the research and highlight relevant programs of significance. Researchers will survey companies working in the defense industrial base to determine the advanced manufacturing techniques they use, would like to use, and/or would like to see in engineering education. The committee will then issue an open call for nominations to engineering school deans to identify capstone and other engineering courses that use those techniques. The committee will develop evaluation criteria and select the programs to be highlighted during the workshop. The criteria will likely include the range and types of advanced manufacturing technologies covered, inclusion of technologies of particular interest to the defense industrial base, and the extent to which the program has demonstrated positive student outcomes (i.e., has been shown to prepare students to use the technologies in their job). The workshop agenda will include an overview of the current state of the use of advanced manufacturing techniques in capstone design and other engineering courses, discussions on how to bridge identified gaps between the technologies used in the defense industrial base and those used by undergraduate engineering students, and effective practices for infusing the former in capstone design and other engineering courses.

Presenters will also describe the major drivers of change in their capstone and other engineering courses, such as new technologies or workforce and talent demand. The output of Phase I will be the workshop transcript, which will capture the discussions and will be provided to the committee as input to its consensus report.

The committee may conduct one or more open sessions in which experts are invited to make presentations that supplement information obtained in the workshop.

Phase II

Findings and Recommendations: The committee will review workshop materials and other relevant information to develop a short consensus report with findings, options, and recommendations. The committee's study will be informed in part by past studies related to domestic manufacturing such as *Making Value for America*[1]. The study committee shall develop a final briefing that will present the overall findings of the scope of the current study and recommendations for applying the findings and for further study.

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[1] National Academy of Engineering, 2015, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work: Summary*, Washington, DC: The National Academies Press, https://doi.org/10.17226/21700.

B

Workshop Summary

INTRODUCTION

On February 24–25, 2022, the National Academy of Engineering (NAE) and the National Materials and Manufacturing Board sponsored a workshop, Infusing Advanced Manufacturing into Engineering Education. The workshop was held as part of the information-gathering process being carried out by an NAE committee working on the project Strengthening the Talent for National Defense: Infusing Advanced Manufacturing in Engineering Education through Capstone Design Courses. The goal of both the workshop and the entire study was, according to the project's statement of task (see Box 1-1), to "examine advanced manufacturing techniques for the defense industry and explore how undergraduate engineering courses can better introduce advanced manufacturing." The following pages summarize the presentations and discussions held during the workshop.

By the time the workshop was held, the committee had already hosted a number of meetings at which they had heard from various experts from academia, industry, and government in the areas of advanced manufacturing and engineering education, and the information gathered at those meetings was combined with the presentations and discussions at the workshop to provide the foundation for the committee's deliberations. The ultimate result of those deliberations was the consensus report of which this workshop summary is an appendix.

BACKGROUND AND CONTEXT

In her welcome and introduction to the workshop, study committee cochair Maxine Savitz offered some background on the study and workshop. The study was sponsored by the Industrial Base Analysis and Sustainment Program of the Department of Defense and was being carried out under the auspices of the National Research Council's National Materials and Manufacturing Board and the National Academy of Engineering. As part of the study, the committee had been asked to conduct a workshop to explore the needs of the defense industrial base and to examine ways in which undergraduate engineering education could facilitate the adoption of advanced manufacturing technologies.

The 2-day Zoom workshop had been divided into four sections, Savitz explained, two on each day. The first three sessions were structured as panels in which each panelist would speak briefly and then jointly participate in a discussion with questions posed by the moderator and members of the audience. The final session would have breakout sections in which the participants in each section would discuss a set of questions on various topics related to engineering education as it related to advanced manufacturing. Audience members were encouraged to submit questions via Slido to be addressed in the various sessions.

After Savitz's welcome, John L. Anderson, president of the NAE, spoke to provide a context for the workshop and describe its goals. "This is an opportunity for industry, academia, and government to come together for the purpose of generating and integrating ideas about advanced manufacturing and formulating methods to effectively introduce these ideas into engineering curricula in both the undergraduate and the graduate level," he said.

Innovation, which the US Chamber of Commerce has descried as the economic currency of the next century, arises from a confluence of engineers, scientists, business professionals, and government leaders, Anderson said, noting that all of those groups were represented at the workshop. However, innovation is only part of the story. Once a device has been conceived and designed, it must be manufactured, and the design and creation of effective manufacturing processes is a key part of the innovation ecosystem. Unfortunately, Anderson continued, “manufacturing is sometimes a forgotten word in the vocabulary of innovation because it often lacks the glitz that new ideas and discoveries generate.” Universities, for example, often place too much emphasis on the idea phase of innovation and neglect the manufacturing phase.

As an illustration of the important of manufacturing to innovation, Anderson spoke about the invention of the neodymium-iron-boron magnet, which is today found in nearly all cell phones, wind turbines, electric vehicles, and laptop speakers. This year, Masato Sagawa was awarded the Queen Elizabeth Prize for Engineering for his innovation of this magnet. “Dr. Sagawa won the prize,” Anderson elaborated, “for both the idea of the magnet’s composition and for the advanced sintering process to manufacture the magnet with reproducible quality and low cost, thus giving it the dominant market position among permanent magnets and electrical devices.” In short, Sagawa’s work went from invention to development and, finally, to manufacturing, which, Anderson said, is “the epitome of engineering.”

Because tomorrow’s manufacturing capabilities will be determined by today’s students, “it is critical for engineering students to appreciate the importance of manufacturing and the advances made with respect to speed, safety, quality, and cost,” Anderson said. To that end, colleges and universities must not only teach about the importance of manufacturing but must also shape their curricula in ways that take into account the needs of manufacturing. “Richer and more relevant educational experiences result in better prepared students to take their positions in our technical workforce,” he said.

Industry also plays a vital role in education, he continued, as it needs to inform faculty, students, and the agencies that fund research about the hurdles that must be overcome to reach the next generation of design for manufacturability. And, he added, “it is also important that government recognize the role of engineering, specifically manufacturing, in advancing technology. This is how the public will see a return on this investment in basic research.”

The workshop offered a unique opportunity to improve manufacturing education, he said. “We can learn from different sides and angles and integrate concepts for the teaching and advancement of manufacturing methods.” In particular, he said, he was looking for the workshop participants to carry out “thoughtful discussions” concerning the best ways to prepare future engineers with the knowledge and expertise they will need to take advantage of advanced manufacturing technologies to help create a stronger and more sustainable future for this country.

“I suggest that what we are doing over the next 2 days is building important bridges, bridges that promote strategic movement and remove obstacles to achieve a desired goal,” he said. “As bridges create new paths, these discussions can open new opportunities for us as a community to reach critically important outcomes.”

Following Anderson’s introduction, the study sponsor, Adele Ratcliff, spoke briefly. Ratcliff, who is the director of the Industrial Base Analysis and Sustainment program in the Office of the Department of the Assistant Secretary of Defense for Industrial Policy, reiterated Anderson’s comment about the need for pivoting from the current heavy focus on innovation to paying more attention to what is needed to ground engineer students in manufacturing. “As technology has become more complex today, whether it is rare earth magnets or the next generation of advanced electronics, often the technology has become so complex and the manufacturing process needed to produce that becomes so complex, it is really hard to differentiate which is which,” she said. “Which is the enabler to innovation? Is it the manufacturing process, or is it the precursor of what people call the technology itself? I argue that today likely it is those manufacturing processes, but our engineering programs seem to have not kept pace with that.” That was a key question being asked of the workshop attendees, she said: Have engineering programs kept pace with the growing importance of manufacturing processes, and, if not, what should those programs look like?

The gap between an idea for a product and the successful production of that product—that is, the manufacturing step—is often referred to as the “valley of death,” Ratcliff noted, because good ideas often fail to be transformed into viable products. However, she continued, “I do not view that as the valley of death. I view that as a valley of opportunity. That is where we convert our ideas to reality—through that manufacturing process.” But what will it take to restore the manufacturing capabilities and leadership that the United States has lost in recent decades, and how can US engineering programs contribute to that restoration? Those are the questions that the workshop should address, she said.

ADVANCED MANUFACTURING

Because the workshop was focused on infusing advanced manufacturing into engineering education, understanding the workshop’s discussions requires first having a clear sense of what advanced manufacturing is. In general terms, “advanced manufacturing” simply refers to manufacturing with new and more effective tools, techniques, processes, or materials, but that means that the manufacturing processes that can be described as “advanced” are constantly changing. What would have been considered advanced manufacturing 20 years ago is probably not thought of as advanced today. And, unfortunately, there is no generally accepted consensus on what constituted advanced manufacturing today, nor was any effort made at the workshop to come up with a list of manufacturing processes that should be considered advanced.

However, as was apparent by the various examples that they provided, the workshop participants themselves had a sense of what advanced manufacturing entails in today’s world, particularly as it applies to defense technologies, and this section examines the various examples of advanced manufacturing that the workshop participants discussed as a way of providing a sense of what advanced manufacturing entails in today’s world.

José Zayas-Castro of the National Science Foundation listed a number of specific areas being supported by the foundation’s Advanced Manufacturing program, which provides support for researchers doing work in the area of advanced manufacturing. The specific areas being supported, he said, include autonomous systems, biomanufacturing, breakthrough materials and materials design, digital design and manufacturing methods, nanomaterials and nanomanufacturing, novel semiconductor design and manufacturing, and smart manufacturing. Autonomous systems are those that operate with a high level of independence and are able to decide how to respond to various unforeseen situations; they often are able to learn and improve their performance without human intervention. Digital design and manufacturing refers to systems that are fully digitized, so that data are collected and analyzed digitally and the processes are controlled digitally, providing greater flexibility and making it possible to respond quickly to changes; a digital system could, for instance, monitor the output of a process and make changes to the process in response to any problems it detected. Smart manufacturing refers to an approach to manufacturing that uses digital information technology to allow the system to be much more connected, flexible, and responsive, leading to greater efficiencies and faster responses to changing demands.

Chris Saldaña of the Georgia Institute of Technology mentioned both selective laser sintering and CNC (computer numerical control) machining as examples of advanced manufacturing platforms along with 3D printing and advanced composites. Amy Fleischer of California Polytechnic State University, in speaking of advanced manufacturing topics that are being integrated into the engineering school’s course, spoke of multi-axis CNC machining and modeling, reverse engineering with 3D scanning, and and data analytics and smart manufacturing with real-time control. And William Bigot of Ascent Aerospace emphasized the importance of digital technologies used to monitor and control manufacturing processes; the information and analysis provided by these technologies can help operators understand how well their processes are working and even predict when a machine will need maintenance or repair.

Perhaps the most commonly mentioned example of an advanced manufacturing process during the workshop was *additive manufacturing*. This is a broad term that refers to a process in which an object is created by building it up, as opposed to subtractive manufacturing, where one starts with a solid block of metal or other material and removes pieces of it through machining or other techniques to create the desired shape. The best known and most common example of additive manufacturing is three-dimensional (3D) printing, where an object is created layer by layer.

Michael Sarpu of Lockheed Martin commented that the main value of additive manufacturing is build something that could not otherwise be built. People first become familiar with 3D printing, for instance, by creating something simple such as a ball of a cup, but those are not the sorts of items that additive manufacturing should be used to build because it is not, at least so far, a particularly fast process. So it is important to think about additive manufacturing—and, more generally, about advanced manufacturing—in the correct way. "If we think about it just to replace things we do today, then you lose," he said, "because I can always injection-mold or five-axis high-speed-machine something quicker than I additively produce it. But if I come up with a structure that I cannot build any other way, now, all of a sudden, advanced manufacturing becomes that cornerstone of a manufacturing process."

On a related note, Sarpu said that advanced manufacturing also has implications for the engineering process. "For the first time probably ever, we in manufacturing can now build things that an engineer cannot conceive," he said. "When you think of the power of additive manufacturing and other technologies, we can now create things that cannot be conceived by a human." This reality, he predicted, is going to lead to the growing importance of generative design processes, which will automate much of the design work that engineers have historically been responsible for. This is turn raises the question of who will design these generative design tools for the engineers to use. That will require a completely different sort of design thinking, he said.

ORGANIZATION OF THE SUMMARY

This summary is intended to capture the presentations and discussions that took place during the 2 days of the workshop. It contains four chapters in addition to this introductory chapter. Chapter 2 examines the state of manufacturing engineering education mainly from the perspective of academics and educators involved in training engineers and others who will go into the manufacturing workforce. Chapter 3 provides an industry perspective on the workforce needs of advanced manufacturing, while Chapter 4 looks at government and nonprofit institute efforts to improve manufacturing and manufacturing education, with a particular focus on advanced manufacturing. With these three chapters having provided an overview of the current state of advanced manufacturing and manufacturing engineering education, Chapter 5 collects and summarizes the many comments made throughout the workshop concerning what should be done to improve the state of advanced manufacturing and, particularly, manufacturing engineering education in the future so as to make the US advanced manufacturing sector as effective, productive, and competitive as possible.

As per the policy of the National Academies of Sciences, Engineering, and Medicine, this workshop summary is the product of the workshop rapporteur and does not represent any National Academies position on the issues in this area. All opinions and recommendations expressed here are the opinions and recommendations of the individual workshop participants who made them, and while there may have been general agreement among those participants on certain issues, there was no attempt to reach a consensus on any issue, and no statement in this workshop summary should be interpreted as indicating such a consensus.

THE STATE OF MANUFACTURING EDUCATION

A significant part of the workshop was devoted to understanding the current status of engineering education as it applies to advanced manufacturing; the goal of these presentations was to set the stage for later discussions about what more can be done to better prepare engineering students for jobs in advanced manufacturing. To this end, several of the workshop's presentations, including the keynote, were focused on engineering education in colleges and universities. This chapter recaps the keynote address as well as the four presentations from Session 3, Undergraduate Education in Manufacturing, as well as other contributions related to manufacturing engineering education made in other parts of the workshop.

KEYNOTE ADDRESS

The keynote address was given by Kyle Squires, dean of the Ira A. Fulton Schools of Engineering at Arizona State University (ASU). The session moderator, Robert Sproull, summarizing details from the ASU website, described the Ira A. Fulton Schools of Engineering as the largest and most comprehensive engineering school in the United States and noted that those schools offer a variety of opportunities beyond the classroom, including undergraduate and graduate research, peer mentoring, entrepreneurship, student organizations, internships, and community service. In particular, he said, "The newest of the Fulton Schools is the School of Manufacturing Systems and Networks, which prepares graduates to tackle the next generation of engineering challenges essential to sustaining global economic growth, strengthening supply chains, and transforming manufacturing systems."

Squires began by saying that he hoped to offer some context for the discussions in the rest of the workshop. He would do this in three parts. First, he would introduce and describe the Fulton Schools of Engineering and, more broadly, ASU. Then he would talk about the evolution of the engineering schools over time. And finally he would describe the thought process that led to the decision to create the new School of Manufacturing Systems and Networks, which is now in the process of recruiting faculty and building a new facility for the school, which will be open for occupancy in January 2025.

A key fact about ASU, Squires said, is that it is a very innovative place. "There are constantly new ideas churning, ways to advance student's success, positioning the university for growth, and doing that in ways that really are different," he said. And indeed, the university has been ranked number one in innovation by *U.S. News & World Report* since the magazine began its innovation rankings in 2016.

As described in its charter, the university is built on three pillars. The first is that it is a public university dedicated to providing access to students, "measured not by whom it excludes but by whom it includes and how they succeed. The second is that it is devoted to advancing research and discovery of public value; that is, the university emphasizes research that matters and helps improve life in some way. And the third is "assuming fundamental responsibility for the economic, social, cultural, and overall health of the communities it serves." This is a key distinction between public and private universities, Squires said. Public universities are responsible to their community, the taxpayers, and various other stakeholders. "We really do think about that in terms of the ways that we advance all that we do within the Fulton Schools," he said.

ASU has done well in translating its research into outcomes, Squires said, particularly as measured by patents. It is among the top 10 US universities in terms of the number of patents issues and is 11th worldwide. It also rates well in terms of entrepreneurial outputs. When calculated per $10 million of research expenditures, the schools of engineering rank fifth nationally in terms of numbers of start-ups, sixth in intellectual property disclosures, and seventh in licenses and options.

Of ASU's 134,000 students (about 50,000 of whom are online), 27,000 are in the seven Fulton schools of engineering. About one-third of the 7,000 students in ASU's Barbara and Craig Barrett Honors College are engineering students. There are 25 undergraduate degree programs and more than 50 graduate programs in engineering. "We are creating programs to draw in a very wide range of students to come into engineering," Squires said. "I think in the context of manufacturing, that is vital, that experience base."

The engineering faculty, with about 370 tenured and tenure-track professors and another 100 or so lecturers and professors, also excels, he said. For example, faculty members have received 32 National Science Foundation career awards over the past 3 years. "When you are hitting about 10 career awards per year, that is significant," Squires said.

The seven schools of engineering sit on two campuses, one in Tempe and one in Mesa, which are about 20 miles apart. The new school of manufacturing is on the Mesa campus. "We intend for that

School of Manufacturing to represent—and I use this phrase deliberately—the center of gravity for manufacturing within the Fulton Schools," he said. "Every discipline of engineering has some engagement with manufacturing. It is the intersection of those disciplines that we are trying to capitalize on here through our new school of manufacturing."

Switching to the topic of how the schools of engineering evolved over time, Squires began by saying that in 2009 ASU's engineering programs were organized into 14 departments. Then, inspired by the National Academy of Engineering's Grand Challenges of Engineering, the university reorganized the college of engineering into five interdisciplinary schools with the goal of making the college more adaptable and more responsive, connecting disciplines, and creating new opportunities for faculty and students. The five schools were: the School of Biological and Health Systems Engineering; the School of Computing and Augmented Intelligence; the School of Sustainable Engineering and the Built Environment; the School for Engineering of Matter, Transport, and Energy; and the School of Electrical, Computer, and Energy Engineering. The Polytechnic School was added in 2014, and the School of Manufacturing Systems and Networks was added in 2021. The new structure enables connections that "drive research forward in new and creative ways" and increases responsiveness to opportunities both internal and external to the university, Squires said.

Furthermore, the 2009 realignment was crucial in making the establishment of the manufacturing school possible. "We did not know it at the time," he said, "but we were basically seeding the ground to enable establishment of this school…. [W]e had to establish the structures and thought process to be able to do that."

The Fulton schools also have transdisciplinary connections with a number of other segments of the ASU community, he added, including the School of Earth and Space Exploration (which does significant work with NASA), the Biodesign Institute, the business school, the School for the Future of Innovation in Society, and the School of Arts, Media, and Engineering.

The reorganization has offered a number of lessons, Squires said. First, by removing barriers between the departments, the move encouraged faculty members not only to interact with other faculty members whom they might not have spoken with before, but also to "think bigger." Faculty members are more likely to think beyond their traditional areas and to ask "Why not?" It represents a major change in mindset, he said.

Furthermore, from an organizational and operational perspective, the move has allowed the engineering college to leverage its resources in new ways and to scale curricular and extracurricular programs. As an example, Squires spoke about the introduction to engineering course offered to students in their first semester. The course has more than 80 sections, he said. "We have a team of lecturers that we flood into those sections to engage those students. We use our current student body to help support it. But it is a scalable structure."

Turning specifically to what the college has learned about building engineers, Squires said the lessons can be grouped into three broad lessons. First, the students should be treated as engineers from day 1. Students are engaged in the design/build process from the beginning and given a wide variety of opportunities to discover and follow their passions. Second, build community within the college by developing an engineering mindset and reinforcing values. Student organizations, peer mentors, and student ambassadors are crucial in this process, he said, because "the students are always going to be the best ambassadors and role models and examples." Third, meet learners where they are. For example, one of the largest residence halls on campus is for engineering students. "We teach classes there," Squires said. "We have tutoring there. We meet our students there for career coaching. It is an example of basically making those entire set of experiences embedded."

In the final part of his talk, Squires spoke about the thinking behind the new School of Manufacturing Systems and Networks and the decisions that went into shaping it. One of the key considerations, he said, was what was happening in the surrounding community and how to respond to that. For example, Arizona has become a major center for US semiconductor research and manufacturing, with a number of companies, including Intel and NXP, having existing semiconductor fabrication plants and Taiwan's Semiconductor Manufacturing Corporation building a new $12 billion chip factory and

Intel spending $20 billion to build two new chip plants. Furthermore, the area has long had strengths in such areas as equipment manufacturing, chemical and material suppliers, and semiconductor packaging. "Those will continue to grow as we are … attracting new companies," he said. "We need to be responsive to that need. The workforce needs here in engineering, in manufacturing, in technology are immense. That is a strong signal that drives our thinking."

At the same time, ASU was successful in convincing the State of Arizona to provide seed funding for the New Economy Initiative. The idea behind that initiative, Squires said, was to be responsive to the growing technology landscape in the area by hiring more engineering faculty and providing more opportunities for expansion by meeting the demands in manufacturing engineering. Simultaneously, he said, the plan was to establish research centers in such areas as energy, communications, and manufacturing "as a way to connect our faculty and research students to the corporate base and speed the translation of innovation out into practice."

The reorganization and growth of the Fulton Schools of Engineering took place against the backdrop—and in response to—this environment in Arizona. For example, the School of Computing, now renamed the School of Computing and Augmented Intelligence, is in the process of being reimagined. The choice of the term "augmented intelligence" was a deliberate one, he said, as people sometimes think of the more common term "artificial intelligence" as implying that computation is taking the place of human thought, while "augmented intelligence" signals that their work in computing is designed to advance the human condition by assisting in innovation.

The creation of the School of Manufacturing Systems and Networks was done specifically with the strong manufacturing base in Arizona in mind. The manufacturing of the future will span the design, realization, technical management, operations, and optimization of systems and networks devoted to creating things. In particular, Squires defined a manufacturing system as a "combination of elements that function together to produce the capability required to meet a need" and commented that such systems are "increasingly networked in new ways to promote efficiency and innovation. Working in partnership with the Polytechnic School, which is very solution-focused and has many technology programs within it, the new manufacturing school will give the Mesa campus of ASU a distinctive identity and respond to the opportunities offered by the local strengths in semiconductor manufacturing, aerospace, and medical devices, he said.

More generally, Squires continued, the new manufacturing school is intended to combine research, academic programs, faculty expertise, and industry partners to address the next-generation challenges that will define the future of manufacturing. There will be many such challenges, and Squires offered examples from three specific areas: process science and engineering; robotics and automation; and data analytics, cyber, and artificial intelligence.

In process science and engineering the college is involved in, among other things, new resins for stereolithography, polymer chemistry in biofabrication, and cellular structures for energy absorption. "This is informing the way in which we give the school structure, the way we drive future hiring," he said.

In robotics and automation, ASU engineering is working on precision automation, human–robot collaboration, and smart and connected factories. Human–robot collaboration will make it possible to do really innovative things in manufacturing, he predicted, while smart factories, while not a new idea, are a very versatile idea that offer many opportunities for the school of manufacturing.

In data analytics, cyber, and artificial intelligence, Squires again listed three areas in which ASU engineering is doing work: manufacturing quality control, heterogeneous data fusion and behavior modeling, and secure and resilient systems. In the area of manufacturing quality control he spoke about how it is now possible to use the great amounts of data collected during manufacturing processes to make improvements mid-stream by analyzing the data and acting on them in real time. "We do not have to make … a thousand of these parts and then go measure some and discover there was a flaw," he said. "Mid-process improvements are possible."

Wrapping up, Squires described the School of Manufacturing Systems and Networks as having three "structural elements": a knowledge base, new process technologies, and support for regional priorities. The knowledge base includes knowledge in such areas as robotics, automation, data analytics and machine learning, security, logistics and management, and design. Among the new process technologies being worked on there are additive manufacturing, micro- and nanotechnology, semiconductor manufacturing, and the manufacturing of emerging materials. In supporting regional priorities, the manufacturing school will focus on such areas as aerospace and defense, semiconductors, medical technology, and the automotive industry, particularly innovation in energy storage batteries. Finally, the school is committed to helping develop the manufacturing workforce for the area—not just engineers but also the other workers that the industry relies on. “Our manufacturing school will also be a connector for technology-focused workforce training opportunities [for] technicians that move into fab or move into a large factory,” he said. “They do not necessarily need engineering degrees, but we are vital to providing the modern set of skills and training to enable those graduates to thrive.”

UNDERGRADUATE EDUCATION IN MANUFACTURING AT FOUR INSTITUTIONS

Session 3 was moderated by Sundar Krishnamurty, the Isenberg Distinguished Professor in Engineering at the University of Massachusetts Amherst; Chi Okwudire, an associate professor at the University of Michigan; and David Parekh, the chief executive officer of SRI International. The basic issues to be addressed were what advanced manufacturing technologies are taught in undergraduate education, how capstone courses address advanced manufacturing technologies, what advanced manufacturing technologies are most important to industry, and the best practices and exemplary engineering courses that incorporate advanced manufacturing technologies.

The four speakers were Amy Fleischer, dean of engineering at California Polytechnic State University, San Luis Obispo; Guillermo Aguilar, head of the mechanical engineering department at Texas A&M University; Susannah Howe, a capstone design instructor at Smith College in Northampton, Massachusetts; and Chris Saldaña, the manufacturing group chair at the Georgia Institute of Technology.

California Polytechnic State University

Fleischer, whom Krishnamurty described as pioneering the college experiential learning-based engineering curriculum, began by describing the manufacturing engineering degree program at Cal Poly. It is one of the university’s smaller undergraduate programs, she said, with only about 25 students graduating from it each year, compared with the engineering program as a whole, which has about 6,000 undergraduate students in 14 different degree programs. Still, she said, the manufacturing engineering program exerts “a valuable influence on our overall curriculum.”

Students in the mechanical engineering program are offered a concentration in manufacturing, and about 50 of those students graduate each year with that manufacturing concentration. These students tend to be creative and to want an extra hands-on part of their education, Fleischer said. Furthermore, the manufacturing engineering program offers a number of service courses across the school’s engineering curriculum, and not only mechanical engineering students but also those majoring in aeronautical engineering, biomedical engineering, and materials engineering take many of the courses provided by the manufacturing program.

The engineering students at Cal Poly are somewhat different from those in other schools, Fleischer said, in that they come into the program looking for hands-on learning. “Our motto— and not just for engineering, but across the entire university—is learn by doing,” she said, so hands-on learning is integrated into many of the university’s classes. “Students here at Cal Poly are already kind of inclined to want to do manufacturing. As we talk to the students who are in the program, they say building things is really cool. They really like that. It’s drawing them in, they are very excited about that.”

Indeed, she said, there are increasing numbers of students entering who are interested in hands-on building experiences because students are getting exposed to such experiences in high school and even earlier with such programs as maker spaces and FIRST Robotics. The availability of three-dimensional scanners and printers is also playing a role, she added. “We are drawing a lot of those students into Cal Poly who want to continue to work in those areas.”

First-year students in the manufacturing engineering program are exposed to basic types of manufacturing—electronics fabrication, materials removal, materials joining, casting, and so on—and then in later years the students learn about more advanced types of manufacturing. The manufacturing classrooms combine lecture spaces with laboratory spaces, so students can learn something in the classroom and immediately go practice it in the lab. The lab spaces have a combination of traditional hand-driven equipment and basic CNC (computer numerical control) machines, with the students moving to the more complicated machinery as they advance through the program. After the students have mastered different techniques, they combine them to create machines from scratch.

The manufacturing program is also integrating advanced manufacturing into its curriculum, Fleischer said, mentioning specifically additive manufacturing and multi-axis CNC machining and modeling. “We are moving into reverse engineering with 3D scanning,” she added, “and now a nice emphasis on data analytics and smart manufacturing with data in real-time control is being integrated into our course work.”

Switching topics, Fleischer said that it is very important for a program like Cal Poly’s manufacturing degree to have strong industry partnerships. For example, the department has a partnership with Haas Automation. “They help us keep our labs up to date and make sure the students are working on the most cutting-edge pieces of equipment,” she said. Indeed, she added, the partnerships run the gamut of manufacturing practices, from the digital focus of Apple to Haas, which is a traditional machining company, with companies like Solar Turbines falling somewhere in the middle. The program also has an industrial advisory board, she said, “and we are always talking to them about what makes the most sense for our programs.”

Students have a variety of ways to get hands-on experience outside of the class-associated labs. For instance, the engineering school uses student techs extensively in all of its facilities to maintain the equipment and help train other students. There are also many clubs with a manufacturing-related focus, from a blacksmithing club and a cast-in-steel foundry club to a chapter of the Society of Manufacturing Engineers. A variety of vehicle teams engage in competitions with vehicles they have designed and built, from a human-powered vehicle team to traditional racecar teams to a hyperloop team. And each year the university designs and builds a float for the Rose Bowl parade, which generally included automated moving parts.

The university has a tremendous amount of facilities to support all these activities. “We have basically what’s an airplane hangar,” Fleischer said. “That is a full shop with most of our club space.” Each year 2,000 students are given basic training that gives them the fundamentals they need to be able to work in that shop, and most of the faculty and most of the staff in the college have also completed this training. A second facility with much more advanced equipment is dedicated to work on senior design projects.

Every single engineering student in all 14 of the college’s degree programs does a senior capstone project, and most of them have a significant build phase. The mechanical engineering program in particular requires all of its students’ projects to go to prototype. The college also offers an interdisciplinary senior design projects, and students in the manufacturing program do blended projects that combine industrial engineering and manufacturing engineering. “As they work through those projects,” Fleischman said, “they are building not only the prototypes but also looking at costing and how would they transition to scale manufacturing.”

With these sorts of experiences, she said, Cal Poly’s engineering graduates are highly sought-after by industrial companies. “A lot of them go into the defense industry and aerospace industry, which are both very strong here in California, but also into things like the sporting goods industry and national labs.” The college also places place undergraduate students directly at the Jet Propulsion Laboratory and

Lawrence Livermore National Laboratory, she said. “It is unusual to place undergrads, but they come in with a really great skillset.”

Texas A&M University

Aguilar began his presentation by giving an overview of Texas A&M’s Department of Mechanical Engineering. It has roughly 1,500 undergraduate students and 500 graduate students, and it awards more than 500 degrees each year. There are about 90 tenure-track and academic-professional-track faculty, including 43 in endowed faculty positions and seven who are members of the National Academy of Engineering. Research expenditures for the most recent fiscal year were almost $30 million. “This is a large operation,” Aguilar said. “It is one of the biggest departments in the country, and obviously that shapes out the curriculum that we have.”

With that, Aguilar began addressing the questions that had been asked of each of the panelists, beginning with how the department incorporates advanced manufacturing technologies into its undergrad curriculum. The existing curriculum actually has very little room in which to introduce advanced manufacturing topics, he said, although manufacturing is covered to a certain degree in such courses as Principles of Materials and Manufacturing as well as Materials and Manufacturing, and students in the department’s capstone courses can choose to have an engineering lab. One possibility would be to introduce advanced manufacturing elements into engineering science courses, Aguilar said, such as using three-dimensional printing to produce a gear as part of the statics course or to print items in a fluids or heat transfer lab experiment. “Those kind of things would be useful,” he said, “and to some extent we are covering that.”

Turning to the next question—on the types of manufacturing experiences that are available to undergraduates—he said that the need for such experiences has been filled to some extent by internships, co-ops, capstone courses, research, and independent studies, but that such experiences are not available to all studies.

On the question of what industry is asking of academia and what interaction the department has with industry, there is a mixed bag, he said. Some manufacturing companies argue that the department should continue to prepare its students very strongly in fundamentals and that industry can afford to train them later on, but others—mainly smaller companies—are looking for students who have more hands-on experience and are ready to contribute without on-the-job training. Either way, Aguilar added, the department takes into consideration the input it gets from industry and sees advisory boards as instrumental in helping the program keep track of industry trends, “and we do everything we can to try to adapt our curriculum to the current needs.”

In response to a question about what the department is hearing from its alumni who have gone into manufacturing, Aguilar said that most of them are still adapting to the new advanced manufacturing way and they offer insights into the sorts of changes that will need to be made to the curriculum to better prepare students for work in advanced manufacturing. Over the short term the needed training can be carried out with co-ops, directed studies, internships, and the like; the problem with this approach is that these are accessible to only some of the students. Over the long term it will be necessary to make changes in the curriculum, but doing so will require either taking time away from core courses—and thus short-changing the training in fundamentals—or else cutting into the time spent on general education courses, but “that is a steep hill to climb,” he said, “considering all the changes that need to be approved at the upper levels of the university.”

On how to move students from design and prototyping to manufacturing, Aguilar said that serious investments will be needed and, unfortunately, not every institution will be able to afford them. Modern manufacturing generally requires major capital investments, and the closest thing that Aguilar’s department has been able to achieve is small-scale desktop devices such as lasers, three-dimensional printers, and CNC machines that can be used to provide some hands-on training to students.

Addressing the question on capstone courses—specifically, how they are evolving and what goals and pressures are driving the change—Aguilar said that most are drifting toward smaller-scale, less traditional heavy manufacturing and more design and prototyping, but that is "not quite closing the loop" with advanced manufacturing. It is still not feasible to create structurally sound designs with three-dimensional printing or other advanced manufacturing using the cheap desktop machines available to students. "We really think we need to close the loop" by providing students with access to advanced manufacturing tools, he said.

On the topic of how to attract students to manufacturing, Aguilar suggested taking advantage of "the cyber world that many of our students are now hooked on." By hooking them on visuals and games, they can then be guided into building their own devices. However, he warned, it will be crucial to get them to move beyond just enjoying the cyber world as users—they need to become creators. It will also be important to get K–12 education involved in the task of attracting students to manufacturing, he added. "This is not something that higher education can solve independently."

Manufacturing could be made more attractive to students by making sure that the visuals are of the sorts of things—robots, unmanned aerial vehicles, electronic devices—that already appeal to the younger generation. Students also need to see that what they make has societal value, Aguilar said. "Nowadays students grow up with a very deep social conscience, making them aware of things like how to provide drinking water for remote areas or better health care or leveraged freedom from a wheelchair, or walking and running blades for amputees," he said. "Those kind of things students can quickly engage with and be attracted to." And he suggested making reverse engineering a larger component of the curriculum.

Finally, he spoke about what steps are needed to better integrate advanced manufacturing into undergraduate engineering education. It will take, he predicted, a "big infusion of resources to make advanced manufacturing training devices accessible to the many students we train now nationwide." However, he added, this is not something that many institutions will be able to afford, at least not at the necessary scale, and so the best approach may be to partner with industry and with government to provide the sort of equipment necessary to expose students to advanced manufacturing as part of their education.

Smith College

The next speaker was Howe, whom Krishnamurty described as a national leader in capstone design courses and in "advocating for capstone design and promoting design innovations in engineering curriculum." Howe spoke mostly about such capstone design courses, and her talk covered three main topics: a set of decennial surveys about capstone design, a research initiative funded by the National Science Foundation (NSF) studying new employees in their transition from capstone design to the workplace, and the capstone course that she teaches teach at Smith College which, she said, is very different from the ones at Cal Poly, Texas A&M, and Georgia Tech.

The Capstone Design Survey has been carried out three times so far—in 1994, 2005, and 2015—with the next one scheduled for 2025. Howe, who directed the surveys in 2005 and 2015, said that the goal of the survey is to understand the current practices in capstone design, how these courses are evolving, and how can they be improved. The surveys take about 45 minutes to complete, so they are somewhat detailed. There were 360 respondents in 1994, 444 in 2005, and 522 in 2015, and the greatest number of responses came from those in the mechanical and aerospace engineering fields, followed by electrical and computer engineering, civil and environmental engineering, chemical engineering, and biomedical engineering. Only a few of the respondents were in the manufacturing field, Howe said, so the survey results are not specific to manufacturing but apply to the engineering field broadly speaking.

Discussing what they surveys revealed about the details of capstone courses, Howe showed a series of graphs detailing the results.[1] Most capstone courses lasted either one or two semesters, with more than half of the respondents in 2015 reporting two-semester capstone courses. Furthermore, there was a clear trend over time to have longer capstone courses, with some capstone courses today lasting as long as 2 years. The most common structure for capstone courses was to have the class and project done in parallel, although a significant minority of the courses were class followed by project or project only. There were no class-only capstone courses, Howe reported, so the project is clearly a major part of such courses.

The survey results indicate that the number of students taking capstone courses at various institutions has been growing over time, she said, and most projects are done by teams of students, most typically with three, four, or five team members. The total student time spent per project varied widely and was a function of team size as well as of the length of the capstone course, with a majority of respondents reporting a total time per project of somewhere between 200 and 1,000 hours, but some reporting less than 200 hours and others reporting well over 1,000 hours and even over 2,000 hours. “So it’s worth noting that this is a nontrivial undertaking,” Howe said. “This is not the same as a small final project that you might have at the end of a different kind of course. This is a big undertaking and often done by multiple students at a time.”

The sources for the capstone projects included industry, government, faculty research, external competitions, and the students themselves. In 2015, 80 percent of the respondents reported that industry or government were the source for at least some of their students’ capstone projects. Much of the funding for the projects came from the colleges and universities themselves, but a significant percentage of it came from the projects’ sponsors, with students providing some of the funding as well. The amounts supplied by the external sponsored varied widely, with some sponsors providing nothing and others as much as $30,000 per project; in 2015, 60 percent of the respondents reported sponsors provided an average of more than $1,000 per project and 20 percent reporting an average sponsor funding of more than $5,000. The most common project expenses were for supplies, hardware, software, faculty time, and travel.

Next Howe described some results from a project that looked at the transition from capstone project to workplace for a number of engineering students from four different institutions. One part of the project involved doing weekly surveys during the former students’ first 12 weeks of work, asking them what transferred from capstone to their first work experience. A large majority of the respondents said that self-directed learning was a key skill that had transferred, Howe reported, while teamwork and communication were also critical. “Within the first 12 weeks, these are skills that our new graduates were using on the job,” she said. “And, sure, they were using technical work skills as well,” but the importance of the technical skills depended upon how closely the jobs they had corresponded to the type of work they did in their capstone projects, while the self-directed learning, teamwork, and communication skills were valuable regardless of the specific technical requirements of a job.

Howe ended her presentation with a brief description of the capstone design course that she teaches at Smith, which is called the Smith College Design Clinic. Smith is a small institution and has about 25–40 students graduate each year with its bachelor of science degree in engineering science. The two-semester capstone course has a large range of sponsors in such fields as civil, environmental, mechanical, electrical, chemical, materials, and industrial engineering, many of whom have some connection with manufacturing. “And so while we don’t have a manufacturing degree, we don’t have a manufacturing track or focus,” Howe said, “it turns out that about 15 percent of our graduates have jobs right now in manufacturing and some of them are doing very specific work in advanced manufacturing. So, despite the fact that they are not coming from a manufacturing engineering program, they are pursuing careers in manufacturing.”

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[1] S. Howe, L. Rosenbauer, and S. Poulos, 2017, “The 2015 Capstone Design Survey Results: Current Practices and changes Over Time,” *International Journal of Engineering Education* 33(5):1393-1421.

The lesson, Howe concluded, is that a career in advanced manufacturing is not necessarily limited to graduates with manufacturing degrees. Even institutions without a manufacturing program can be sending students and graduates out into the manufacturing workforce.

Georgia Institute of Technology

Saldaña is, in addition to being Georgia Tech's manufacturing group chair, the instructor for Georgia Tech's capstone design course and also lead faculty for a new NSF industry–university cooperative research center in advanced manufacturing. He spoke about the university's efforts to build an "ecosystem" for an undergraduate experience centered around manufacturing education.

Like Texas A&M, Georgia Tech is a large university, Saldaña said. Its mechanical engineering department has 1,800 undergraduates and about 850 graduate students. Studio and recitation sessions generally have 20–25 students, but course sections will have 50–300 students. Delivering a high-quality education at that scale is a challenge, he said, particularly as one of the institution's goals is to provide experiential learning opportunities to students using its physical laboratories.

Georgia Tech's manufacturing education efforts involve both the school's formal curriculum (i.e., its required and elective courses) and a combination of supercurricular activities (such as makerspaces and competition teams), undergraduate research, and entrepreneurial activities. "There is a lot of learning that goes on outside of the classroom in these self-directed kinds of activities," he said, and one of the challenges faculty members face is combining the formal curriculum with the other work in a seamless way.

In Georgia Tech's formal coursework, he continued, "advanced manufacturing finds a home in our design and manufacturing sequence, which consists of four courses that take students from design to prototyping and then to manufacturing. The courses are Introduction to Engineering Graphics and Design; Creative Decisions and Design; Design, Materials, and Manufacture; and Capstone Design. The first is a "typical CAD [computer-aided design] course where we learn about 3D modeling and design and mess around a little bit with 3D printing," Saldaña said.

In the next course, typically taken by sophomores, the students design robotic systems for a competition and realize that design with a rapid prototyping process. The students come in "geared up" to fabricate things, he said. "They want to get hands-on, get out of the classroom and work with equipment, and we find a lot of energy associated with that kind of activity." Because of the large number of students taking the course, it was important to reduce the amount of time students spent fabricating their items, so the department moved to computer-aided manufacturing (CAM) approaches. And while the move to CAM was made for more practical reasons, Saldaña comments that such CAM-based approaches "port really well to advanced manufacturing kinds of concepts."

From there students move into the manufacturing courses. The basic one teaches students about the different kinds of processes that are involved in manufacturing. "That's where you address concepts related to scaled manufacturing," he commented. Students can also choose various manufacturing-related electives which cover such topics as process analysis, additive manufacturing, and artificial intelligence and machine learning, where students learn about digital manufacturing.

Finally, students integrate what they have learned in a capstone design course. These are often company-sponsored projects, Saldaña said, such as one time where students worked with Milwaukee Tool to produce new kinds of equipment. In such cases students must think about whether their designs can be made at scale.

Georgia Tech has a wide variety of fabrication resources on campus so that students can get experience with a range of equipment. To help provide this equipment, the university partners with a large number of companies.

"We also work with companies to actually port some of their materials to our curricula," Saldaña said. For example, the university has worked with Autodesk to bring in some of its online materials for computer-aided manufacturing and CNC training to include in some of the university courses.

The mechanical engineering department has a number of physical resources that students can use inside and outside of the classroom, he said, “and that has really morphed into a broader set of makerspaces across the entire college.” Now not only mechanical engineering but also electrical engineering, materials engineering, and biomedical engineering all have makerspaces with advanced manufacturing capabilities where students can learn about various techniques in this self-guided format. The manufacturing capabilities in these maker spaces include a wide variety of things, from manual machine and welding to fused deposition modeling, selective laser sintering, stereolithography, three-dimensional scanning, laser cutting, CNC machining, waterjet cutting, textiles manufacturing, and circuit board manufacture.

Students will learn about these techniques things on their own, so one of the challenges that faculty members face is what to do in the classroom to help augment what students are wanting to do. “What we found,” Saldaña said, “is that when you provide the students with those capabilities, you can really enable them to do a lot of great things.” For example, in response to the COVID-19 pandemic, some Georgia Tech students went into the makerspaces and produced hundreds to thousands of face shields. Then they developed scaled manufacturing approaches that made it possible to produce millions of units in collaboration with companies that the university was already working with.

Moving to supercurricular activities, Saldaña said that advanced manufacturing plays a big role within its competition teams, which use advanced manufacturing techniques to field their systems. These students use pretty advanced technologies, he said, including composites, CNC machining, and three-dimensional printing.

Georgia Tech also has a university-wide initiative to instill entrepreneurial confidence in students and to empower them to launch startups. Some of the resulting startups have been in the manufacturing field—for example, a company looking at analytics for manufacturing and another developing tools for monitoring manufacturing processes—“so they are making use of those same advanced manufacturing platforms that I mentioned earlier,” Saldaña said. The entrepreneurial work can be done as supercurricular work, as course credit, or as part of a capstone project.

In concluding, Saldaña reiterated that it is crucial to consider how all of these different activities can work together to create graduates who will develop the next generation of manufacturing technologies.

Discussion

Okwudire opened the question-and-answer session that followed the presentations by asking what, if anything, the panelists did in their schools to teach students about scale-up. Fleischer answered first, saying that engineering students at Cal Poly are asked, as part of their senior capstone projects, to think about the transition from the prototype to the finished product and, in particular, to consider what it will cost to manufacture the finished product as opposed to the prototype. They are assisted by senior design advisors, most of whom have worked in industry, she said.

Saldaña said that students in manufacturing courses are exposed to considerations related to developing parts that scale, including costing and outsourcing. When they are working in entrepreneurial teams, for instance, “they have an idea for a widget, some sort of device, and then later they have to develop a business plan where they are actually making hundreds of thousands of that same device.” So they must reach out to suppliers to determine what things actually cost. “What we found is that in the entrepreneurial courses you definitely have that experience because they are all trying to develop a business.”

Nest Krishnamurty passed along a question that had been asked by multiple audience members: What can engineering programs do to attract women and underrepresented minorities? Fleischer answered that one of the things that Cal Poly does is to emphasize the impact that engineering can have—how it can help people and be used to change society for the better. “There are programs that we have in manufacturing that really emphasize that," she said, mentioning in particular a lab in which students take on projects that can help people with physical challenges.

Aguilar agreed that such programs can make a difference but argued that it is important to start attracting women and underrepresented minorities much earlier, which will require help from those in K–12 education. "We have to start way early," he said. "Whatever we do at this [university] level is probably a little bit too late." And he said that various studies have indicated that many of the students who decide to go into engineering have made their decisions by middle school, if not earlier.

Saldaña added that it is important to find ways to increase the retention of women and minority students in engineering programs. For instance, he said, Georgia Tech's mechanical engineering makerspace does a good job holding demographic-specific focused events, such as a women's night that is quite popular and even pulls in a number of people from outside of mechanical engineering.

Howe cautioned that women and underrepresented minorities are not a monolith, but rather have a broad range of interests, so it is important to show them the range of career paths that are available to them. In particular, it is important to be flexible with students and let them see the different opportunities that are available to them. In this way they can see what gets them excited and where they find communities of support and change direction if necessary. "The more that we can embed different experiences and skills in manufacturing and across other different disciplines, then new employees will travel in different directions," she said. "But, ultimately, they need to be in a place where they feel they have a community, they have opportunities, and they can make impact."

Next Krishnamurty asked the panelists how many of the faculty at their schools had direct in-the-field experience in engineering. Since Georgia Tech is an R1 university, Saldaña said, many of the faculty are research-focused. About a quarter of the faculty members have industrial experience, but they have usually come from research organizations within the industrial organizations. "However," he added, "I would say we are heavily supported by industry in our research, so everything that we do in our research programs and that we expose our students to, both at the graduate and undergraduate levels, has a basis in industrial operation . . . so in that sense we are not developing systems that are never going to be used."

Fleischer said that with Cal Poly's learn-by-doing environment, great value is placed on industry experience, and such experience is weighed heavily in considering applicants. Among those faculty who teach senior capstone courses, probably 75–80 percent have had industry experience at some point in their careers, and the lecturers in the engineering departments include many people who came to Cal Poly after several decades in industry. Furthermore, the university has a program designed to allow faculty to get industry experience; every 3 years an engineering faculty member can work in industry for a quarter, and the university will help make up some of the difference between the industry pay and the faculty pay. Many faculty members take advantage of this, she said.

Aguilar said that Texas A&M has recently hired more professors of practice specifically to get an up-to-date view from industry. These faculty members are generally put in front of students who can benefit the most, he said, and they are usually the professors who run the senior design courses.

Okwudire then asked the panelists to offer their thoughts on how best to find a balance between teaching fundamentals and providing hands-on experience since departments are limited in the number of courses students can be required to take. Howe answered first, saying that ultimately the goal should be to produce students who learn how to learn because they are going to go to work in an are that will evolve continually. "Even if you teach them everything that is absolutely important right now," she said, "in 5 years, 10 years, 25 years, that is going to be potentially less important."

Saldaña agreed but added that the best balance between classroom learning and hands-on learning will be different from student to student. With self-directed learning, students can follow their own interests and see which areas are of most interest. The important thing here is to provide students with a spectrum of opportunities, such as the opportunity to participate in manufacturing.

Krishnamurty commented that while such self-selection may work well for some high-performing students, it does not work for every student, and certain things should certainly not be optional, such as learning fundamentals. Saldaña agreed and drew a distinction between the sorts of fundamental knowledge that every student should have and the additional knowledge and skills that interested students should be able to develop. Some students will be content with fundamental knowledge about something, while others will want to achieve mastery, he said. “Not everyone is going to hop on a CNC machine and learn how to set it up, for example.”

Parekh, the third moderator, then asked the panelists a question: “If you could additively manufacture a magic wand and wave it over your own program, what would be the main change you would make that you can’t today but that you think would significantly improve its impact in terms of preparing your students for their careers?”

Aguilar answered that he would relax some of the general education requirements for engineering students to create more room for teaching engineering concepts and skills. Furthermore, he said, he would like traditional courses to include “at least some level of advanced manufacturing projects at the end” so that students did not have to wait until their capstone courses to be exposed to hands-on training. Howe disagreed about relaxing the general education requirements, saying, “I feel really strongly that the students learning engineering in a much broader context is really valuable, that it makes them much better engineers and much more flexible in terms of where they go in their careers.”

Saldaña said he would like to see a new modular approach to teaching some courses, where the courses are broken up into modules and students can pick which modules to work on, choosing their own paths within the course work.

Parekh followed up on that by noting how many students had been inspired during the COVID pandemic to jump into health careers because they saw the impact they could have and by wondering whether helping students think about the major, world-changing problems that could be solved through manufacturing might inspire more students to go into manufacturing. Howe answered that it is hard for students to see how manufacturing connects with other large societal and environmental issues when they are learning engineering totally in a silo, “whereas if you are double majoring in government, you suddenly have a completely different perspective on how policies are developed and what the impacts are nationally.” Thus, she said, there is an important role for contextual learning, where engineering is placed in more of an applied setting and students are given more of an opportunity to think across different disciplines. “That is where I see our world going,” she said, “and I think we are setting up our graduates better if we prepare them that way, too.”

Saldaña followed that up by saying that having more challenges seeded by the community could increase interest in engineering. This is already happening in the data sciences field, where companies offer rewards for solving particular problems or developing programs to carry out certain tasks and then individuals and teams work to come up with the best solutions. “So,” he asked, “can we do something like that in manufacturing on a broader scale and democratize addressing these problems by our student teams?”

Krishnamurthy passed along an audience question: “How is robotics and automation integrated into your program’s manufacturing focus?” Saldaña responded that there has been a groundswell of interest in robotics at Georgia Tech, and many of the students coming into the mechanical engineering program have been exposed to robotics in high school through such things as the FIRST Robotics competitions. However, he added, there is little done at the undergraduate level that is aimed at integrating robotics into manufacturing education.

Howe followed up by saying that there are no formal courses in robotics at Smith, but there have been a couple of capstone projects with a robotics focus. Furthermore, she added, “We have a number of students who go into graduate school and pursue robotics further after their undergrad.”

At Cal Poly, Fleischer said, capstone projects may involve bringing together industrial engineers and manufacturing engineers, and since most of those projects are sponsored, the students end up going into active facilities and seeing what is there. “So we do have that direct connection between automation in industry and what we’re doing in our capstone projects,” she said.

Okwudire closed the discussion session with a question about how the different universities handle intellectual property issues arising from projects funded by industry. Howe said that her capstone survey found that the approaches to intellectual property vary by the institution. It is most common that the industry sponsor will own the intellectual property, but it is often split between the institution and the sponsor and sometimes even the students, depending on how the institution is set up. At Smith, she added, all of the intellectual property is given to the sponsor. “It makes it much easier for us to have these projects,” she said. “The students are getting a great educational experience . . . and they get their name on a patent, but ultimately it is owned by the sponsor organization. I feel really strongly that that method works very well for us.”

Fleischer said that Cal Poly’s process mirrors Smith’s very closely. In the vast majority of the cases, the intellectual property remains with the company, and in those cases where it does not, the details are worked out on a case-by-case basis.

Finally, Saldaña said that Georgia Tech’s policies are similar, although companies will pay a little extra to get the rights to the intellectual property ahead of time. The students in the capstone courses are told ahead of time what to expect, so they can opt out of any such projects if they are not comfortable with that arrangement.

BREAKOUT SESSIONS

In the breakout sessions held during the afternoon of the workshop’s second day, a number of speakers described various efforts at engineering and technical education with application to advanced manufacturing. These comments and the discussions they triggered offered a variety of insights into ways to improve the future of the nation’s advanced manufacturing.

The Iron Range Engineering Program

Neil Schroeder from Minnesota State University Mankato described that school’s Iron Range Engineering program, which is offered to students who have taken pre-engineering courses at a community college, typically Itasca Community College in Grand Rapids, Minnesota. Those students then enter the Iron Range Engineering program, taking core and advanced engineering courses and doing engineering design projects that are carried out in partnership with local industries, including US Steel, a local iron mine, and an automation company. After that, the students return to wherever they have come from—including various locations around the United States plus foreign countries—and work full-time in a co-op there to help pay for their tuition. The students also work remotely on courses from the engineering program, typically carrying a 15- to 20-hour workload in addition to their co-op jobs. “So,” Schroeder said, “they leave our program with two-and-a-half years of engineering experience, a bachelor’s in integrated engineering with whatever focus they want to obtain, and two-and-a-half years’ experience in an ABET-accredited program.”

As an example of the sorts of educational students receive that would be relevant to advanced manufacturing, Schroeder mentioned the school’s CIOPS (Creative Innovative Open-Ended Problem Solving) program, which has students doing systems engineering framework analysis on particular systems. For example, he said, one of the project teams is working with a local mine on conveyor systems that move processed rock and iron units along. There is spillage at various points, and the students on the team are analyzing the system as a whole in the plant to identify the specific places where there is spillage, the working of the conveyors at those points, and a solution to the spillage. Currently the mine’s solution is to send a two-person team with shovels to each spillage point to get the material back on the conveyor, but that both is costly and has safety issues. So over the course of a semester the students, working with the requirements and constraints set forth by the client, define and scope the problem, generate ideas, come up with potential designs, and evaluate those designs with decision matrices. And depending on the time-frame of the project and the expectations of the client, Schroeder said, the students will sometimes move all the way through to the fabrication of a deliverable.

The student body in the program is “pretty diverse,” Schroeder said, and they are recruited from places around the country. “We get into classrooms—and now we get into classrooms via Zoom as well—and build opportunities for them to learn engineering, learn how our program is structured, so they know ahead of time how they're going to be delivered content, how they're going to be learning. The program uses a very self-directed, project-based approach.

The program was started to address a "brain drain," he said, with high school students from Northern Minnesota who were interested in engineering actually leaving the area because there were no educational opportunities there. "So this was created to have students from here be trained here and work here," but as the model succeeded, the program expanded and began recruiting outside of the area and, eventually, outside of the country.

At this point one major challenge that the program is facing is how to maintain the quality of the product and the passion of the staff as the program is scaled up. In the past year they have hired three new PhD-level faculty members, and they are also working to maintain the current ratio between students and support staff and to pull in more subject-matter experts from industry. The program is also putting a greater focus on preparing students for advanced manufacturing with such things as an increased implementation of automation, efforts to incorporate more data processing, and teaching their students about the new ways that engineers are looking at problems.

Desirable Traits in Engineering Students

In answer to a question about what universities could be doing to address some of the issues that had been discussed, Michael Packer, recently retired from Lockheed Martin and working with SME (previously the Society of Manufacturing Engineers), offered a perspective on what some of the professional societies are looking for in university education. "What we're looking at from an industrial standpoint is a . . . healthy fraction of students that have the practicum or practitioner's perspective and some hands-on experience," he said, noting that a few university engineering curricula offer this formally, while students at other schools can gain such experience outside the classroom through competitions and other hands-on learning experiences.

Industry also needs students with cross-functional and cross-discipline experience, he said, and he offered the Georgia Tech innovation center as an example of how students from different fields and majors can work together. "There's obviously a lot of mechanical engineering students, but there are industrial engineering students, there are business students, there are econ students, and it's great that all of the students are getting those kind of . . . transdisciplinary experiences, because that's the way real world is when they come into industry."

It is often the small and medium-sized businesses who are most in need of such students, Packer said, because they may not have the time and infrastructure to do the necessary training. Still, he added, even the large original equipment manufacturers (OEMs) are getting more impatient about how quickly their recently graduated new hires are productive. "They're not looking to train over months and months and months," he said. "They need ready-to-run employees." Thus it will be important for industry and individual employers to play an increasing role in defining the requirements for engineering degrees.

At a later point, Packer spoke about the importance of practicums for engineering students, particularly those headed into manufacturing. Years ago, he said, it was common for engineering students to have had some sort of practical experience—say, working on a farm or in a repair shop or a factory, even if it was just sweeping the floors—before they entered college. "If they were in any kind of an industrial setting, they at least had exposure to tools." That is much less common for engineering students today, so many of the practical labs for college engineering students that provide exposure to tools and equipment are aimed at replicating those sorts of experiences. In a similar way, the various types of competitions that engineering students can engage in—designing, building, and racing cars, for instance—"give students the full life-cycle of ideation all the way through product realization and operation."

However, he continued, students also need exposure to "a social and an emotional practicum" before they go into industry. The goal would be to prepare them for some of the social aspects of, for instance, introducing new technology and innovations in an industrial setting. “They have to be comfortable interacting in a substantive way with the mechanics and technicians on the floor and with customers, beyond just engineers.” Engineering students will generally have a decent amount of experience working on teams of engineers from their capstone projects and their co-ops, but they generally do not get experience working with the other sorts of people that are found in a manufacturing setting. “A lot of engineers that are just simply not comfortable going down to the floor and talking to a mechanic or a toolmaker or a technician before they start to put something together,” Packer said, and with today’s digital tools it is easy to believe that because a computer-aided design exists, the product can be build. “Well, that’s not necessarily the case.”

Thus, one of the opportunities for improving engineering education, he said, would be finding a way to have students go and check their designs with people who have manufacturing experience and can tell them whether the designs will work. One approach is to put “speedbumps” in a CAD system that identify points where the engineer or engineering student using the system to design and model something must go validate the design with a subject matter expert. “Force them to go to the floor and talk to people that were experts in making holes and filling holes before they committed to something” because CAD designs that look slick on the computer do not always work out that way on the factory floor.

In response, committee co-chair Maxine Savitz commented that the committee had heard from a faculty member at Auburn University that the engineering students there have various ways to interact with community college students, such as getting certified on a machine that is not available at Auburn but is available at a local community college. “It gives them an opportunity to interact with the people who are coming out of the community colleges, who are essentially the technicians you’re talking about on the floor,” she said. Since there are community colleges located near almost every university, this could be a good way to get engineering students comfortable with interacting with technicians.

Committee member Chi Okwudire offered another example of such a “speedbump.” At the University of Michigan, engineering students who are carrying out design-and-build projects split up the process: a team of students who come up with a design for an object must pass along that design to a second team, which makes the object. “Now they have to communicate it clearly enough that the other team makes it well, he said. “Otherwise it’s their fault. It frustrated them, but it definitely forced them to make sure they communicated well.” This is a different skill than simply designing something, and it helps students develop some of the abilities they will need to work with people on the factory floor who will be manufacturing the objects they design.

Getting Faculty Interested in Practical Aspects of Manufacturing

On a different topic, Savitz passed along a question to the members of the breakout session: How does one get research-oriented faculty members interested in learning about and teaching about the more practical, hands-on aspects of manufacturing? Schroeder answered that one thing his engineering staff does is try to bring faculty members to events hosted by various societies, such and the Society for Mining, Metallurgy, and Exploration and the SME annual meeting. “We bring faculty along for that so they can see the advancements that are happening in the industry, they can attend the technical sessions, and seeing where the concepts and everything are being applied and how they can put a spin on how they’re delivering the content to our students to teach the applied side of it all.”

Okwudire commented that some faculty are just philosophically opposed to spending time on the practical side. “I don’t know how to change that mindset, because if faculty don’t want to do it you can’t force them to do it because of the way things are structured,” he said. “So there has to be a culture change that will facilitate that.”

In response, an audience member noted that in many schools the most important criterion for evaluating faculty members is research money and direct cost—“and it’s got to be because of the way we fund education in this country.” So the faculty, in order to get tenure, go to where the research funding is. “We have not been funding research in basic kinds of machining things or manufacturing things as they do in Germany," the participant said. "So I think the issue is a system-wide kind of problem and not so much 'How do I get somebody interested in this?' Give them money."

Hands-On Learning

Workshop participants spoke about the importance of hands-on learning on multiple occasions throughout the 2 days of the workshop. For example, in one breakout session Al Romig, the executive officer of the National Academy of Engineering, made the point that hands-on learning is an important way to get students, particularly in middle school and high school, interested in engineering and manufacturing. "When a lot of us were growing up we had shop class in middle school or junior high school and high school, and I'm glad to see that coming back now in terms of maker spaces, even at the high school level," he said. "At that high school, middle school, even the latter years of elementary school, getting kids learning how to do 3D printing and that other kind of stuff" can really hook them on building things. "Getting their hands dirty, to use the old phrase, boys and girls—the earlier you can do that, the better you'll set the hook."

Kathryn Jablokow commented that part of the argument for hands-on learning at an early age is developmental. "When you've got the kids younger, they're not going to understand a whole bunch of advanced theory," she said, "but what they understand is what's in front of them, and what they're touching and seeing and feeling."

Avik Basu from University of Michigan added that some students may not get particularly good grades but take very well to working in a machine shop. "They are so enthusiastic. They may not do very well in a regular exam, but they are excellent in the manufacturing shop environment. And those are the types of students that typically excel in manufacturing."

However, Basu added, it can be difficult to scale up this sort of manufacturing experience to offer it to all engineering students. The University of Michigan has about 1,200 engineering students, but only the mechanical and industrial engineering students—about 20 percent of all engineering students—get manufacturing training. Aerospace engineering students, for example, do not have a regular manufacturing course. But Basu has been teaching a freshman engineering course, Manufacturing in Society, together with members of the social science faculty, and these students do get the opportunity to experience such things as computer-aided design and 3D printing. It is important to expose them early to such experiences, he said, because these are students "who can still change their perspective about manufacturing."

On a related topic, Chi Okwudire asked how to balance the value of having students work with industrial-grade machine and the value of keeping the students safe. Certain industrial machines, such as lasers or milling tools, can result in serious injuries to the operators if they do something wrong. It is for this reason that universities tend to rely on safer machines, such as a desktop machine tool or desktop 3D printer, that are not high-powered industrial grade machines. Do students learn enough on these safer machines? "My philosophy is that I would rather have them touch it, even if it is not an industrial grade," Okwudire said, rather than just showing them some industrial-grade equipment and explaining how it works but not letting the students actually operate them. "I find that students would rather play with what people might consider toys but really engage with it and learn something." But is that enough?

One participant suggested that it is because of transfer learning—the students can learn how to do someone on a safer machine and then apply their learning to working with industrial machines later. The key is that the students learn concepts and skills that are applicable across a wide range of machines.

The Value of Experience with Multidisciplinary Teams

In the breakout sessions, a number of people spoke about the value of students gaining experience with multidisciplinary teams. For instance, Chris Saldaña of the Georgia Institute of Technology spoke about a robotics course that he teaches in which business majors participate as part of a technology minor. He has found, he said, that teams with mechanical engineers and a couple of business majors actually perform better than teams with all engineers. “They look at the problem differently, they don’t assume anything,” he said. “There’s that person in the room that is asking questions, and I think that not only are they looking at different approaches and different ideas, but they’re learning that the social cues of working on teams. The business major comes in with this natural kind of apprehension that they aren’t familiar with how to build a robot, or how to do CAD, but what we found is those teams greatly benefit from just the interaction of working with different personalities, and being able to listen to those perspectives.”

Saldaña added that while many of the capstone projects in the mechanical engineering department are focused just on mechanical engineering, there are also interdisciplinary projects in which, say, a materials scientist or a public policy person works on the team, “and I think those students are benefiting from that experience too.”

Speaking from an industry perspective, Al Romig commented that his experience in the Lockheed family is that “students who come out of school are good at teamwork amongst their small little group, but many of them don’t have a good sense of interdisciplinarity.” Most universities are not particularly good at bringing different departments together, so students do not get experience working with others from outside their discipline. “I think there has to be some attention paid to how we can get a better sense of working on multidisciplinary engineering teams,” he said, “and by the way you might want to throw a marketing guy in there as well, or a lawyer sometimes. But I think that’s an important thing that I saw as a shortcoming with the people that I hired over the years.”

In response to a follow-up question, Romig said that interdisciplinary skills are particularly important for companies that make smaller numbers of more complex objects. Specifically, he drew a distinction between “manufacturing” and “production.” In companies that make highly complex aerospace and defense products, what they are doing is really production, not manufacturing. “If you make 50 a year, that’s really a lot,” he said. “If you call it manufacturing, somebody who works at General Motors or Toyota, they’ll laugh at you.” And in situations where highly specialized objects are being produced in small lot runs, he said, it is particularly important that the team of engineers in charge be able to work in an interdisciplinarity team environment.

Doug Nation agreed with Romig’s point and repeated something he had learned from Michael Hammer at the Massachusetts Institute of Technology. “Hammer had many examples of process reengineering, troubleshooting, process change, where teams of diverse individuals came in with very different points of view and were very effective at arriving at remarkably better processes,” he said. So there is great value in engineers being able to work on multidisciplinary teams.

Magdalini Lagoudas of Texas A&M University commented that it can be exceptionally challenging to have students from different majors and different skillsets to work together. It was her experience in teaching a class on innovations for defense, she said, that while the interdisciplinary projects could be “awesome,” it might take a long time before, for example, a computer science major and a chemical engineering major learned to work together as a team. This was an issue for that particular class.

Speaking specifically of capstone projects, Lagoudas said that there are also challenges to bringing different disciplines into them. At Texas A&M there are some interdisciplinary capstone projects, but the question is how to scale this so that all students have that opportunity. “Where I see this worked well,” she said, “is when the faculty who is involved is somebody who came from industry, a professor of practice, for example, who has experience in handling a diverse set of skills and mentoring the team to do well.” But not all faculty have that experience. There are other challenges as well, such as the logistical issue of coordinating capstone projects among different programs. Ultimately, she predicted, the university is going to move in the direction of having more interdisciplinary projects, but industry could speed the process up. “If industry comes to our door and says I have a project but I need both of these sets of skills, then I would think we would be seeing more and more of that.”

In industry, Romig said, interdisciplinary teams generally have a majority of people who have previously worked in a multidisciplinary environment with perhaps only a couple of "newbies" who have not, and the newer hire learn to work on such a team from the more experienced ones. It is likely, he continued, that new hires who had experience with multidisciplinary teams in college would be more comfortable talking with people in other disciplines from the beginning and would not take as much time to adapt. On the other hands, when students have only worked with others in their discipline, that will be a liability for them.

Experience Outside the Classroom

A significant amount of discussion during the breakout sessions was devoted to the sorts of experiences that students gain outside the classroom—from competitions, internships, co-ops, and the like. "I think we under-value and under-resource extracurricular and co-curriculars," one participant said. "We put so much emphasis on the capstone experience as that one-stop shop, get everything you need for experiential learning, . . . but there is this huge disconnect in the opportunity window in the middle where students have to take the initiative to go after internships, co-ops, competition teams, research, things like that." Furthermore, students often have no way to demonstrate to employers the types of skills that they have gained from those experiences. A number of approaches have been tried to address that problem—things like micro-credentialing and digital badges—and more thought should be put into this, he said.

A participant from Pennsylvania State University suggested that one way students can document the skills they develop outside the classroom is through a portfolio. Penn State has undergraduates build a portfolio as they go through their years in engineering. A portfolio might include such things, for instance, as the design of a robot arm, the development and implementation of a particular algorithm, or the solving of inverse kinematics. "We require our students to also finish a thesis at the end of their 4-year educational experience," the participant said. "The thesis, in combination with the portfolio, can really give you a good overview of the skills of that particular student, especially if they start developing the portfolio early on."

A related discussion took place about the value of students taking part in competitions, including what students learn from it and how potential employers should weigh such participation. Participants said that the competitions are valuable not only for students learning hands-on skills but also for them developing the ability to work in teams. However, because they are working in teams, it is not always easy for a potential employee to gauge what skills a student gained from such experiences, so the comment was made that universities should examine ways to capture what students have learned from these competitions, perhaps by having a professor of practice or someone similar monitor what the teams are doing and what contributions the individual students are making.

Lagoudas from Texas A&M said that her university has a program that requires students to get some sort of experience outside of the classroom. The requirement, called Engineering X, is that a student complete something in addition to what is required in the student's major, and the specifics vary by department. It could be a 48-hour challenge, for instance, or it could be an internship, "but each student is required to complete one of those and do a reflection on that," she said. And not all of the options are technical. Some departments, for instance, allow a student to qualify by having been an officer in a student organization, so long as the student can demonstrate having acquired skills that the department thinks are important.

THE INDUSTRY PERSPECTIVE

The session on industry perspective was moderated by Don Kinard, a senior fellow in production operations at Lockheed Martin in Fort Worth, Texas, and Keith Hargrove, who currently serves as a provost at Tuskegee University but has a background in manufacturing and engineering, having worked at both General Electric and Boeing. Kinard began by asking the panelists to introduce themselves and offer a bit about their backgrounds.

Tracee Gilbert is the Tracee Gilbert is the founder and CEO of System Innovation. They deliver engineering and advanced technology solutions to government agencies, educational institutions, and commercial enterprises. They are focused on helping organizations leverage their data, processes, people, and advanced technologies to deliver a new era of systems, products, and services. One focus area of System Innovation is infusing digital engineering with advanced manufacturing (i.e., additive manufacturing).

Mike Packer retired from Lockheed Martin in 2021 after about 45 years in industry.

Mike Sarpu has had a variety of jobs at Lockheed Martin, including running operations for aeronautics, and is now responsible for operations transformation. In that capacity, he is working to use digital processes to manufacture things in ways that could not be done before. Over the past several decades, he said, the company used digital methods essentially to replicate processes that had been used in the past, but it is now looking to use digital approaches to do things in a totally different way. “How do we go directly from a design to a part without all those interim steps and all of that? How do we speed it up? How do we leverage advanced manufacturing technology . . . to put tools and augmentation into the hands of our workforce?”

Bill Bigot, the vice president of sales and marketing at Ascent Aerospace, has been in the business of supplying automation to industry for about 38 years. “At Ascent Aerospace we support the commercial defense and space business, including unclassified as well as classified defense programs,” he said. “We, as a company, provide one of the largest breadth of products in terms of tooling, in terms of automation, and integration. We are not only just providing the big, large, static tooling that everyone needs in order to manufacture aircraft components as well as full aircraft, but also the automation, the processes, and the innovation that goes along with being able to support the operations of those lines.”

THE CURRENT STATE OF ADVANCED MANUFACTURING IN THE UNITED STATES

To open the discussions, Kinard asked each of the panelists how they see the current health of the advanced manufacturing industry, especially the defense manufacturing industry, in the United States.

Bigot began his answer by saying that the industry needs some help, which, he said, is why Ascent Aerospace is doing well. “Our customers worldwide are running into situations where they cannot get qualified people,” he said, and when an advanced manufacturing company does find qualified people and train them, it must worry that those employees will move to a competitor. There is so much demand for qualified employees that “there is always the opportunity for people to move around.” What was common decades ago in the industry—that people would spend 40 or 50 years working for the same company—is not very common anymore.

Thus one of the major challenges facing companies in advanced manufacturing, he said, is finding the right combination of talent and keeping those people on board. The work requires collaborations among people with a range of educational backgrounds and capabilities—for example, someone with a 2-year technical degree, another person with a 4-year engineering degree, and maybe a post-doctoral student or someone with a graduate-level degree. All of these people and talents “need to come together in order to develop the processes, to run the systems, to execute the advanced manufacturing capabilities, and to keep the systems up and running,” he said.

That challenge has been exacerbated by the pandemic, he added, which has forced companies to reengineer their work patterns. “It used to be nothing for several people to be crawling right next to each other all over parts,” Bigot said, but companies—and their employees—no longer want to have so many people working together so closely to produce a product. With advanced manufacturing it is possible to carry out the same tasks with fewer, more highly skilled people using automation or semi-automated techniques. However, this requires companies to develop new capabilities, such as digital techniques that make it possible to monitor processes in detail, understand how well they are working, and even predict when machines will need support or maintenance. These new digital approaches must be integrated into existing processes, he said, requiring that companies—in particular, support companies like Ascent Aerospace—develop new ways of doing things that provide similar or better results when compared with methods that may have been honed over 20 or 30 years.

In response to a question from Kinard about whether Ascent Aerospace has difficulty finding people with skills in such fields as robotics and automation, Bigot said that this is indeed one of the companies concerns, and he offered control engineers as an example. The company must "get them, train them, bring them up to speed, . . . and then retain them for a long period of time so that lessons learned and things that they do day in and day out get to be quite useful and beneficial down the road." But people with the requisite skills are difficult to find, so Ascent Aerospace works with local universities—the company has offices in California, Michigan, and Seattle—to find talented people while they are still in school, offer them internships and other opportunities, and then hopefully hire them after they graduate.

Kinard then turned to Sarpu and asked him the same question about the health of advanced manufacturing, particularly in the aerospace and defense area. It is a complex question, he responded, "because we have to look at advanced manufacturing technologies in probably three, maybe four different ways."

The first perspective is that of what is being done with the technology, he said. "If it is robotics, what are the robotics doing? You first have to have the base process down."

The next issue is what is being done with the advanced manufacturing technology to make the process better. He offered additive manufacturing as an example. "You have metallurgy going on," he said, and there is a machine and controls that are controlling the metallurgy, with two different kinds of engineers needed for those things.

Taking another step back, one must then consider how the process is going to be implemented in a factory that will be creating the product. This is where applications engineers become involved.

"And then the one that we never really think enough about," he said, "is the actual worker that is going to use the manufacturing technology." He works with a couple of universities with advanced manufacturing technology centers where they focus on the tools and the design but seldom pay much attention to the worker who must operate the machines. Sarpu drew a parallel with the first industrial revolution when Henry Ford and others who created the first assembly lines have trouble finding workers who were willing to do the work. They tended to bring in artisans who were used to working with their hands—but not in the way that was required. "To get 10 people, they hired 100, and 90 of them could not take the monotony of the job," he said.

"I think we are going through a similar kind of thing now" he continued, "where we are looking for the skills that we needed in the past when in fact the future is going to require people that can actually . . . become one with the machine. But now, we are looking at human augmentation versus human replacement. I think we all recognize that we still need some of that artisanship in the folks on the floor. But they need to be able to incorporate in these other skills that allow them to utilize the technologies."

Healthy advanced manufacturing requires all these different types of people, Sarpu said: people who can design the machines, people who can install them in factories and get them to work, and people who can operate the machines.

Yet another issue, he said, is that it is now possible, for the first time, to create things that the engineer cannot conceive and that must be designed by a machine. But that raises the question of who is going to create these automated design systems. It requires a totally different kind of engineer.

This sort of machine-assisted or machine-controlled design will be a key to the value of advanced manufacturing, Sarpu said. If it is used just to replace the technologies used today, its value will be lost because, for example, injection molding and five-axis high-speed machining can produce a product more quickly than additive techniques. "But if I come up with a structure that I cannot build any other way, now all of a sudden advanced manufacturing becomes that cornerstone of a manufacturing process."

Getting back to Kinard's original question, Sarpu said that the overall state of advanced manufacturing is healthy, but it will be important to understand the different things that advanced manufacturing offers and act accordingly. “Industry 4.0 is not just industry 3.0 with a little bit of internet thrown in there,” he said. It is a totally different way of approaching manufacturing, and taking full advantage of that will require understanding those differences and making the transition effectively.

Noting that Sarpu’s Zoom background was a Lockheed Martin X-59, an experiment supersonic aircraft designed to have a quiet sonic boom, Kinard asked, “Do you believe that as a nation we have the capability to design and manufacture things like that X-59?” Is the country developing the sorts of engineers and workers that it will take? What are the challenges?

The challenges begin with the basic economics of manufacturing, Sarpu said. In the past, manufacturing had always been a high-level employer of people, and when a factory came into a town, people were excited because it meant that there would be a number of new jobs available. But the more automation that is put into factories, the fewer jobs there are, and today the announcement of a new manufacturing facility does not generate the same excitement. Thus one of the challenges today is how to make manufacturing more attractive. Sarpu told about the time around 15 years ago when he had run a facility in a small community and had a difficult time getting the people in this community to apply for jobs to “build electronics and cables and those kinds of things” because they saw no future in it. “I had to sit down with the parents and walk them through the kinds of opportunities that were there,” he said, “and then, all of a sudden, they would say yes, I get it.”

In short, Sarpu said, one challenge facing advanced engineering will be to make it attractive to the communities where the facilities are located. “What I fear is it is going to be so easy to make manufacturing jobs portable with advanced manufacturing technology that communities are going to be even more leery of making investments in them,” he said. Fifty years ago, building a factory was a long-term commitment because it could not be moved easily, but many of today’s advanced manufacturing technologies—such as additive manufacturing processes—are much easier to move. Furthermore, the increasing use of automation and human augmentation decreases the number of jobs and, combined with the increased ease of moving facilities, makes communities more leery of hosting such facilities.

To address this, Sarpu said, the manufacturing community needs to decide how it will present advanced engineering to the country. “It is not the dirty old factories of the past,” he said. “It is a new kind of factory,” but exactly what kind of factory? It will be important to have an open and honest discussion within the manufacturing community as well as with the rest of the country about what advanced manufacturing even means.

Kinard then turned to Packer with the same question about the health of advanced manufacturing, particularly defense-related manufacturing, in the United States. Packer offered his answer in the context of his own career. Through middle school and high school he worked in pattern shops, iron foundries, and tool and dye shops and went on to spend another 40 years in the industry and also in professional groups such as the Manufacturing Leadership Council of the National Association of Manufacturers as well as the Society of Manufacturing Engineers and the Manufacturing Skill Standards Council, which focuses on the skill standards and certifications of frontline workers.

Over that time, he said, he developed a philosophy concerning advanced manufacturing education. “I view manufacturing engineers as the architects and . . . construction managers of advanced manufacturing capabilities whether they are manufacturing engineers [or] application engineers,” he said. “As the architects and construction managers, there are three primary areas that manufacturing engineers focus on.” One is configuring the systems of the future, deploying the latest technologies into those systems. The second area is the components of the various processes; engineers mature and integrate those processes throughout the value stream. And the third area is workforce and skills development. Skills must be updated continually, Packer said, “and the manufacturing engineers have a frontline position in helping update those and crossing, as Mike Sarpu said, between design engineering and starting to use manufacturing as the innovator for design engineering. Things that could not be conceived in the past can now through artificial intelligence as well as capabilities that did not previously exist.”

Workforce development has a number of aspects, Packer said, including “essentially retooling incumbent workers to be able to work in this new environment, orienting and training the incoming workforce, but also outreach into younger ages to, one, inspire and, two, build an enduring pipeline of future talent that is agile and paying attention and driving the continual advancement of the technologies that are deployed." Another part of workforce development is building a pipeline for engineers, he added. "Manufacturing engineers need to continually upgrade their own expertise and their own body of knowledge to keep pace with all of the digital transformation."

And from the perspective of the development of the advanced manufacturing workforce, Packer said, "I think in general terms we are below healthy. . . . We have gaps in terms of skills both on the floor and in those architects and construction managers of that ecosystem." Undergraduate education is providing some of what is needed, he said, but some of what these students are learning is already obsolete or becoming obsolete by the time they graduate. One approach to dealing with this is the use of industry internships, which can help maintain the freshness and relevance of the skills and knowledge of developing engineers who are headed into advanced manufacturing.

As a follow-up, Kinard asked Packer how other countries differ from the United States in their attitudes and approach to advanced manufacturing. Packer answered that there are several regions around the world—the Pacific Rim, for example, and Germany and Poland and other European countries—that are much more aggressive at pushing advanced manufacturing technologies and also developing their engineers and workforce. "Most of the engineers in Poland are educated in the German engineering system," he said, offering a specific example. "They are very familiar with working side by side and actually spending time on the floor frontline doing the work. It helps them develop an ease of working with the people that are on the floor working with the technologies that they deploy. I think that does help set them apart."

The United States is behind these regions in bridging the gap between engineers and those on the factory floor, he said.

Kinard asked Gilbert if she found many differences between the needs of small businesses and large businesses. "I think the fundamental pain points are very similar," she said, but one difference is that small businesses may find it more important to work with universities. Because small businesses tend to have more limited resources, it can make a bigger difference to them if they are able to leverage the resources of universities.

ARE UNIVERSITIES PREPARING ENGINEERS FOR ADVANCED MANUFACTURING?

Next Kinard asked the panelists to address the question of whether universities are appropriately preparing their engineering students for working in industry. Are the programs too academic? Should there be a greater focus on manufacturing? And, in general, what should be done differently in engineering education?

Gilbert answered first and began by saying that in her experience with mechanical engineering departments and manufacturing engineering, the education has been very traditional and that moving to the future it will be important to help students develop multidisciplinary skills and the ability to work in teams with people from different. "The one area that I do appreciate about engineering education today," she said, "is that they are provided with the critical thinking and logical reasoning skills to be able to learn new skills very quickly." But there remains much works to be done in terms of students developing the skills needed to work in an "end-to-end digital environment" (Box B-1).

Furthermore, she added, most of the focus in engineering education is on developing technical skills, with the capstone course being one of the few opportunities for students to develop the nontechnical skills, such as "working together in teams, building consensus, helping to drive decisions," that are very important in working in industry.

Kinard followed up by observing that his experience with engineering classes is that they tend to be very academic but not very practical. Thus he learned a lot of theory, but it was often not applied. "Is that part of the issue?" he asked. Gilbert answered that it absolutely is. The upside of this approach is that students with a theoretical background generally have the ability to transition effectively to industry because they have the skills to learn applied processes. “But,” she added, “I think that we do have to reimagine our engineering education curriculum to be more in line with how we apply engineering and practice.”

Next, Kinard asked Sarpu the same question, adding that he had always thought of innovation as lying at the intersection of engineering and manufacturing. That is, one must not only be able to imagine an innovation, but must one must also be able to build it. Otherwise it is not innovation. “Are we preparing our students to handle that interface there?” he asked.

“I think that the universities are doing an okay job,” Sarpu said, but that there should be greater emphasis on connecting what engineering students are learning in class with what goes on in a manufacturing facility, particularly as universities are moving away from teaching such things as welding, grinding, and machining. “I grew up working in a gas station and learned how to weld and run a lead and all of that stuff,” he said. “That is what brought me into engineering.” Today, though, people are mainly coming into engineering for other reasons, which can be a problem when a manufacturing company brings in a researcher to do a practical, hands-on type of job.

The bigger issue, however, may be how companies are choosing whom to hire, Sarpu said. A company may, for example, choose to hire an engineer who graduated from a prestigious school with a 4.0 grade point average (GPA) when in reality that would not be the best person to implement technology in a manufacturing plant. A student with a 3.2 GPA who had experience designing and building a vehicle with a Formula SAE team might be a much better choice in terms of being able to apply engineering skills. A related part of the issue is that companies do not always think about which specific type of engineering they should be hiring—an applications engineer, a materials engineer, a process development engineer, or whatever. “I think a lot of time our staffing process lets us down because we just say ‘engineer.’”

So part of the solution will be to consciously look for the right sort of hires, he said, but it will also be important to recruit hands-on types into engineering. Companies should go into high schools and look for “those really bright folks” who are designing and building cars or doing robotics and encourage them to go into an engineering career and into manufacturing. This is necessary, he said, because at least some of those bright, hands-on students do not see themselves as engineers.

In conjunction with this, industry should consider whether there are other ways of finding people who can work in manufacturing other than graduates of 4-year engineering programs. What sorts of qualifications should be required, if not such a degree? “I think the people are out there,” he said, but it may be necessary to look for them in a different way. And one focus should be to look for potential hires who have a desire to continuously learn because technology is evolving rapidly, and the skills that people learn in college are likely to become obsolete within a decade or two. “The 50-year career of doing the same thing is never going to happen again,” he said, “because technology is changing too fast. . . . Maybe we have to think differently about the way we hire.”

In response to a question about whether the industry’s difficulty in hiring qualified people is due to not paying enough, Sarpu said that he believes that engineers in some areas are well paid, while other areas may be underappreciated. As an example he said that he has seen engineers move from one specialty to another, such as from manufacturing engineering to research engineering, because of the difference in pay. Thus it may be necessary to “re-level things.” At the same time, he added, there are jobs with engineers in them that technicians could do. One solution might be setting up a 2-year certificate program for people to handle certain jobs that would pay better than technicians’ jobs but not as much as engineering jobs.

Moving to Bigot, Kinard asked the same question: “The engineers that you hire and have hired—do they have the right skills? Are we able to turn out engineers that have the skills you need to do the kind of work you do?”

The universities are doing a reasonably good job, Bigot answered, but “what we really need is someone that has gotten in and gotten their hands dirty.” A student who has experience with welding or the other sorts of activities that go into building something will have a better understanding of the manufacturing process, which is important for engineers who design items that must be manufactured or who design new processes. Bigot said his company would like to be able to get such engineers, and he emphasized the importance of programs that allow students to spend 6 months or so working for industry, providing value to the companies they work for and also preparing the students for jobs after graduation.

Ascent Aerospace, which is in Macomb, Michigan, works with engineering programs at both the University of Michigan and Michigan State University with the goal of identifying and attracting some of their best students. It is the universities' responsibility to prepare their students well and not just by teaching them mathematics and theory but also by teaching them how to apply what they have learned. And it is industry's responsibility, Bigot said, "to bring them in and to give them a taste of the various disciplines of what they could perhaps do so that when they come out, they really have a better understanding of where they want to go."

Finally Kinard asked Packer the same question. In particular, he pointed out that European countries such as Germany tend to have both a technical track and a university track for students, with the technical track providing more hands-on training. Do US engineering students need more of this sort of hands-on experience?

Undergraduate engineering education is a mixed bag, he said, with some things done well and some things not done at all. In decades past, he continued, many of the students who went into engineering had grown up with experience working in various places—gas stations, pattern shops, farms—that helped them develop logical reasoning and critical problem solving related to working with equipment. All of that hands-on work, combined with industrial arts education in the high schools of the time, helped create students with a broader engineering perspective which made them more comfortable with finding and applying practical solutions to various problems.

A number of universities continue to have such an approach to engineering education, Packer said, and he mentioned Kettering University—previously the General Motors Institute—in Flint, Michigan, as a school where students will spend 6 months on the floor of a factory and 6 months in classrooms. Similarly, some more advanced programs—such as the engineering programs at the Georgia Institute of Technology—provide facilities where students can work with industrial equipment and gain hands-on experience with various machines and technologies.

Such innovation centers offer many opportunities to augment the theoretical work done in classrooms, Packer said, with activities such as design-and-build competitions and capstone courses. They also offer the opportunity for students from different areas—not just different engineering areas, but areas such as economics and business—to interact and work on teams to complete a project. And that is important, he said, because an increasingly important skill in industry is the ability to work in cross-functional teams to identify problems and come up with solutions.

Kinard commented that in some universities students are not allowed to handle equipment because of safety concerns; instead the students give their designs to technicians, who build them. This prevents students from gaining experience in actually building things, which in turn keeps them from developing a sense of what is involved in the manufacturing of a particular design. Packer agreed that this can be a problem but pointed to the Georgia Tech innovation center as proof that it is feasible to let students handle machinery. In this case, the innovation center is managed and run by students, including the safety training and the certification of students and others to operate the equipment.

BOX B-1
Digital Engineering

In introducing herself and her work, Tracee Gilbert of System Innovation offered a description of digital engineering. In previous work in the Office of the Under Secretary of Defense for Research and Engineering, she led the development of the digital engineering concept, strategy, and initial implementation efforts across the military services as well as in industry, academia, and various government agencies. Digital engineering, she said, is "an engineering approach that captures and analyzes data in a digital format, which is semantically rich and interconnected to enable both people and machines to leverage the power and advancements in technology across the complex life cycle of both systems and products." The move to digital engineering will be crucial to advanced manufacturing, she said, and thus also for engineering education.

The Department of Defense (DoD) digital engineering strategy has five basic goals, Gilbert said. The first goal is to formalize the development, integration, and use of digital models. These models and the data they depend upon are conceived of as constituting a continuum across the engineering life-cycle. "We are integrating traditionally stovepipe models and data, making manufacturing a part of a larger digital model-based enterprise," she said.

The second goal is to use data to provide an authoritative source of truth so that authorized stakeholders have access to the most up-to-date and consistent information available over the digital engineering life-cycle.

Goal number three is to incorporate technological innovations that help to improve the practice of digital engineering.

Goal number four is to establish the supporting infrastructure and environment necessary to perform activities in an integrated digital ecosystem.

And the fifth goal, which Gilbert said is often overlooked but still critical in transformation efforts, is to use softer skills such as change management and strategic communications to transform the culture and the workforce. During her time at DoD, Gilbert said, advanced manufacturing made great strikes and demonstrated that it can realize cost and schedule savings versus traditional manufacturing, "but digitalization is really needed to take advanced manufacturing to scale."

Gilbert also described a digital engineering competency framework that defines those the knowledge, skills, abilities, and behaviors that DoD looks for in its digital engineering workers. Developed by the Systems Engineering Research Center, a DoD university-affiliated research center, the framework has five broad groups of digital competencies: data engineering, which includes the necessary data governance and data management skills to manage the data assets within the digital enterprise; modeling and simulation; digital engineering and analysis; systems software, which involves systematically applying digital engineering approaches to the development of software; and the digital enterprise environment, which includes the skills necessary to creating and maintaining the hardware, the software, and networks involved in the digital engineering enterprise.

Given the importance of digital engineering to advanced manufacturing, Gilbert said, this digital engineering competency framework could be very useful in informing undergraduate engineering education.

BREAKOUT SESSIONS

In the breakout sessions on the workshop's second day, one set of topics was centered on the general question of how industry can better engage with universities at an undergraduate level in order to assist and improve advanced manufacturing.

In one session moderator Don Kinard with Lockheed Martin described what his company does to work with universities in order to set the stage. The company has 60,000 engineers and scientists across its various divisions, and engages with universities in a variety of ways. At the highest level it has open research contracts with eight universities, and it participates in various ways in most of the universities that are close to Lockheed Martin sites. For instance, he is chairman of the Industrial Advisory Board for the University of Texas at Arlington in mechanical and aerospace engineering, while other company executives sit on engineering boards for Texas A&M, Texas Tech, The University of Texas, and the University of Houston. Kinard also gives presentations to universities that are interested in advanced manufacturing, that's one way.

Another major connection with universities is that Lockheed Martin hires about 3,000 engineering students as interns every year. The company also hires many permanent employees every year, Kinard said, and "if you intern with us you're essentially guaranteed to get at least one job offer from us." After hiring, most of the training is done in-house. Because Lockheed Martin is so large, it is able to run internal training programs that are more comprehensive than anything that colleges could provide in part because the company has many large, expensive pieces of equipment that universities could not afford to provide.

Concerning the question of how companies such as Lockheed Martin could do a better job working with engineering education programs, he noted, the obvious answer is that they could just provide more more to universities. But, he said, Lockheed Martin already provides a lot of funding to universities, "so that's not the right answer."

One possible answer, he continued, is suggested by his own experience when he was a graduate student at Texas A&M. "Texas A&M had a program funded by the federal government to train engineers, so they were cost-sharing engineers to go to graduate school at Texas A&M to learn composites," he said. "While I was in the graduate school down there, this program started, and the opportunity to take a lot of composites processing, composites mechanics, viscoelasticity classes, and that helped me eventually to get a job with Lockheed." That was one of the best examples of cooperation among government, industry, and academia that he has seen, Kinard said, "but those programs for the most part have gone away." On the other hand, those programs are fundamental in Europe, with governments providing funding for applied research and having strong connections with academia and industry. "And those programs have, I would say, certainly contributed to the fact that a lot of our advanced technology has moved overseas."

Al Romig, the executive officer of the National Academy of Engineering, offered two possible answers to Kinard's question of what industry could do to improve engineering education for advanced manufacturing, both of them based on his experience at Sandia National Laboratories and at the Skunk Works, Lockheed Martin's advanced development programs. First, he said, both Sandia and the Skunk Works had university faculty members on sabbatical come work with teams there. "That's a good way to build bridges into the faculty," he said. "I've noticed that ended up turning on some real pipelines of new talent that I thought was very useful." In a later discussion, Don Kinard of Lockheed Martin said he thought this was an interesting idea. What he has found is that a large percentage of the professors in engineering programs have never worked in industry, and such sabbatical could provide them with some useful exposure to that segment.

The second approach Romig mentioned was providing internships for high school students. "They weren't paid," he said, "but they get three credits for doing it, they come in a couple afternoons a week, and you try to really sink the hook about really getting these kids interested in engineering. And by the way, you stick them off in a prototype lab somewhere—you didn't have them just run around at the Xerox machine."

One way to attract students into engineering, Romig said, is to get the word out about how compelling much of the work is that engineers do. Helping to build things to defend the nation or improve human health is a compelling mission, he said, and that can be a selling point. "I think incumbent upon us, upon engineers, is to get the message out there about how engineering is about solving problems that help people in society, et cetera. It could be about improving the nation, it could be about improving human health, it could be about improving sustainability, but the compellingness of missions will attract people to the field and will attract them to companies."

Sinan Bank of California State University, Chico, praised the value of engineering students having internships with industry but said that it would be valuable if they were longer than the typical 3 months of a summer break. Kinard noted that Lockheed Martin used to offer work–study programs where engineering students would spend a summer and a semester with the company, but the problem with that was making sure that the students could get their classes in because classes were not offered every semester. "I think you hit the pain point," Bank replied. "The structure of universities in the United States is creating the difficulty." That is why the company he was working with ended up hiring mostly interns from Europe, because universities there had classes dedicated to work and study programs.

EFFORTS BY GOVERNMENT AND NONPROFIT INSTITUTES

The session on government and nonprofit institute efforts to improve manufacturing and manufacturing education was moderated by committee members Maxine Savitz and Thomas Kurfess. Savitz moderated the panelists' presentations, while Kurfess led the following discussion.

In introducing the session, Savitz said that the past 10 years have seen exciting advances in advanced manufacturing technologies that have come about through innovations in science and technology as well as improved manufactured products and manufacturing processes. These developments are particularly important for the defense industrial base, she said, which relies on the products of advanced manufacturing to provide the cutting-edge weapons and systems required by the US military. "The education and training of practitioners of these new technologies are essential to applying advanced technology to design, to prototypes, and then, most importantly, to the manufacturing processes," Savitz said. "Rapid technology transfer from research to manufacturing is a key requirement."

Manufacturing USA, originally known as the National Network for Manufacturing Innovation, was launched about 10 years ago, Savitz noted. It is a joint federal effort among the Department of Defense (DoD), the Department of Energy (DOE), and the Department of Commerce, working through the National Institute of Standards and Technology (NIST), to create a network of regional institutes in the United States. The network's focus is on developing manufacturing technologies through public–private partnerships among US industry, universities, and the federal agencies. Since 2012, 16 individual Manufacturing USA institutes have been established by the federal government, of which nine are managed by DoD, six by DOE, and one by the Department of Commerce. The four presenters on the panel represented activities from four different federal agencies or institutes, she noted.

With that, Savitz introduced the presenters. The first was Jennifer Pilat, the vice president of strategy and engagement at MxD, one of the first DoD manufacturing innovation institutes. In her job Pilat leads the institute's efforts to make US manufacturing more innovative, globally competitive, and cybersecure and to develop the necessary workforce.

The second speaker was John A. Hopkins, the chief executive officer of the Institute for Advanced Composites Manufacturing Innovation (IACMI), one of the first DOE of manufacturing innovative institutes. It focuses on advanced composites, technology for vehicles, wind turbine blades, and compressed gas storage systems.

Third was Pravina Raghavan, the director of the Hollings Manufacturing Extension Partnership (MEP) at the National Institute of Standards and Technology. MEP works with public- and private-sector partners to strengthen communities in US manufacturing, particularly small and medium-sized manufacturers.

The fourth speaker was José Zayas-Castro, the director of the Division of Engineering Education and Centers at the National Science Foundation as well as a professor of industrial and management systems engineering at the University of South Florida College of Engineering.

MxD

Pilat began her presentation by explaining that MxD, which stands for manufacturing times digital, is one of the oldest institutes in the Manufacturing USA network. It focuses on research and development projects, workshops, and testbeds in a number of areas, including cybersecurity, resilient supply chains, and predictive analytics and maintenance. It houses the National Center for Cybersecurity in Manufacturing, helping manufacturers deal with the cyber threats that arise from digital connections with the outside world. Finally, it has a number of workforce programs aimed at helping manufacturers train and retain skilled workers.

Launched in 2014 with $70 million in funding from DoD and currently on a $60 million renewal from DoD, MxD provides a nonprofit pre-competitive environment that industry, academic, and government members can take advantage of. MxD is based in Chicago, where it has a major location that includes a 22,000-square-foot manufacturing testing, validation, and demonstration facility. It has 320 member organizations, anchored by DoD and 20 global manufacturing and technology leaders. Since its inception it has invested more than $100 million into 120 projects that apply technologies to real-world real manufacturing challenges and opportunities.

In its cyber efforts, MxD works with DoD to ensure that the manufacturers in the defense industrial base (DIB) are cybersecure. "We want to make sure that as many organizations as possible can be qualified to remain in the DIB," Pilat said, "and that we can grow the defense industrial base with innovative partners that are secure and thinking about how to integrate cybersecurity and their operations from the outset." MxD does this, she said, through awareness building, training, providing tools and services, examining the skills that workers need to have, and supporting the standards process for the different cybersecurity requirements.

In MxD's workforce efforts, she said, the institute is focused on the workforce of the future. What are the skills that engineers who are in school now will need in their jobs after graduation? What roles will they play, and how can they prepare themselves for those positions? "We put out a lot of curricula and training opportunities to make sure that we are mapping students and existing workers to skill sets that they need to be successful."

In the context of the workshop, Pilat said, the most important thing that MxD does is to provide opportunities for students to be involved in real-life applications of technology in manufacturing. "They do not have to wait to get through their studies before they can see how something that they are studying is actually going to make a difference on a factory floor or help enable the creation of a new product, a new material, or a new process."

MxD has been involved in a large number of projects since its inception, she said, and the sweet spot for the institute is to deal with technological challenges that are too large for any one entity to solve on its own. It combines its federal funding with contributions and expertise from academic and industry partners to build technological solutions, test and validate them, and then hopefully transition them into real-life applications.

Pilat then offered brief descriptions of several MxD projects in which undergraduate engineering students were involved as examples of how students can be exposed to advanced manufacturing. In one case an undergraduate student at the Missouri University for Science and Technology worked with the project team to create an automated machining system that compensated for the variation in the casted or forged parts that were being machined. "The project outcome essentially reduced the amount of scrap produced through this process to zero," Pilat said. This saved the manufacturer, Caterpillar Inc., hundreds of thousands of dollars, and the company hired the undergraduate student to implement the solution in its facility. It is an example, she said, of a student getting to solve a problem in real time and, at the same time, developing connections that "opened up doors that maybe would not have been otherwise there for them."

Another example involved the development of a tool to virtually build parts, quantify the quality of the manufactured parts, and predict their mechanical properties. Such a tool would be used in the creation and certification of low-volume, high-value metallic parts. In this case the project was led by a professor, Federico Sciammarella, who directed advanced research and materials and manufacturing at Northern Illinois University. He did not have a PhD program providing students to work with, Pilat said, so he hired undergraduates and master's degree graduate students to work in his lab on the project. "He also routinely presented updates and results of the project to his classes and engaged them in the follow-up research," she said. Many of the undergraduates stayed on to do master's degrees in manufacturing. The experience provided the students with "a real-life context that grounded their theoretical and fundamental experience with a real-life practical application," she said.

A third example was a project to develop a supply chain risk alert—in essence, modeling disruptions to a supply chain using data that are available to an organization or publicly available, and then using that model to predict supply chain disruptions. Again, a number of students were involved in the project. "It has created years of opportunity for students to engage in a problem that is a very real and common problem across the manufacturing supply chain," Pilat said.

INSTITUTE FOR ADVANCED COMPOSITES MANUFACTURING INNOVATION

In the next presentation, Hopkins of IACMI, also known as the Composites Institute, spoke about what the institute is doing to prepare students for the composites manufacturing workforce and thus increase US competitiveness. IACMI was founded in 2015 with funding from DOE's Advanced Manufacturing Office. Its goal was to address technical challenges to the large-scale deployment of fiber-reinforced polymer composites intended for use in key energy-related applications, such as building lightweight cars or large and highly efficient wind turbines.

To achieve that goal, Hopkins said, the Composites Institute formed a national consortium with 160 members representing 31 states. The members included 130 companies, 40 percent of which were large companies (Boeing, Airbus, Lockheed Martin, Northrup Grumman, Ford, Volkswagen, DuPont de Nemours, BASF, etc.) and the rest were small and medium-sized manufacturers. Other consortium members included universities, national labs, trade and professional nonprofit organizations, state economic development offices, and international partners. The consortium, Hopkins said, has invested more than $50 million in strategic infrastructure to carry out validations for composites manufacturing across the supply chain, from precursor chemicals to composite components and systems. It has also cooperated in creating a series of industry-led collaboration spaces for workforce development programs. These programs are targeted at every segment of the workforce pipeline, from STEM outreach to graduate education, and a major emphasis of the programs is on providing hands-on experience for technician training and undergraduate students.

The primary way that the consortium engages with undergraduates, Hopkins said, is through the IACMI internship program. The students are recruited nationally and then placed into technology projects at various partner locations. The students are also given mentoring and professional development to build soft skills. The IACMI intern program now includes 124 interns appointments (92 undergraduate and 32 graduate) from over 40 home institutions working at more than 40 host locations, Hopkins said. And 38 percent of IACMI interns are female—double the national average of people working in the field.

The internship program has incentives to include supply chain partners as collaborators, which means that most of the projects have multiple companies participating. "This helps technical project outcomes better serve as a stepping stone to commercial deployment," Hopkins said, "and also provides a larger, more diverse network of partners for internship hosting and mentorship."

The intern experiences are designed to be the start of an ongoing connection for the students' career and professional paths, he said, so these experiences need not only to be relevant but also to connect the next steps in the pathway. And, he continued, since the interns are an active part of the composites community, they have a big head start in identifying, qualifying, and pursuing the next steps in their paths.

The interns are also asked, as part of their service to the community, to assist in various sorts of training. This includes STEM outreach, where the students talk to younger students about their experiences in the field about manufacturing as one option for those interested in STEM opportunities. The interns are also involved in introductory technician training in order to broaden their range of experiences in the composites community.

The multifaceted approach of the internship program, Hopkins said, has been "demonstrated to be successful in supplementing undergraduate engineering career paths."

HOLLINGS MANUFACTURING EXTENSION PARTNERSHIP

Next, Raghavan described the work of the Hollings Manufacturing Extension Partnership (MEP) and what it does to help infuse advanced manufacturing into engineering education. MEP is a national network with centers located in all 50 states and Puerto Rico. The various centers work collectively to help provide small and medium-sized manufacturers with the resources they need to improve operations, get to new growth paths, and remain competitive in the global marketplace. “We work hand in hand with the private sector to make sure that they have all the critical needs, including financing, capital, workforce, [and] the new technology out so that manufacturers can remain competitive,” she said. It is a partnership among the federal government, state governments, universities, and nonprofit organizations with funding provided by the federal government, state investments, and private-sector fees.

Listing the MEP’s accomplishments, Raghavan said that in fiscal year 2021 is worked with more than 34,000 manufacturers from nearly all industries, helping those manufacturers to make $14.4 billion in new and retained sales and to create or retain 126,000 jobs. With $50 million in funding from CARES Act, MEP helped more than 5,000 manufacturers pivot and get into new products and new industries, producing such things as personal protective equipment, in order to keep working through the COVID pandemic.

Of the 51 centers in the partnership, 18 are at universities, which provides a direct connection between industry and academia. Another 26 members are nonprofit organizations, and either are state-based; these non-university members generally have a strong connection with one or more universities. The university connection is important, Raghavan said, because the schools provide access to potential employees as well as to new technologies that small and medium-sized manufacturers can take advantage of.

Several of the MEP–university collaborations take place via a partnership with the Association of Public and Land-Grant Universities. For example, Northern Illinois University (NIU) is collaborating with the Illinois MEP, and Ohio University is partnering with Ohio MEP Southeast, which is part of the Ohio MEP. NIU and the Illinois MEP worked together to expand the applied learning model in NIU’s College of Engineering and Engineering Technology with a dedicated professor of a practice in manufacturing, Raghavan said. “That professor serves as a link between the small and medium manufacturers and the engineering teams in the university’s multidiscipline senior design program,” she said. The Ohio collaboration established a partnership with small and medium-sized manufacturers to help them address challenges they encounter while implementing new technologies, such as robotics and systems for factory automation. And a third collaboration, between the University of Louisville and the Kentucky MEP Center (the Advantage Kentucky Alliance), helped test an accelerated three-dimensional printing program for use in manufacturing; that program is aimed at helping small and medium-sized Kentucky manufacturers in the automotive and aerospace sectors adopt 3D technology, in part by providing them with technical assistance and guidance on how to adopt that new technology into their current systems.

MEP centers also engage directly with university engineering students to support manufacturing projects, Raghavan said. These are not official internships, she explained, but instead they are more closely aligned with cooperative education. “Students are typically paid for their time spent on working in our MEP centers on projects so that the university gets a boost,” she said. “The student gets a boost, and the small/medium manufacturer can access talent, but also the ideas.” Some of these projects were state-funded and put students into internships with smaller manufacturers, she added. “We work a lot with the state government to make sure we can have those happen.”

The MEP centers are also helpful in capstone projects for senior engineering classes, Raghavan said. “We really do try to make sure we can cultivate that partnership with the universities in all of the 50 states so that students get access to what it is like to be a small/medium manufacturer and how they can help drive that economic innovation.

Finally, Raghavan encouraged participants to look into Manufacturing Day, which is hosted and coordinated by the MEP National Network on the first Friday of October each year. “The purpose of it is to show the reality of modern manufacturing careers and encourage companies and educational institutions to open their doors so that students, parents, teachers, and community leaders can glimpse what it is really like—as opposed to seeing what they think it is like—and inspire the next generation of skilled workers.”

In closing, Raghavan said that the manufacturing industry employs over 12 million people, making it the fifth-largest employment sector in the United States, and that manufacturing jobs offer the opportunity for upward growth and mobility. “More than 81 percent of those jobs require true, real-work level experience,” she said, “but can become a path to growth.”

NSF ENGINEERING AND EDUCATION PROGRAMS

In the next presentation Zayas-Castro described the NSF’s programs on engineering and on student education in science and engineering. He focused on two NSF directorates: the Directorate of Engineering, which provides support for advanced engineering contains the Division of Engineering Education and Centers (EEC); and the Directorate of Education and Human Resources, which contains divisions of undergraduate education and of human resource development and which is heavily involved with workforce development. “These divisions and directorates work collaboratively in an interactive fashion to try to advance and to synergize our efforts,” he said.

NSF’s Advanced Manufacturing program supports fundamental research aimed at revitalizing American engineering. It is a funding program, so that it funds researcher doing work in the area of advanced manufacturing. The specific areas being supported include autonomous systems, biomanufacturing, breakthrough materials and materials design, digital design and manufacturing methods, nanomaterials and nanomanufacturing, novel semiconductor design and manufacturing, and smart manufacturing.

Zayas-Castro added that the researchers who receive grants to advance fundamental understanding and knowledge in advanced manufacturing typically are also generating “new ways to infuse their advances into the graduate or undergraduate curriculum” and sometimes even into the K–12 curriculum or K–14 curriculum.

NSF also has two major center-based efforts that seek to bring together work from across the agency and bring it to bear on particular issues. The first effort involves engineering research centers, or ERCs, which are typically funded for 5 years at about $25 million, with a possible renewal of another five years. As examples, Zayas-Castro mentioned ERCs focused on creating self-powered sensing, computing, and communications systems to enable data-driven insights for a smart and healthy world (ASSIST); advancing nano-biomanufacturing methods with the ultimate goal of producing functional heart tissue (CELL-MET); and creating a scalable and cost-effective nanomanufacturing infrastructure (NASCENT). These ERCs generally have participation from both undergraduate and graduate students and help shape the participating universities’ undergraduate and graduate curricula.

The second type of center-based initiative involves industry/university cooperative research centers (I/UCRCs), which conduct research that is directly relevant to their industry and government members. As examples he mentioned WindStar at the University of Texas–Dallas, the Center for Bioplastics and Biocomposites at North Dakota State University, the Center for the Integration of Composites into Infrastructure at West Virginia State University, and the Center for Atomically Thin Multifunctional Coatings at The Pennsylvania State University.

Turning to workforce development programs at NSF, Zayas-Castro discussed two programs, Research Experiences for Undergraduates (REU) and Research Experiences for Teachers (RET). REU involves students working with active researchers in summer programs that allow the students to do hands-on work. A typical REU site has a group of 10 or so undergraduates who work in the research programs of the host institution.

The RET in Engineering and Computer Science program supports summer research experiences for K–14 educators with the goal of fostering long-term collaborations among universities, community colleges, school districts, and industry partners. Zayas-Castro offer two examples of RET programs in manufacturing: Integrated Nanomanufacturing at Boston University and MFG Simulation–Automation at Penn State.

In closing, Zayas-Castro spoke of two EEC programs focused on engineering education and broadening participation: Revolutionizing Engineering Departments (RED) and Broadening Participation in Engineering (BPE). “It is critical to stimulate new and revolutionary ways of infusing new knowledge, new understandings, and new ways for how students learn," he said, "and also to develop a much more creative way of broadening participation and being inclusive—as our director says, 'reaching the missing millions.' That is very critical for the manufacturing sector." To that end, RED is intended to (1) develop new and revolutionary approaches and strategies that will enable the transformation of undergraduate engineering education and to implement organizational change strategies at the local level in order to propagate this transformation of engineering education and (2) strengthen the future US engineering workforce by enabling and encouraging the participation of all citizens in the engineering enterprise.

"In summary," he said, "all these efforts between the divisions and the directorates create synergy and create a chain effect that clearly supports undergraduate and graduate education, innovation, collaboration between universities, academia, industry, and government, from basic research to translating that basic research into the curriculum and supporting long-lasting partnerships on collaborations."

DISCUSSION

Kurfess opened the discussion period by asking the panelists about industry's need for engineers versus its need for "people on the floor"—technicians and other nonengineers. Zayas-Castro answered first and said that both engineers and others with technical skills are in great demand in manufacturing, and he noted that many nonengineers, after having acquired the techniques, tools, and knowledge for working in a manufacturing plant, decide that they want to pursue a degree in engineering—which is something they can do, especially with the advent of online programs such as the ones described in the keynote address by Kyle Squires of Arizona State University,

Raghavan agreed with Zayas-Castro, commenting that the presenters had focused mainly on engineers because that is what they had been asked to do but that manufacturing has a strong need for non-engineers with technical skills. "I think this field is open," she said. "We do not have enough workers for anything." This makes is vitally important to figure out how to do workforce development, she added, and part of workforce development will be "getting people to realize that manufacturing is cool and sexy." Most people do not realize how interesting manufacturing work can be, using things like robots and three-dimensional printing. "How do we change that narrative so people want to come in?" she asked. "Not just engineers. All help is needed and wanted."

Hopkins answered by referring a figure he had exhibited that indicated that for every position in manufacturing requiring a master's degree or higher, two people with bachelor-level professional degrees were required along with six or more workers with a high school degree, a 2-year degree, or a certificate So, he said, the bulk of the workforce need in manufacturing is actually at the technician level, and that is where his group has focused its efforts. "To me," he added, "one of the big opportunities is to connect across the continuum," and it is important to help workers at various levels of the hierarchy understand better just what is involved up and down that hierarchy.

Pilat emphasized that there are 2 million current manufacturing vacancies, and they run the gamut from professional engineers to technicians working on the manufacturing floor. "Yes, we need to focus on all aspects." Referring to a hiring guide recently released by MxD which look at some 250 roles in the area of manufacturing cybersecurity, she said that one option for finding employees is to look in other fields for candidates with skills that can map appropriately into manufacturing roles.

Kurfess then a second question, this one focused on the sorts of new and exciting jobs that will be appearing in manufacturing in the coming years, such as those involved with manufacturing electric cars. How do both students and faculty get involved?

Pilat responded that MxD, working with its industry partners, has a variety of ways for students to get involved in manufacturing, including apprenticeship programs on digital skills and cybersecurity. "We have a strategic investment planning process where we go out to our ecosystem to understand the technologies that they are working on that they are looking for funding, and then we put out project calls," she said. "They can respond to that, and we get very regular engagement with students through the faculty that are responding to those calls.” MxD has also developed an emerging technology program that seeks to get universities and students exposure to and involvement with new technologies at an early stage.

Hopkins mentioned a similar program at IACMI that is focused on innovative technologies but is also concerned with workforce issues. “We have a testbed that we have been running for a year,” he said, “and we are planning to replicate sites at different places with partners in the upcoming months.” This will be important, he said, as it will be a test of how well the approach will scale up—and scaling “is really important for making a dent in the need.”

Raghavan said that the MEPs have various approaches to bringing students into contact with small and medium-sized manufacturers—internships, apprenticeships, etc.—to get exposure and experience.

Zayas-Castro said it would be valuable for university faculty to become familiar with manufacturers, MEPs, and others involved in the industry and then “try to infuse the manufacturers into the classroom and the classroom into the manufacturer, beginning from the first year on. The students can start going back and forth and floating and weaving into that continuum.” He also suggested that students who have had internships at manufacturers should share their experiences with other students through word of mouth and social media.

Kurfess then asked what might be limiting the use of internships and apprenticeships. “Is it funding? It is opportunities? Is it connection to companies?”

Hopkins answered that one factor is “the relative scarcity of faculty who have a true appreciation and capacity to engage meaningfully in a manufacturing context.” Because of cultural differences between academia and industry, it is not always easy to find faculty members that have the awareness, appreciation, and capacity to support meaningful engagements.

Raghavan added that another factor is the awareness of opportunities and the ability to match the talent with the companies. This is a particular issue with the small and medium-sized companies she works with, whose average size is perhaps 30 employees. These companies do not have the resources to go and find the potential hires with the talents they need. Conversely, many students and others who might be interested in a job in manufacturing are not aware of the opportunities that exist. Again, this is a particular issue with small and medium-sized companies.

Kurfess agreed. “I grew up in a machine shop in the Chicago area, and it was just hard to find people,” he said. “But they were out there. I connected up a lot of my buddies in high school with a lot of these different shops. They absolutely loved it. It was a good-paying job. They learned some cool skills. But again, how do you make that connection? How do you go out and recruit?” One possible solution, he suggested, might be to set up area clearinghouses with job opportunities and potential employees.

Next Kurfess passed along an audience question about how the different agencies and organizations interested in manufacturing communicate and collaborate. “We do try to work with each other,” Raghavan said, mentioning various organizations that NIST works with, such as MEP centers, an institute at the Department of Commerce, and the Department of Defense. “It is not as formal as people would like it to be,” she said. “Especially on the MEP side, it tends to be more localized because that is where our centers sit. . . . But we try to make efforts.” NIST also works some with the private sector, she said, adding that it is important to determine the key industries that the United States wishes to be dominant in, particularly in advanced manufacturing.

Pilat commented that many of the collaborations that take place with stakeholder-like organizations happen “because there is an individual relationship or an individual passion.” These are valuable, but it is not enough to simply rely on such individuals. “How do you make the national imperative so that it is occurring to more people that there should be more collaboration and that some of the barriers that do exist to collaboration are overcome?”

Kurfess then asked a question about the values of nontraditional programs such as certification programs. Hopkins said such an approach is very important. “It is important for transportability. It is important with understanding what the pathways are to multiple career paths and helping with resiliency.” IACMI is working to help “deliver composites manufacturing training that fits into some of those traditional training certificates as well as those that are merging in what is ultimately a more digitally driven manufacturing need space."

Raghavan said that certification is a critical part of what NIST is trying to do. "It is another pathway and another door as people reimagine their careers," she said. It is important that there is not just one avenue for people to get where they want to go.

In the closing minutes of the discussion period Kurfess gave each of the panelists a chance to make any further comments that wanted to close with.

Pilat said that one of the most important things to consider when thinking about the changes that need to happen in manufacturing-related education is where the industry is heading and what sorts of skills will be important in coming years. That consideration should shape undergraduate curricula and certification programs. She added that one of the difficulties in this area is that solutions can be very difficult to scale. To that end, conversations of the sort that were taking in the workshop "provide an opportunity to highlight those things that are working and should be tried in other areas."

Hopkins said that in recent decades there has been decreasing interest in manufacturing as a career and as a subject for education and training. "Our institutes are to some extent an experiment in terms of how we build that back and how we recreate it and prepare for the quickly changing needs of the future," he said. "I hope that we continue this dialogue and continue to ask that question in terms of what is manufacturing for the country and how do we best support it."

Raghavan said that, especially from the perspective of small and medium-sized businesses, change is difficult, "so sometimes leading them to what needs to be done is tough." It is important to try different pathways, she said, because there is not likely to be just one solution. "The playbook now has to be expanded, and realize that maybe we do not even need a playbook. We really need to start thinking really in many different paths and many different ways."

Zayas-Castro concluded the session with two comments. First, he emphasized the importance of collaboration among industry, academia, and all of the various stakeholders involved in manufacturing. Then he suggested to the workshop organizers that the study they are preparing should have some messaging aimed at students and their parents helping them to understand the attractive opportunities available in manufacturing.

LOOKING TO THE FUTURE

At various points throughout the workshop, panelists and audience members spoke about what should be done to improve advanced manufacturing and the education pipeline that provides the engineers, technicians, operators, and other workers in the advanced manufacturing workforce. Those comments and suggestions are collected and organized in this chapter to provide a synthesis of the workshop participants' many ideas about how to create a better future for advanced manufacturing in the United States.

IMPROVEMENTS TO ENGINEERING EDUCATION

Much of the discussion during the breakout sessions during the workshop's second day was devoted to the question of what changes might be made to engineering education in order to provide a better and more-ready workforce for advanced manufacturing. Committee co-chair Bob Sproull framed the issue in this way: "Advanced manufacturing is changing pretty fast, and the kinds of changes that we may be able to discuss in our report—in education or in the way companies train people and so forth—will probably happen somewhat more slowly. Consequently, we have to be thinking about how to intersect the needs of the industry in 5 or 7 or 10 years, not tomorrow. That requires some imagination about what advanced manufacturing is going to be like in 5 or 7 or 10 years and what the skills are that are going to be important for running it. . . . And if we can't predict the future, which probably we can't, what do we do, and do we have enough flexibility to adapt to it?"

As discussants pondered the sorts of changes that might profitably be made to the current engineering education system to benefit advanced manufacturing, a variety of themes emerged.

Hands-On Experience

The value of hands-on experience for engineers—particularly those involved in manufacturing—was a recurring theme throughout the workshop, and in the breakout sessions on the second day a number of people talked about the importance of such experiences and how opportunities for them might be increased in the future. In one of the breakout sessions, for example, Michael Packer of SME commented about how few students in K–12 get hands-on exposure to manufacturing now that industrial arts and industrial education are mostly gone from middle and high schools. Thirty to 40 years ago, he said, most of the students coming into mechanical engineering programs in college had practical experience, "either on the farm, fixing equipment and figuring out how to design things, or they grew up in tool and dye shops or machine shops. They may have only swept the floors and got to do some things now and then with machinery, but they were exposed to it." Such students are rare now coming into engineering programs. "Many of the students in the 4-year institutions, if there is a lab like an IDEA Lab at Georgia Tech, it's the first time they've seen a machine tool in many cases," he said. "So we've got to somehow correct all of that."

One approach to giving K–12 students more exposure to tools and machinery is SME's PRIME (Primary Response in Manufacturing Education) Schools program, which exposes young people to potential careers in manufacturing by giving them hands-on experience with industrial sponsors. "So we do have young people who are exposed to it, trained in it," he said. "Some will go right into the work force, and some will go into advanced education, maybe 2 years, maybe 4 years." So there are existing programs that address the need for more hands-on experience; the question is how to spread these more widely. "We need to do a better job of exposing and introducing manufacturing as a . . . good career choice for anyone at the early fundamental grades."

Another approach to exposing students to manufacturing, Packer added, is the various sorts of technology competitions—robotics, cars, drones, and so forth. "They do get to at least get exposed to equipment and some of the hand tools." Kurfess added that at Oak Ridge National Laboratory every summer intern has to print his or her own desk using a three-dimensional polymer printer. "They get very excited about designing and printing their own desk," he said, but not every place has the set of facilities that Oak Ridge does.

Neil Schroeder from Minnesota State University Mankato agreed with Packer that hands-on experience is important for engineers and others who are going into manufacturing and added that such experiences separates out these students from "the pool of textbook engineers that get mass produced." Kurfess expanded on that, saying that at Georgia Tech there are many students who are really good at taking tests but have no real-world experience. When it comes to hiring someone for a manufacturing job, he said, he would choose a student with a 3.0 grade point average who has worked in a bicycle shop or repair garage over a student with a 4.0 GPA but no relevant experience.

Committee member Bob Sproull, who was moderating that part of the breakout session, asked if there might be some type of curriculum focused on hands-on experiences, where students could get a series of relevant experiences and be better prepared for jobs in industry. Schroeder answered that for his program's students there are just too many different types of possible manufacturing jobs for something like that to be possible. "Getting them into the industry and practicing as an engineer is really what's helping our students move forward and get that experience," he said. Since a major part of the engineering program at Minnesota State University Mankato involves the students having co-op jobs with various industry partners, the students get a chance to accumulate practical experience in a manufacturing segment they are interested in working in. "Just getting that hands-on experience through practice so you can thrive once you get that piece of paper is huge," he said.

Engineering Curricula

In one breakout session there was an extended discussion of the sorts of things that engineering students should learn in their college programs. How much calculus, for example, should be taught in an engineering program? Many engineers report back after graduation that they seldom if ever use calculus, and it can be an obstacle to technicians with a 2-year degree who wish to return to school to get a 4-year engineering degree but never learned calculus. One participant, J Shelley of California State University, Long Beach, commented, "I have no problem with differentiating a major and saying a 'manufacturing engineer light' position that doesn't have calculus but has systems and logistics and process flow and all of these other things that are not engineering but they still require classroom time and there's theory that goes along behind it. Just because it's not calculus-based doesn't make it wrong."

Continuing with that line of thought, session moderator Bob Sproull mentioned the presentation on the workshop's first day by Tracy Gilbert in which she mentioned the Digital Engineering Competency Framework being put together by the Department of Defense. It does not mention manufacturing; instead it is about acquisition engineers, who specify and manage acquisition programs. The diagram that Gilbert showed had "a lot of pretty deep engineering in it," Sproull said, but there was nothing related to calculus. "'I think that's pretty interesting, because when you get into high levels of systems engineering, you're generally not doing the kind of analysis for which calculus is suited," he said. "There may be other technologies like simulation and so on, or even analytics, that are much more important for that kind of engineering. And I think it should be called engineering."

Thus it might be the case, Sproull continued, that there could be types of engineering programs that skipped certain courses, such as calculus, that have always been considered as part of an engineering education. People with such a background might not be referred to as engineers, or at least not as mechanical engineers or any of the other types of engineers who generally do need to know calculus, but they would be very valuable to industry in many different types of roles. Guillermo Aguilar of Texas A&M University pointed out that such an approach had already been talked about, with a distinction being made between B.A. and B.S. degrees in engineering, with the B.S. degree being more math-intensive, but the distinction never really caught on.

Shelley said that the local community college, Antelope Valley College, has gotten special dispensation from the community college chancellor's office to offer a B.S. program in aerospace manufacturing (with the degree actually awarded through Cal State Long Beach), specifically to feed students into Lockheed Martin and Northrup Grumman for their liaison engineering positions. "So we have a pipeline that we can start talking about some of these unusual credentials, and how do we recruit, how do we keep these people further educated in their careers," she said. She suggested that it would be very valuable to develop a systems engineering major specifically based on what Lockheed Martin and Northrup Grumman need for manufacturing. In this case, she said, it could be possible to get students a master's degree in systems engineering without loading them down with a great deal of additional calculus.

Gilbert emphasized the importance of students developing digital capabilities. "The digital transformation is here," she said. "It has impacted every aspect of our lives. It is incumbent upon engineering education to really catch up to where we are." Undergraduate engineering students do get the chance to develop applied skills through capstone projects, co-ops, research opportunities, and internships, but those are all external to the official curriculum within engineering education. "It is incumbent upon our industry partners and our academic partners to engineer the solution and reimagine how we educate our workforce with applied skills," she concluded.

Packer contended that engineering education should not neglect some of the less glamorous but essential aspects of advanced processes, such as precision controls, sensors, and gears. There are areas where the United States tends to fall behind the rest of the advanced world.

And on a related topic, William Bigot of Ascent Aerospace said that it will be important to not wait until after high school to start introducing engineering topics to students. Offering a sports metaphor, he said that when he was teaching his son's elementary school football team, they tried to replicate what the junior high team was using for its their offense and defense. That team in turn tried to replicate what the high school team was using. And the high school sought to replicate what the University of Minnesota was using. The idea, he said, is to start teaching early on concepts that will be important later. Applying this idea to engineering, it is important to think about the sorts of skills that high school students should be taught so that by the time they graduate they have enough understanding to be thinking about what sort of career path they would like to take.

"I really think that the message is, let us get in early," he said. "Let us teach what we need our students to understand at whatever level that might be. Let us help them . . . find that niche and what they do well, and then let us help them expand beyond what they are doing."

Manufacturing Major

Several participants spoke about a manufacturing major or a manufacturing engineering major as one way to prepare students better for jobs in advanced manufacturing. Christopher Brown of Worcester Polytechnic Institute (WPI) in Worcester, Massachusetts, said that WPI previously had an undergraduate major in manufacturing which is no longer available, but the school does offer undergraduate and graduate degrees in robotics. Originally, he explained, WPI was created to produce manufacturing engineers for the wire-drawing industry in Worcester, which led the world at the time, but eventually the school abandoned the manufacturing program because of the difficulty of of getting research funding in that area from places like the National Science Foundation. Brown was the director of the manufacturing program until it was shut down, and he described his interactions with the institute as a "constant battle." "They were asking me to justify manufacturing by who is coming here that wouldn't have come here otherwise just to get a major in manufacturing, but it was nothing they were tracking, and they gave me no resources to track it, so it was clear they were setting manufacturing up to lose." The manufacturing program was inside the mechanical engineering department, which was a big department, and the head of department let the program wither. "He just had too much on his plate, and manufacturing wasn't his favorite thing, and it wasn't bringing in the research funding, which is the main metric."

Kathryn Jablokow, who was a moderator of that breakout session, commented that resource issues like this can be a challenge. However, she added, "being at NSF, I can tell you that the research funding for advanced manufacturing is exploding in lots of new directions and in all different ways. So the amount is certainly strong and the directions are changing a lot." Indeed, she added, part of the reason she was serving on the National Academies committee that hosted the workshop was "to inform NSF what's happening in academia and in industry to try to get a better sense of where we should be channeling the funding for advanced manufacturing research."

Sundar Krishnamurty said that one of the challenges facing a manufacturing major is that there are so many different types of manufacturing that it becomes difficult to know exactly what should be included. "How do we bring in continuous batch and discrete? What are the common set of issues for converting raw materials into finished product? And then bring in the question of sustainability, not only cost quality throughput but also the efficiency of your manufacturing." Different manufacturing technologies have widely different techniques, so one must ask what the core set of concepts is that students should learn about manufacturing. However, he added, "most of the manufacturing courses start with machining processes and go into robotics and automation" and do not touch on large segments of manufacturing. "I have not seen any comprehensive thinking about what constitutes a manufacturing curriculum," he said. "Probably you guys have been teaching it for years, so you may have a better idea about that. But where is the curriculum for that?"

In a related thread, Brown commented that one way to teach engineering students so as to prepare them for a rapidly changing work is to focus on basic principles of manufacturing. "I have been trying to teach the basic principles that will apply to manufacturing and have applied to manufacturing forever," he said, "and I think we need to do a better job of defining those and in figuring out what those things are." For example, while it may be useful to teach students something about three-dimensional printing, that is changing so rapidly that anything they learn may be obsolete in a decade. "But things like tolerances aren't changing," he said. Similarly, uncertainty will remain a major issue, as will the issue of how to integrate tolerances and uncertainty into process design and control. "How do we define value?" he continued. "And how does that translate to produce specifications, and then process design, no matter what the process is? How do we produce value? How do we keep it sustainable?" All of these are basic principles that should be given more attention in engineering education.

In a similar vein, other participants spoke of the possibility of developing a "science of manufacturing." One participant noted, for instance, that there is a clear distinction drawn between computer science and computer engineering, with a balance kept between learning a concept and putting it to practical use. Could something similar be done with manufacturing?

Brown responded, "Every manufacturing textbook that I have looked at—and I have been teaching manufacturing at WPI for over 30 years now—is basically an encyclopedia of methods and there are no overarching principles that link everything together." It would be valuable to have a collection of basic principles, axioms, corollaries, and theorems about manufacturing that could be used in teaching manufacturing in the same way that certain physics principles are used in teaching. "So we need an Isaac Newton for manufacturing," he said. "That would get us away from courses that are just a series of facts and 'Here's this manufacturing process, here's how we analyze it, here is what you can make.'"

The underlying principles could be fairly simple, Brown continued. "We could start with something like 'Create value and reduce waste.'" He pointed to the development of axiomatic design by Suh Nam Pyo at the Massachusetts Institute of Technology which lays out principles for design and asked if something like that might be done for manufacturing. The benefit of such an approach, if successful, would be that the basic principles would remain even as manufacturing was changing rapidly.

Sundar Krishnamurty agreed that this could be valuable, and he offered an analogy to the drawing of designs. Even as design moved from two-dimensional drawings to three-dimensional drawings to computer-aided design and beyond, "still the concept of how to capture the visualization part of the drawing aspect hasn't changed," he said. "We are looking for some underlying principles that can be supported whether it is industrial revolution 1, 2, 3, or 4."

Committee member Thomas Kurfess offered a different sort of argument for the importance of the fundamental when he spoke about the likely results of increased automation on the workforce. In the late 1970s, he said, people were worried about bank employees losing their jobs because of the introduction of automated teller machines (ATMs), and indeed there was a small decrease in the workforce, but then the numbers of bank tellers went back up—but now, not having to spend so much time on handling money, they were taking on more complex tasks, "and so now you have a more capable workforce." The same thing can be expected with the future of the manufacturing workforce. "Yes, we're going to be augmenting our workforce from the lower skill level all the way to the highly trained engineer and sort of moving them forward," he said. "What does this mean really? And what kind of training do we really need for the engineers?" The best approach would be to retain the fundamentals and then supplement with other skills, he said. For example, even with computers taking on a greater role in design, engineers are likely to still need to work with CAD (computer-aided design) if for no other reason than that engineers will still need to visualize things. Schools should start teaching new things such as generative design, but it should not be "blind generative design," he said, but rather teaching students how to lead the computer to optimize their designs and things like that.

Familiarity with Systems

In one of the breakout sessions, Kimberly Sablon of Texas A&M University brought up a particular skill set that will be useful to teach engineering students who are headed into advanced manufacturing. Noting that she had recently moved to academia from the defense sector, where she was the director of Army Science and Technology in the US Army Futures Command, she said that the future workforce will need students who are comfortable with a systems-based approach, so, in particular, universities should be introducing the idea of convergence research in manufacturing. “It’s an area that I think is really important,” she said, “especially when you’re talking about things like hypersonic weapon systems.”

In the future, she said, it will be increasingly important for students to be comfortable designing and working with multi-material systems—for example, improving methods to concurrently manufacture dissimilar materials with very high-performance interfaces. So one thing that universities could do to improve manufacturing engineering education, she said, would be to presenting real world problems that challenge students to think innovatively about ways in which they can combine various disciplines, such as how to integrate digital technologies with more traditional manufacturing technologies.

Robotics and Automation

Ashwin Dani from the University of Connecticut spoke briefly about a robotics program that is being set up there. It will be offering an undergraduate degree in robotic beginning in the fall. The program will be interdisciplinary, with various departments, including electrical engineering and mechanical engineering, participating. The university has another interdisciplinary program between the schools of management and mechanical engineering, which has a great deal of focus on manufacturing. And as part of that program, Dani has been coordinating a manufacturing robotics course. In short, he said, there is a close connection between robotic automation and manufacturing.

In response to a comment from Kathryn Joblokow, Dani noted that robotics is not a new field—it has actually been around for several decades—and that the main applications of robots in the early days was in the automobile industry. And even today, he added, many of the opportunities and challenges that are emerging in the area of advanced robotics are found in a manufacturing context. “Manufacturing is one of the main domains where robotics finds lots of use cases and lots of job opportunities as well,” he said, and he envisions that there will be ways to integrate robotics and manufacturing in the curriculum in the future.

Data Analytics

Chris Saldaña of the Georgia Institute of Technology said that some of the manufacturing companies he works with are trying to apply artificial intelligence and machine learning, so it will be useful to them to be able to hire graduates who are able to analyze data and, more generally, are comfortable using computer applications to work with data. It is particularly important, he continued, that these hires have been exposed to open programming languages, noting that many universities use the proprietary program MATLAB, which many companies do not have access to. Manufacturing engineers—for example, mechanical engineers working in a manufacturing environment—are particularly valuable to companies if they have been trained in data science. “The industry talks about them as unicorns,” he said. “They know a little bit about process, but they also know a bit about computing and analysis, to add value to that data.”

In a related comment, Amy Fleischer of California Polytechnic State University said that manufacturing education at Cal Poly will be getting a greater emphasis on data analytics, smart factories and smart manufacturing in the coming years. Furthermore, she added, “we are looking at integrating course work that blends together our computer science department with our manufacturing and mechanical engineering departments with a focus on cyber security." Not only is this an important area with many opportunities, she said, but she has found that the students there are really interested in these sorts of topics.

Use of Virtual Reality and Augmented Reality in Engineering Education

As several participants suggested, one opportunity to improve engineering education is with increased use of augmented reality (AR) and virtual reality (VR). For example, Saldaña mentioned using AR goggles to give students the feel of walking around a factory floor, seeing the machines operate, visiting a machine shop, and so on. "I think there's a lot of opportunity with the advances that are happening in that space to enhance education," he said, "but the challenge that we have at the university is it's evolving so quickly if we buy into a technology now, they're saying Apple is going to come out with an augmented reality headset later this year, so there's challenges just in the speed at which those technologies are maturing." Still, he said, AR and VR should open up a number of potential valuable opportunities for better connecting industry with academia, and the technologies may prove particularly valuable for smaller schools who cannot afford the sorts of facilities that a place like Saldaña's Georgia Tech can.

Thomas Kurfess, also from Georgia Tech, added that many companies are already using VR in their training to give workers a feel for how to control a machine without the risk of doing any damage to the machine or anything else. Previously, he said, there had been various issues with web-based VR devices, "but now we're moving to a cloud-based capability, where you've got some local processing, some remote processing, and you've merged those together and you actually have a much better set of capabilities. The students really struggled when they were trying to do some of this web training and so forth with licenses and all sorts of stuff. Now it seems to be much more seamless. I think it does allow you to move a lot of things forward and to get a feel for things."

As an example of VR-based training, Saldaña said that Lincoln Electric has a virtual reality welding simulator. "You actually have a torch, and then it gives you a score," he said. "So it's like a video game for people who are learning welding." VR can also be used to simulate machine tools, he said, so it may be possible that VR-based training tools could be developed for various different kinds of manufacturing technologies which could lead to better manufacturing education.

Kurfess commented that such VR tools could both cut training costs by reducing the use of physical manufacturing labs in training and also improve safety.

Krishnamurty noted that AR and VR have both been used for a long time in the training of medical workers and also pilots. "For example," he said, "if you look at the amount of training that a pilot gets in the virtual simulator, it is considered as one of the training aspects of the real world training. Similarly, doctors are getting trained for surgery using this technology." So it seems like that manufacturing education could also benefit from the development of such tools.

Alex Woltornist of Cornell University said that another benefit of AR and VR training tools is that it is much less expensive to keep them up to date than physical equipment. If a university purchases a modern manufacturing machine for students to learn on, that machine may be obsolete in 5 or 10 years, necessitating another expensive outlay. But by investing in AR and VR training technologies, the university can keep its updating costs down to what it takes to replace the software.

However, he added, the initial development of such AR and VR training technologies is likely to be very expensive—too expensive for individual institutions to afford—so it would make sense for a consortium of institutions to work together to develop a VR environment and then share it for training. "I see this incredible opportunity on the VR side," he said, "and I think we are right at the point now because we're really thinking about it. Two or three years ago we just couldn't do it."

Chi Okwudire did offer one caveat about AR and VR training, however. Using such technologies makes sense, he said, but not if they are the sole training methods. There should still be physical hands-on training of some sort, and the goal should be to find a happy medium between the physical and the virtual.

Communication and Collaboration Skills

A number of workshop participants spoke about the importance of engineering students developing communication and collaboration skills. Michael Packer, for instance, talked about the "India ink and vellum days" several decades ago, when engineers did their designs in ink on vellum. However, before an engineer would commit a design to ink on vellum—which was a permanent design—he or she would go down to the factory floor and talk with various people such as toolmakers, machinists, assemblers and so on because "you didn't want to have to go to the supply room to get another sheet of vellum." Today, however, with so much done digitally, there is not the same pattern of thinking about a final design, so engineers tend to be more cavalier about their designs. Still, he said, "just because you could do it on CAD doesn't mean that it can be executed," so it remains important to speak with the people on the floor before deciding on a design. This in turn means that it is an important—albeit often overlooked—skill for engineers to have a comfort level with and a capability in talking to and asking questions of the technicians, operators, and others who make a factory run. But this social ability of engineers—being comfortable interacting and communicating with technicians and other non-engineers—is something that engineering schools struggle to develop, Packer said. More should be done to help engineering students—especially those headed into manufacturing—develop this skill.

Al Romig made a similar point, telling a story about a part that had been designed with modeling and simulation. "It took a six-axis mill and about $20,000 in 1980 dollars to make this part," he said, "and if they would have talked to the metallurgists and the engineers before they actually designed the part and put it as part of the computation, that could have been avoided." The lesson is that the people who design a part need to communicate with the people who will have to build it, and this is particularly important today with the growing emphasis on modeling and simulation in design. "People sometimes forget that you need to keep yourselves grounded in the reality of what you can actually build."

Self-Directed Learners

In one of the breakout sessions there was discussion about the importance of training engineering students to be self-directed learners. The discussion was triggered by a presentation by Susannah Howe of Smith College on the transferrable skills learned from capstone projects; the first on the list was self-directed learning. "There is not nearly enough emphasis on how we look at self-regulation, motivation, lifelong learning," one participant commented. "I'm trying to think about where does that fit in this push to change how we develop a specific type of curriculum."

Bob Sproull agreed that this is an important characteristic for engineers to possess and said that if engineers could be safely assumed to be self-directed learners, "we wouldn't be so concerned about what is exactly in the curriculum this week or what's going to arrive on the factory floor next week because we've got workforce that will figure it out. And they will probably teach other and they will do all kinds of things that are much better than the classical education pipeline."

Another participant said that a modern engineer should be flexible and adaptable in the face of new technologies. "It's knowing how to adapt to things," he said. "I think that is where self-direction and self-regulation really come into play." There should be a way to shape curricula and credentialling so that not only do students get the opportunity to develop their self-learning capabilities, but potential employers have a way to judge how well a student has developed such capabilities.

NONACADEMIC ISSUES

While most of the focus on engineering education was aimed at the sorts of things that students should learn, there was also some discussion on non-academic issues that affect the engineering workforce.

The Cost of Education

Throughout the workshop a number of participants noted the high cost of an engineering education in the United States and contrasted that with Europe, where college educations are generally free to the student. For instance, Michael Sarpu of Lockheed Martin said that when he went to college he got a 4-year engineering education for less than $15,000, and his first-year salary was $19,000, so in his first year he made more than it cost him to go to 4 years of college. Now college students may have $100,000 or $150,000 or more in student load debt when they graduate, he said, and while that may make sense for students going into high-paying jobs, it does not necessarily make sense for students going into engineering. “We have to come up with this middle spot where it does not cost $150,000 to get an education,” he said. “If we are going to build manufacturing the United States, we have to create jobs at that level.” Not every employee is going to be a graduate of a top engineering program with a grade-point average of 4.0. Instead, many of the most valuable employees will be graduates of state schools with a GPA of 3.0 but with plenty of hands-on experience, and programs should be built with that in mind.

This is a particular issue with advanced degrees, said Christopher Brown, a workshop participant. “In a lot of countries [in Europe] they fund right through the doctorate and not on a meager stipend as we do here,” he said. “Generally they fund you with an engineer’s salary. So . . . as a result, they have a large number of people from their region and from their schools that go on for doctorates, more than we do. Very few of our undergraduates go on for advanced study because they need to get out and pay back those loans.” Kinard responded by commenting how when he gave presentations to graduate engineering programs at The University of Texas at Arlington, he found that several of the classes had absolutely no US citizens. “It’s pretty wild when you think about that,” he said. “Most engineers tend to leave as an undergraduate for the reason you pointed out—they have got to pay back those loans.”

Attracting More Students to Engineering

A number of workshop participants said that the current demand for engineers is high, with at least one participant characterizing an engineering degree as a near-certain ticket to a good job. Thus manufacturers and other employers of engineers are interested in drawing a larger and more diverse crop of students into the field. Thus it will be important to determine ways to make engineering more attractive to students.

One participant, for instance, said that it will be important to change the narrative of what working in manufacturing means. “Students have this perception of manufacturing as this ugly factory type of idea, but that is not what modern manufacturing is,” he said. “It touches so many other places and disciplines and you can work in manufacturing in a ton of different ways. Nearly every engineering discipline has overlap with manufacturing to some degree.”

It will be important to get this message across to students, he said, and there are various possible approaches. “Maybe that means opportunities at the K–12 level through different types of extracurricular activities,” he said, or perhaps manufacturing could be infused into existing courses, activities, and competitions in order to expose students to it and change their perceptions.

Concerning diversity, Don Kinard asked Tracee Gilbert of System Innovation how academia and industry can attract a more diverse engineering workforce. Gilbert said it is important to start very early. “It is very hard to recruit students once they have gotten to the undergraduate level,” she said, since students have to take advanced classes in high school and do well in those advanced classes to even be accepted into an undergraduate institution. “I think it is very critical to start very early on in the pipeline, attracting diverse students to STEM,” she said. “But also, I think the applied side is very critical as well because engineering . . . actually touches every aspect of our lives. I think that we can attract diverse candidates by opening up that space of allowing diverse candidates to see how they can contribute and make an impact across a number of different applications.”

Kinard then asked specifically about attracting women engineering, noting that people have been trying to increase the number of women in the field for many years without much success. “Just as the practices of engineering in our undergraduate schools are antiquated,” Gilbert said, “I would also say the culture is very antiquated and not inclusive. . . . There has been progress, I have to say. But there is still a lot of work to be done in terms of creating inclusive environments for diverse candidates and diverse students and women in engineering.” She added that there do exist some exemplars—schools that do a good job of creating an inclusive and supportive environment for women and minorities—and the community can learn from those exemplars.

Michael Packer said that employers can play various roles in attracting more students to engineering—and to manufacturing in particular. For instance, industry employees take part in various activities designed to increase the engineering pipeline, from supporting engineering competitions and facilitating merit badges for boy scouts and girl scouts at a plant to serving on university industrial advisory boards or acting as ABET evaluators. “What I think employers can do,” Packer said, “is recognize and acknowledge that those are investments and provide the time away to go and do that.”

Industry could also work in various ways to increase the number of manufacturing programs offered in US universities, he said. There are more than 400 mechanical engineering programs accredited by ABET and the American Society of Mechanical Engineers, but only about 50 programs in the United States that are accredited by ABET in manufacturing engineering or manufacturing technology. Industry can help change that, Packer said, by showing the need and helping flesh out what the appropriate body of knowledge should be that is passed along to students in such programs.

Gilbert suggested that there are ways to make better use of the country’s 2-year college programs in advanced manufacturing. While the country could certainly make better use of all of the different pieces of the engineering pipeline, from high school through 2-year and 4-year colleges and graduate programs, the community colleges may be a particularly valuable focus since the education there is now free in a number of states and because a growing number of students are choosing to enter community colleges instead of 4-year programs out of high school, even if they go on to a 4-year program later. “I think it is incumbent upon us to determine how we can better utilize community colleges,” she said.

Finally, Packer said that in preparing their students for careers, many high schools focus on college preparation, yet college prep is just one dimension of career planning—not everyone will be going to a college or university—so career planning should also take into account those students who may be going to a community college or other 2-year program or into some other type or training or straight into a job. But no matter what path a student will take, it is important for students and their counselors and parents to see the relevance of a science, technology, engineering, and mathematics (STEM) education to achieving the student’s desired career.

IMPROVING ADVANCED MANUFACTURING

While the general topic of the workshop was approaches to improve engineering education as a way of assisting and improving advanced manufacturing, some discussion took place on the topic of how to improve and expand the US advanced manufacturing sector and, more broadly, the country’s entire manufacturing enterprise. This topic is tied to the issue of improving engineering education, as Don Kinard of Lockheed Martin noted, because a stronger manufacturing sector will be more attractive to students. “I think engineering students are smart enough to realize that a lot of manufacturing isn’t in the United States anymore,” he said. “Is that having an effect? Does anybody think that the lack of manufacturing and the lack of advanced technology development is, in fact, one of the factors that are discouraging people from being more manufacturing-oriented?"

So toward the end of the workshop's second session, moderator Don Kinard asked that session's participants what the United States needs to do as a country to improve advanced manufacturing. He mentioned in particular that the nation is lacking in such things as machine tool businesses and robotic businesses. "Those essentially do not exist in the United States anymore," he said. "They have all moved overseas.' And something similar is true in biotechnology, where few US companies operate the sorts of bioreactors needed for industrial production. So, he asked, how can government, industry, and academia collaborate to improve the country's capabilities for doing advanced manufacturing?

William Bigot agreed with Kinard that it is important to bring such manufacturing back to the United States, most probably with the assistance of government-sponsored programs with that purpose But rebuilding that sort of capability in the United States will require having a workforce with the necessary skills, and it will thus be important to have workers that are familiar with the processes that are being automated. "Before you actually create a new process . . . that is more automated, you have to know what the existing process is," he said. "If you do not have any idea what that is, you are not going to do a very good job of optimizing the automated version of it."

So, Bigot, continued the first step will be to look into the sorts of programs that can encourage the building of those sorts of advanced manufacturing capabilities in the United States. "We need to then make sure that our universities and 2-year college trade schools actually allow students to actually do that work," he continued. They need to have the hands-on experience with manufacturing processes, whether it is using a bandsaw or operating an additive manufacturing process. And, he added, "it is really the students teaching the students. I think that is the kind of mindset that we need to think about and figure out a way to implement."

Kinard followed up by asking Bigot if he thought that free market capitalism could restore manufacturing in the United States, and he commented that countries such as China and Germany have industrial policies that target specific industries to build. "President Biden recently talked about a $52 billion bill for chip manufacturing," he said. "He is also talking about battery manufacturing. Is that what it takes to make the difference here?"

Bigot answered that there are certainly things that the United States can learn from these other countries. In particular, the United States should decide which directions it should take in manufacturing and then invest in those areas. "I think your example on battery technology is a really good one," he said. "How do we build the manufacturing capabilities and bring the people to the level they need to be in order to support that business?" Furthermore, he added, the country is nowhere near where it needs to be in terms of aerospace and defense manufacturing. It is important to take a critical look at those industries and decide what is needed for the future and what will be needed to get to that future. Then industry, academia, professional societies and other stakeholders will need to get behind that effort.

Kinard then asked the same question of Michael Sarpu of Lockheed Martin. "Do you feel like, as a country, we have to pick technologies that we are interested and then develop this government, industry, academic kind of connection? Is that what we need to do to make sure that we can do what we have to do as a country?"

"I think we need to pick our spots," Sarpu answered. The days of Henry Ford when steel and rubber went in one side of a plant and automobiles came out the other are gone. "Are we going to 100 percent vertically integrate the F-35 within the walls of Lockheed Martin? Absolutely not. It does not make sense." So it will be important to decide which parts of manufacturing to focus on based on which bring the most value to the nation, although, he added, there are different ways to determine what constitutes "value," and that is a decision that will have to be made. But once a decision has been made as to which aspects of manufacturing to focus on, it will be important to pursue those in a big way. "We cannot do a little bit here, a little bit there because the problem is then you are still competing with overseas sources or other sources that maybe are not playing by the same rules that we are playing by," he said.

But the real key will be deciding which industries to focus on. He offered an analogy with additive manufacturing: “Do not build a coffee cup with additive,” he said. “Build something that you cannot build any other way. I think we have to look at what technologies we bring into the country the exact same way.” As an example, he pointed to the question of manufacturing semiconductor chips, which has been an area of focus recently because of how global chip shortages have affected the US auto industry. Should the goal be, he asked, to manufacture domestically all of the chips that are needed for US manufacturing? “Or do want a chip foundry for critical things that are of importance to our nation or to our national security or to our power grid? How do you want to do it?” Creating such capacity will require a partnership with industry, government, and academia, he said, but choosing what capacity to focus on should come down to what will have the biggest impact.

Echoing Sarpu, Michael Packer of the Society of Manufacturing Education (SME) then said, “I think we have to pick our spots and we need to not get too enchanted with the advanced technologies in and of themselves.” Manufacturing USA and the various related institutes are doing a relatively good job of advancing the clearly important technologies, but what has been missing are the “less glamorous, but absolutely critical technologies that are components to those advanced technologies,” he said. As examples, he pointed to precision motion control, where Japan dominates; precision gearing, which is a German specialty; and precision sensors and advanced sensors, which generally are sourced from China and Taiwan. It may not be particularly glamorous to set up an institute for precision motion control, he said, but the United States cannot afford to be dependent on other countries for such critical components. “We have to very carefully dissect what an integrated advanced system consists of and identify those that are absolutely crucial success factors to that advanced system,” he said.

Later, in the breakout sessions on the workshop’s second day, participants returned to the issue of whether the United States should have some of industrial policy on several occasions. In one session, for instance, Kinard mentioned Denmark and China in particular as two countries that choose desired areas of focus for their manufacturing sector and then fund research and development in those areas. “In fact,” he said, “I want to say that we are probably one of the only countries that I am aware of in the Western world that does not have industrial policies that select business areas that they want to develop and keep inhouse. We tend to be in pretty much a free market kind of world over here, and we may be the only ones in that free market, to be perfectly honest.”

One of the results is that the engagement among employers, industry, universities, and government is much tighter in most other countries than in the United States, which Kinard suggested explains some of the loss of manufacturing that the United States has experienced. “For example, pretty much all robotics is overseas now,” he said. “All machine tools are overseas. You heard about chip production—basically we don’t have capabilities for it anymore. Biotechnology is much more overseas than it is in the United States because we haven’t incentivized or funded that as a country.”

Christopher Brown said that his experience with the Swiss Federal Institute of Technology in Lausanne, Switzerland, agreed with Kinard’s assessment. “There are all kinds of things we could do in Lausanne that we can’t do here because our basic costs were all taken care of,” he said. “We could do all kinds of service for industry without worrying about paying for it, or them paying for it. It hurts us competitively.”

Another factor that limits US competitiveness in advanced manufacturing, Kinard said, is that while the US government generally relies on market forces to encourage manufacturing innovation, those market forces may at times restrict it. As an example, he mentioned that Intel had recently announced it was going to spend about $20 billion to get back into chip manufacturing in a major way, and, as a result, the company’s stock price because of concerns over short-term profitability.

“The free market economy is not going to save us here if we want to make stuff in the United States and we want the jobs and the protection of our supply chain,” Kinard said. “People don’t realize it, but almost every drug comes from China, and certainly the precursors do. Most all of them do. All of the robotics and most of the advanced technology that supports manufacturing all comes from somewhere else, and most of that is because we decided to let companies just go for—how would I call it?—shareholder value.”

CONCLUDING REMARKS

To wrap up the workshop, Alton Romig, the executive director of the National Academy of Engineering, offered some closing thoughts. After thanking the speakers and participants, he commented that he had heard a number of really interesting topics at the workshop and mentioned in particular the area of cybersecurity in manufacturing. One of the ideas that has been discussed within the Department of Defense, he said, is building arsenal ships or arsenal camps that can create weapons and other items on demand. For instance, a ship close to the theater of action might have three-dimensional printers or other advanced manufacturing devices along with the supplies and raw materials required by those machines "so that all you had to do was move a file and build a part and deliver it to the warfighter." But then it becomes crucial to ensure the integrity of the files that provide instructions to the machines and to make sure that the files have not been corrupted in a way that defective parts are produced; this requires paying attention to cybersecurity. "I thought that was very important," he said.

One of the lessons of the workshop, Romig said, was that the problems facing advanced manufacturing are complex and will require teamwork and consortia to solve. "I don't know who the smartest person is in a given room," he said, "but all of us together are smarter than any one of those individuals."

On a different topic, Romig said he found the distinction between manufacturing and production to be interesting. Some manufacturers—auto makers and companies that produce consumer electronics, for instance—may turn out hundreds of thousands or even millions of products in a year, while other types of companies, such as aircraft manufacturers, may build just a few hundreds of their product over the course of a year. "Building these very complex systems where the numbers are relatively small brings a whole set of challenges that are different than you would find in truly mass production," he said, "and I think that is an important thing to keep in mind as we move through this."

One of the key lessons, from the workshop, he continued, was the value of hands-on experience in manufacturing. "You can't teach someone how to do joining, do machining, do casting, do direct printing, whatever it might be, purely from a textbook," he said. "You have got to actually be able to build and make something."

A related lesson was the value of getting manufacturing into engineering education, and workshop participants offered various suggestions on how to do this, Romig said, including having specific manufacturing engineering programs or putting manufacturing components into existing engineering classes. However it is done, he said, the key is that engineering students get some exposure to manufacturing.

One particular way that engineering students can be exposed to manufacturing is through capstone projects. Those projects are most valuable, Romig said, when they involve more than just a collection of mechanical engineering students or chemical engineering students and instead involve students with expertise in a variety of areas. "As I said earlier, real-world engineering is really much more of a team sport and it is multidisciplinary," he said. "I think it will be useful if more universities got the notion of building multidisciplinary teams in order to attack capstone projects."

By contrast, he continued, many of the team competitions that engineering schools participate in—such as the ones where students design, build, and operate a solar-powered car, say, or a drone—tend to involve individual students from a variety of disciplines and provide a much better simulation of what students are going to find when they get to the real world.

Engineering students need to learn to think beyond simply designing devices to considering whether there is a market for a given device, Romig said. "People are not going to pay for you to develop something that is only going to sit on a shelf and never actually be used." Engineering students also need to get involved in research and development, he added, whether it is through internship programs or any of the various types of industry-academic collaborations.

Finally, Romig said, it will be important for government, academia, and industry to work together to shape engineering education to help improve advanced manufacturing. In other countries the government may set the direction through industrial policies and pick fields that the country will focus on, but this generally does not happen in the United States. There are a few exceptions, such as the establishment of Sematech, a consortium of semiconductor manufacturers established in the late 1980s to revive the US semiconductor industry, but for the most part the US emphasis on the free-market economy limits the options for such approaches in this country. “So,” Romig said, “we need to have other vehicles by which we can get government, universities and industry to work together through collaborations, internships, sabbatical leaves, et cetera.”

C

Requests for Information and Responses

The Committee on Strengthening the Talent for National Defense: Infusing Advanced Manufacturing into undergraduate engineering education prepared industry and academic requests for input (RFI) to gather inputs for this report. The results were not statistically valid since the number of responses was too small, but they did provide interesting perspectives. There were 157 responses, including 99 from academia and 58 from industry (37 percent of the respondents) reporting 19 large, 10 medium, and 13 small businesses [small businesses <100 employees; mid-size 100 to 999 employees, large >1,000 employees]).

Suggestive perspectives:

- 65.7 percent of respondents stated that current undergraduate engineering programs do not adequately prepare engineers for advanced manufacturing.
- The responses highlighted a range of gaps and weaknesses, from a lack of exposure to advanced manufacturing technologies to limited hands-on experience in engineering programs, as well as an overall absence of manufacturing acumen in engineering graduates due to a lack of knowledge of the state-of-the-art in manufacturing capabilities.
- Only 14.7 percent of the respondents commented that there exist strong collaborations among colleges, universities, community colleges, and public–private partnerships in educating engineers for advanced manufacturing.

ACADEMIA RESPONSES

In response to a request for input issued by the committee, 58 stakeholders from the manufacturing industry (37 percent of the respondents) and 99 from academia (63 percent of the respondents) highlighted the importance of practicums (and other experiential learning activities) in preparing students for careers in advanced manufacturing: 88.9 percent mentioned internships, and 80.6 percent mentioned hands-on labs as key elements to prepare undergraduate engineering students for advanced manufacturing implementation. These numbers are slightly higher than the percentage (77.8 percent) who mentioned engineering fundamentals as a key element. This suggests that hands-on experiential learning is at least as important as didactic learning of engineering fundamentals for infusing advanced manufacturing in undergraduate engineering education. Similarly, in answer to a question about which programs produce graduates that are best able to bring advanced manufacturing technologies to industry, the majority of the respondents highlighted programs with internships, hands-on curricula and co-ops. Similar sentiments were shared by a variety of experts who addressed the committee over the study period. For example, Alan Schaffer, a board member of the Global Foundries and Potomac Institute for Policy Studies stated: “We wait too long to let people do hands-on work. Close the gap between what you make and how you make it.” A report on the Future of Manufacturing conducted by ASME and Autodesk highlighted a quote from Prof. Dandu of Kansas State University, Salina, stating that: “One of the major skills the mechanical engineering student is lacking is that manufacturing aspect, which has to be integrated into the design. How will it be manufactured? How will it be handled by the users?"

Feedback from our RFIs and selected interviews indicates a wide range of university capabilities with respect to manufacturing in undergraduate programs. Some schools have targeted advanced manufacturing with specialty programs such as Georgia Tech, Auburn, and Cal Poly among those surveyed or interviewed. Most of these schools focus on basic shop processes and perhaps additive manufacturing but others have specialized programs in robotics and automation. Some universities have specific manufacturing engineering degrees, and some integrate manufacturing into mechanical engineering or other degree programs. Many universities, however, do not have the resources to provide hands-on manufacturing experience to their students outside of some capstone projects and clubs focused on car and rocket intramural competitions. In addition, a common comment from universities was that their undergraduate engineering curriculums do not have room for additional coursework in manufacturing without dropping some of the basics and cited safety concerns with allowing students unfettered access to manufacturing equipment without sufficient supervision and training. ABET accreditation was also cited during the discussions with universities as hinderances for curriculum changes to undergraduate education. Capstone courses sometimes involve manufacturing but there wasn't a focus on manufacturing that we could discern from the RFIs and interviews.

INDUSTRY RESPONSES

Advanced manufacturing technologies cited through our RFIs of industry including basic machining, additive, automation and robotics, and advanced metrology. These technologies are used based on cost/benefit analysis which recognizes the typically low volumes for DIB production which doesn't allow the massive automation used for consumer electronics or automotive production lines to be cost effective. In addition, defense programs quickly become fixed price which does not incentivize continued company investments in manufacturing technologies since profit is negotiated.

Feedback from our industry RFIs and selected interviews indicates a wide range of university capabilities with respect to manufacturing in undergraduate programs. Some schools have targeted advanced manufacturing with specialty programs such as Georgia Tech, Auburn, and Cal Poly among those surveyed or interviewed. Most of these schools focus on basic shop processes and perhaps additive manufacturing but others have specialized programs in robotics and automation. Some universities have specific manufacturing engineering degrees, and some integrate manufacturing into mechanical engineering or other degree programs. Many universities, however, do not have the resources to provide hands-on manufacturing experience to their students outside of some capstone projects and clubs focused on car and rocket intramural competitions. In addition, a common comment from universities was that their undergraduate engineering curricula do not have room for additional coursework in manufacturing without dropping some of the basics and cited safety concerns with allowing students unfettered access to manufacturing equipment without sufficient supervision and training. ABET accreditation was also cited during the discussions with universities as hindering curriculum changes to undergraduate education. Capstone courses sometimes involve manufacturing but there wasn't a focus on manufacturing that we could discern from the RFIs and interviews. Industry responses tended to favor intramural rocket, aircraft, and car clubs as well as industry internships for undergraduates.

Large DIB Tier 1 companies hire thousands of interns every year to support the supply chain of graduates to fill their requirements and encourage undergraduates to hire on after graduation. In the past there were also work-study programs with industry where undergraduates were paid to spend summer/fall/spring semesters working as engineers which added typically a year or two to their studies but reduced their student debt. Summer intern programs are more common in the past 5 years or so although the Covid-19 pandemic has impacted these programs also.

Summary of industry responses (mix of small, medium, and large businesses):

1. Responses as to whether universities prepared engineers for manufacturing were mixed, mostly negative overall with the chief reason being the lack of practical, hands-on experience. This was consistent across small, medium, and large companies that responded.
2. Respondents tended to support teaching engineering fundamentals, and participation in internships, capstones, and hands-on labs. Other needs included teaching of corrective action, PLM (product life management), MES (manufacturing execution system), CAD IT tools and processes, and GD&T (geometric distancing and tolerancing). There was also general agreement that manufacturing skills were desirable for most engineering disciplines (perhaps software engineering is an exception).
3. Overall, there was minimal involvement with universities and institutes among the respondents which wasn't that surprising since these involvements tend to be concentrated at large/med corporations.
4. Respondents identified basically all the advanced manufacturing technologies on the RFI as being of interest and the reasons for their interest were also consistent–return on investment. These technologies included robotics, automation, advanced metrology, additive manufacturing, augmented reality, etc
5. Digital technologies were important to almost everyone that responded. Digital technologies included CAD tools as well as modeling and simulation tools.
6. Dependence on suppliers was mentioned by a few but didn't appear to be a large issue.
7. Comments on impediments for advanced manufacturing including investment requirements, lack of clear financial benefit, and management willingness to change.
8. Responses to employer provided training for new engineers was mixed with larger companies providing in-house training as might be expected. Many respondents identified on the job training as the primary training approach.
9. Several respondents suggested hiring engineering faculty with industrial experience would help.

QUESTIONS IN THE REQUEST FOR INFORMATION

Questions are intended to probe the education for undergraduate engineers involved now or in the future in the implementation of advanced manufacturing and not necessarily those engineers who support manufacturing operations.

Questions for Academia Respondents

1. Using a broad definition of advanced manufacturing (AM) (i.e., including robotics, metrology, automation, additive manufacturing, AR/VR, etc.), which advanced manufacturing technologies are taught as part of your current undergraduate engineering education (UEE) curriculum?
2. Why and how were these particular advanced manufacturing technologies chosen?
3. Please list and label both required and elective UEE courses that include advanced manufacturing technology components, including courses in manufacturing or manufacturing engineering.
4. From your list of courses above, rank the top three courses that you believe provide your students with the most exposure to advanced manufacturing and explain why. If possible, please provide a link to the course descriptions.
5. If applicable, please list any courses in manufacturing or manufacturing engineering (required or elective) that are offered at the graduate level, either as part of a supplemental year (e.g., a 4+1 program) or as part of an advanced degree (e.g., masters).
6. If your programs and courses in manufacturing are described on your website, please provide

a URL link to it.

7. Do you offer an advanced manufacturing concentration, certificate, or MS degree in your curriculum? If so, how many students are participating in the concentration (i.e., what fraction of your graduates)?
8. Does the treatment of AM technologies in your curriculum cover the full range from design, to prototyping, to manufacturing?
9. Please rank order where you place the most emphasis: Design, Manufacturing, Prototyping
10. Briefly explain how your UEE curriculum goes beyond design and prototyping to manufacturing (i.e., how it teaches students the activities by which raw materials are transformed to finished products) at a large scale.
11. Do your ABET assessment criteria include advanced manufacturing knowledge or skills as objectives or outcomes?
12. Do you think ABET assessment criteria should include advanced manufacturing knowledge or skills as objectives or outcomes?
13. Where does "advanced manufacturing" stand in the priorities for changing or enhancing coverage in your undergraduate engineering education (UEE) curriculum?
14. How are emerging advanced manufacturing technologies influencing your UEE curriculum? How do you address the fact that we don’t always have examples of new technologies and results readily available for use?
15. Do changes to your curriculum related to advanced manufacturing (AM) tend to focus on fundamental engineering concepts or on properties of specific advanced manufacturing technologies? How do you integrate these new topics into a (presumably) already-full curriculum?
16. How is industrial participation or expertise in manufacturing and advanced manufacturing technologies coupled to your UEE program?
17. Are your industrial collaborators or employers of your graduates requesting more advanced manufacturing coverage? If so, what technologies and/or kinds of knowledge and skills are they requesting?
18. Do you partner with other colleges/schools/departments on your campus to provide advanced manufacturing exposure for your students? If so, please explain the nature of the collaboration and the uses of advanced manufacturing (prototyping, small-scale production, major manufacturing) involved.
19. Do you partner with community colleges in your area to provide advanced manufacturing exposure for your students? If so, please explain the nature of the collaboration and the uses of advanced manufacturing (prototyping, small-scale production, major manufacturing) involved.
20. Do you partner with engineering firms, laboratories, etc., to provide advanced manufacturing exposure for your students? If so, please explain the nature of the collaboration and the uses of advanced manufacturing (prototyping, small-scale production, major manufacturing) involved.
21. Do you partner with any other educational institutions? Is there a best practice at another institution that inspires you and you are trying to emulate?
22. Do you interact with the Manufacturing Innovation Institutes or other industrial consortia in any way that influences your UEE curriculum (or in other ways)? If so, please describe these interactions.
23. How do your UEE capstone courses (and similar practicums) address advanced manufacturing technologies? What are the goals of the advanced manufacturing components of these courses?
24. Within your UEE capstone courses (or similar practicums), please rank order where you place the most emphasis: Design, Prototyping, Manufacturing

25. What are some best practices and methods for collaboration and experiential learning related to manufacturing that you can suggest?
26. Do your undergraduates come into contact with manufacturing experience outside your institution (e.g., industrial training institutions, manufacturing firms/internships)? If so, please explain.
27. How do you attract students to your manufacturing curriculum (e.g., makerspaces, open access shops for students, unique new approaches)? What ideas do you have for improving student uptake?
28. What are the demographics of the students that you are attracting/would like to attract to your manufacturing curriculum?
29. If you could "rebrand" manufacturing to make it more appealing to today's young people, how would you do it?
30. How do we make the manufacturing innovations found in major firms (e.g., defense industrial base "prime contractors") available to all undergraduate engineers, and thus support small and medium-scale businesses?
31. As industrial design and manufacturing move more to digital integration, including concepts such as the digital thread and digital twins (characterized as "Industry 5.0" or the like), what changes do you foresee in undergraduate engineering education? Will all engineers need to be more digitally savvy? Will functional specialization need to increase? What will be the role of education vs. industry?

Questions for all respondents:

1. In your view, what are the principal impediments to greater adoption of advanced manufacturing technologies?
2. Can you suggest potential ways to overcome such impediments?
3. We welcome your thoughts about improving the contribution of undergraduate engineering graduates to advanced manufacturing in the industrial base and its ecosystem. If the questions above have missed important points, please comment here:
4. Can you recommend people, businesses, or academic institutions working to improve the adoption of advanced manufacturing (for the defense industrial base or other industries) that we should investigate as part of our study? Can you highlight any "best practices" we should study?
5. If we wish to contact you for more information, are you willing to provide your name and email address? We will keep all of your answers confidential. If you provide an email address, we will recognize that you have responded to our questionnaire and will not pester you with further reminders.
   Name:
   Title:
   Affiliation:
   Email:

Questions for Industry Respondents

For the purposes of its research, Gartner defines SMBs by the number of employees and annual revenue they have. The attribute used most often is number of employees; small businesses are usually defined as organizations with fewer than 100 employees; midsize enterprises are those organizations with 100 to 999 employees.

1. Are you a small, medium, or large business by the definition above? (Small, Medium, Large,

High volume, Low volume)

2. Roughly how many Engineers do you hire annually?
3. What types of Engineers do you typically hire to support your Manufacturing Operations? (Mechanical, Electrical, Electronics, Chemical, Computer, Manufacturing, Industrial Engineering, Advanced Manufacturing, Engineering or Industrial Technology, Other)
4. What advanced manufacturing capabilities are important to your business and would like to have Engineering graduates exposed to? (Industry Automation, Robotics/Mechatronics, Additive Manufacturing, Advanced Metrology, Automated Inspection, Automated Material Handling Systems, Advanced Materials Processing, Advanced Composites, Machining, etc , IoT Equipment Sensors, AR/VR applications, Integrated IT systems (ERP, MES, PLM, etc, Advanced PLM/CAM/MES systems, Artificial Intelligence, Data Analysis, Digital Twins, Modeling and Simulation, Other)
5. Do current undergraduate engineering programs adequately prepare Engineers for advanced manufacturing?
   Why? or Why not?
6. What are the business considerations for adopting advanced manufacturing technologies in your firm? (ROI, Customer Expectations, Quality, Capacity, Capital Expenditure reduction, Capability, AM Talent availability, Other)
   Comments?
7. To what extent do you collaborate with colleges, universities, community colleges, and public–private partnerships in educating engineers for advanced manufacturing? (To a minimal or no extent, To a medium extent, To a great extent)
   Comments/Examples?
8. What kinds of UEE elements are important for advanced manufacturing implementation: (Engineering Fundamentals, Hands on lab experience, Customized programs for AM, Facilities for AM, Extracurricular activities/clubs, Design Capstone projects, Internships, Scalability/Cost effectiveness, Quality Standards, Certification, and Processes, Other)
   Comments?
9. What specific advanced manufacturing training do you provide to your new hire engineers in-house?
10. Can you provide examples of best practices for advanced manufacturing in UEE that you have observed?
11. If you have identified schools that produce UEE graduates best able to bring new advanced manufacturing technologies to your operations what features distinguished them? (Customized advanced manufacturing programs, Faculty Specialization, Overall reputation in Engineering, Hands on curriculum, Facilities and Resources for AM, Location to your operations, Diversity Programs, Cooperative Industry Programs, Internship programs, Industry engagement with curriculum)
    Comments?
12. Please suggest any DIB firms whose approach to AM and related workforce you think our study should examine. Are there “best practices” you can recommend?
13. Do you have any specific suggestions for universities to better prepare Engineering graduates to support manufacturing?
14. To what extent do you depend on your suppliers to develop and implement advanced manufacturing for your operations?
15. What is the importance of digital modeling and simulation to your operations? Do UEE graduates come prepared with these skills?
16. Are there any government programs such as the manufacturing institutes you use to develop advanced manufacturing?

D

Briefers to the Committee

October 27, 2021

William B. Bonvillian, Massachusetts Institute of Technology
A. Adele Ratcliff, Industrial Base Analysis and Sustainment (IBAS) Program, Department of Defense

December 2, 2021

Jim Segelstrom, McNally Industries LLC
Gregory Harris, Auburn University
Dhruv Bhate, Polytechnic School, Arizona State University

January 5, 2022

Kathleen Thelen, Massachusetts Institute of Technology

January 27, 2022

Robert Higham, The Barnes Global Advisors
Anna Hoff, Ford Werke GmbH
Christian Hinke, Research Campus Digital Photonic Production (DPP) Aachen and RWTH Aachen University (affiliated with the Fraunhofer ILT)
Kris Ward, Society of Manufacturing Engineers
Alan Shaffer, Global Foundries and Potomac Institute for Policy Studies

March 8, 2022

Becca Jones-Albertus, Advanced Manufacturing Office at the Office of Energy Efficiency and Renewable Energy, Department of Energy
William Olbricht, Chemical, Bioengineering, Environmental and Transport Systems, National Science Foundation
John Jackman, Division of Undergraduate Education, National Science Foundation

August 10, 2022

Jesús Soriano Molla, Partnerships for Innovation (PFI), National Science Foundation

February 24–25, 2022, Workshop Panel Moderators and Briefers

John L. Anderson, National Academy of Engineering
A. Adele Ratcliff, Industrial Base Analysis and Sustainment (IBAS) Program, Department of Defense
Kyle Squires, Dean of the Ira A. Fulton Schools of Engineering, Arizona State University
Jennifer Pilat, MxD
John A. Hopkins, IACMI
Pravina Raghavan, National Institute of Standards and Technology
José Zaya-Castro, National Science Foundation
Michael Sarpu, Lockheed Martin
Michael Packer, Manufacturing Leadership Council
William E. Bigot, Ascent Aerospace
Tracee Gilbert, System Innovation
Amy Fleischer, California Polytechnic State University
Guillermo Aguilar, Texas A&M University
Susannah Howe, Smith College
Christopher Saldaña, Georgia Tech
Alton D. Romig, Jr., Executive Officer, National Academy of Engineering

E

Committee Members Biographical Information

MAXINE L. SAVITZ, NAE, *Co-Chair*, retired as general manager of technology/partnerships at Honeywell, Inc., formerly Allied Signal. She is a member and served two terms as vice president of the National Academy of Engineering (2006–2014). She was appointed to the President's Council of Advisors for Science and Technology in 2009 and served until January 2017; she served as vice co-chair from 2010–2017. Dr. Savitz was employed at the U.S. Department of Energy (DOE) and its predecessor agencies (1974–1983) and served as the Deputy Assistant Secretary for Conservation. Dr. Savitz serves on the Board of the American Council for an Energy Efficient Economy (Emeritus) and on advisory bodies for Pacific Northwest National Laboratory, FERMI National Laboratory, CRDF Global and Energy Futures Initiative. In 2019–2020, she chaired the visiting committee for the Harvard John A. Paulson School of Engineering and Applied Sciences. Past board memberships include the National Science Board, Secretary of Energy Advisory Board, Defense Science Board, Electric Power Research Institute (EPRI), Draper Laboratories, and the Energy Foundation. Dr. Savitz's awards and honors include the following: elected a fellow to the American Academy of Arts and Sciences in 2013; C3E Lifetime Achievement Award in 2013; the Orton Memorial Lecturer Award (American Ceramic Society) in 1998; the DOE Outstanding Service Medal in 1981; the President's Meritorious Rank Award in 1980; recognition by the Engineering News Record for Contribution to the Construction Industry in 1979 and 1975; and the MERDC Commander Award for Scientific Excellence in 1967. She is the author of about 20 publications. Dr. Savitz has served on numerous National Academies of Sciences, Engineering, and Medicine committees and boards and participated in multiple National Academies activities.

ROBERT F. SPROULL, NAE, *Co-Chair,* retired as vice president and director of Oracle Laboratories, an applied research group that originated at Sun Microsystems. Since undergraduate days, he has been building hardware and software for computer graphics: clipping hardware, an early device-independent graphics package, page description languages, laser printing software, and window systems. He has also been involved in VLSI design, especially of asynchronous circuits and systems. Before joining Sun Microsystems in 1990 (acquired by Oracle in 2010), he was a principal with Sutherland, Sproull and Associates, an associate professor at Carnegie Mellon University and a member of the Xerox Palo Alto Research Center. He is a coauthor with William Newman of the early text, *Principles of Interactive Computer Graphics*. He is also an author of the book *Logical Effort*, which deals with designing fast CMOS circuits. He is a member of the National Academy of Engineering, a fellow of the American Academy of Arts and Sciences, and has served on the U.S. Air Force Scientific Advisory Board and as a technology partner of Advanced Technology Ventures. He is currently a member of the National Academies Committee on Science, Engineering, Medicine, and Public Policy (COSEMPUP), and an adjunct professor of computer science at University of Massachusetts Amherst.

STEPHANIE G. ADAMS is the fifth dean of the Erik Jonsson School of Engineering and Computer Science since 2019 at the University of Texas at Dallas. She is also a professor of systems engineering. Dr. Adams is a pioneer in engineering education. In 2003 she received a National Science Foundation (NSF) Faculty Early Career Development (CAREER) award to research effective teaming in the engineering classroom. In addition to teamwork and team effectiveness, her other areas of research expertise include broadening participation in STEM (science, technology, engineering and mathematics), faculty and graduate student development, global education, and quality control and management. Dr. Adams has served in leadership roles in several organizations, including as president of the American Society for Engineering Education from 2019 to 2020, on the advisory board of the National Society of Black Engineers and on the board of directors of the Women in Engineering ProActive Network. Prior to joining UT Dallas, Dr. Adams was dean of the Frank Batten College of Engineering and Technology at Old Dominion University. She also served in various academic leadership positions at Virginia Tech, Virginia Commonwealth University, the University of Nebraska-Lincoln, the NSF Division of Engineering Education and Centers, North Carolina State University, Texas A&M University, Texas Tech University, South Plains Community College and 3M Co. Dr. Adams is an honors graduate of North Carolina A&T State University, where she earned a bachelor of science in mechanical engineering. She earned a master of engineering in systems engineering from the University of Virginia, and a PhD in interdisciplinary engineering and management from Texas A&M University, where she concentrated on industrial engineering and management.

S. KEITH HARGROVE is the provost and senior vice president of academic affairs at Tuskegee University. Previously, he served as the dean of the College of Engineering at Tennessee State University (TSU). Dr. Hargrove received his BS in mechanical engineering from TSU, MS from the Missouri University of Science and Technology as a GEM (National Consortium for Graduate Degrees for Minorities in Science and Engineering) fellow, and the Ph.D. from the University of Iowa as a CIC (Committee on Institutional Cooperation) fellow. He is a Certified Manufacturing Engineer recognized by the Society of Manufacturing Engineering and registered Professional Engineer. Dr. Hargrove was a Boeing Welliver Faculty Fellow in 2008, and has worked for General Electric as a Manufacturing Engineer, and with Battelle Pacific Northwest Laboratories, NIST, Oak Ridge Laboratories as a researcher in advanced manufacturing engineering. He has been awarded research contracts and grants with Lockheed Martin, Sikorsky, US Navy, Air Force, and NSF for work in manufacturing, advanced materials, and engineering education. Dr. Hargrove is a K12 STEM advisor and board member for several local schools, and is the author of “Navigating Academia: A Guide for Women and Minority STEM Faculty” (Academic Press), and “In Search of Academic Leadership—A Primer for Faculty Development.”

KATHRYN W. JABLOKOW is a professor of engineering design and mechanical engineering at Penn State University and currently serves NSF in the Civil, Mechanical and Manufacturing Innovation Division as program director for the Engineering Design and Systems Engineering program. Dr. Jablokow is widely recognized for her expertise in cognitive diversity and its impact in engineering education and practice, including manufacturing education and student design experiences. Her research includes the use of rapid manufacturability analysis tools to enhance decision-making in engineering design education, as well as the characterization and mediation of manufacturing fixation in design education and practice (i.e., interventions to address an engineer’s overreliance on a specific manufacturing technique). Dr. Jablokow has received many major teaching and research awards, including the W. M. Keck Foundation Teaching Excellence Award, the American Society of Mechanical Engineers (ASME) Ruth and Joel Spira Outstanding Design Educator Award, and multiple Best Paper Awards. Dr. Jablokow is a fellow of ASME, a senior member of IEEE, and a member of ASEE, Sigma Xi, and the Design Society. She earned her BS, MS, and PhD degrees in electrical engineering from The Ohio State University in 1983, 1985, and 1989, respectively.

DON A. KINARD is a senior fellow for Lockheed Martin Aeronautics Production Operations and has been with LM for 36 years. Dr. Kinard supports Digital Transformation as well as programs such as F-35. Prior to his current assignment he was lead for F-35 production rate transition and earlier the director of F-35 Production Engineering responsible for Joint Strike Fighter Tooling, Planning, Manufacturing Engineering, and Aircraft Systems Testing. Before joining F-35 in 2004, Dr. Kinard held various positions in both Engineering and Manufacturing during his 18 years on the F-22. He is the lead for the

LM Corporate Strategic Technology Advisory program for Advanced Manufacturing as well as the Manufacturing Fellow's team whose objectives are to develop and share engineering, manufacturing, and sustainment technologies throughout all of the LM business units. His technical interests include materials and structures, digital thread/twin integration, digital transformation, Industry 4.0, manufacturing technology, manufacturing system design, and production management.

SUNDAR KRISHNAMURTY has served as professor and head of the Department of Mechanical and Industrial Engineering at UMass Amherst since 2015. In 2020, Krishnamurty was named the Ronnie & Eugene Isenberg Distinguished Professorship in Engineering, which was created to enhance interdisciplinary teaching and research between fields of management, engineering, and science. He is a fellow of the ASME, and he is an elected member of the 2020-2022 Department Head/Chair of the ASME Executive Committee. Krishnamurty is the site-director for the NSF-sponsored Industry-University Cooperative Research Center (I/UCRC) Center for e-Design, a joint research coalition comprised of seven universities working closely with numerous businesses and government organizations. His research interests include advanced manufacturing, manufacturing automation, predictive analytics in design and manufacturing, and innovation and entrepreneurship. He was a member of the Brain Trust for the UMass Advanced Manufacturing Summit in Spring 2021 and a member of the Chancellor's Task Force for the UMass Innovation & Entrepreneurship in 2020. Krishnamurty received his BS in civil engineering at the Indian Institute of Technology, Kanpur in 1982; an MS in civil engineering at the University of Pennsylvania in 1984 and PhD in mechanical engineering from the University of Wisconsin-Madison in 1989.

THOMAS R. KURFESS, NAE, is a professor and the HUSCO/Ramirez Distinguished Chair in Fluid Power and Motion Control in the George W. Woodruff School of Mechanical Engineering at Georgia Institute of Technology. Previously, he was the chief manufacturing officer at the Manufacturing Demonstration Facility at Oak Ridge National Laboratory. Previously he was the BMW Chair in Manufacturing and a professor in the Campbell Graduate Engineering Center at Clemson University. His current research focuses on the control of precision grinding systems that involve the development and implementation of adaptive controllers for precision grinding operations, including bore grinding, through feed centerless grinding, and surface grinding. Ultrarigid machine tools with open architecture controls are employed. The results of this work are used in a number of industrial environments. His project on precision measurement involves the use of coordinate measurement machines to verify part geometry in three dimensions. Currently, the metrology systems developed in this project are being used in the verification of parts on actual production lines. Dr. Kurfess is a fellow of the American Society of Mechanical Engineers, and has received both the Presidential Faculty Fellowship and the Presidential Young Investigator Award from NSF. He received his Ph.D. from the Massachusetts Institute of Technology and he is a member of the National Academy of Engineering.

CHINEDUM OKWUDIRE is an associate professor at the University of Michigan. Prior to joining Michigan, he was the mechatronic systems optimization team leader at DMG Mori USA. His research is focused on exploiting knowledge at the intersection of machine design, control and, more-recently, computer science, to boost the performance of manufacturing automation systems at low cost. He has recently led the development of a new educational track in Additive Manufacturing, and co-led the development of Smart Manufacturing curriculum at the University of Michigan. Dr. Okwudire has received a number of awards and recognitions including the NSF CAREER Award; the Young Investigator Award from the International Symposium on Flexible Automation; the Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers; the Ralph Teetor Educational Award from SAE International; and the Russell Severance Springer Visiting Professorship from University of California, Berkeley. He participated in the 2014 Frontiers of Engineering Education Symposium. He has co-authored a number of best paper award winning papers in the areas of control and mechatronics. Dr. Okwudire received his Ph.D. degree in mechanical engineering from the University of

British Columbia in 2009 and joined the mechanical engineering faculty at the University of Michigan in 2011.

DAVID PAREKH is chief executive officer of SRI International. He serves on various boards, including the board of trustees of the Connecticut Science Center and the board of the Advanced Robotics for Manufacturing Institute. Previously, he served as corporate vice president, research, and director, United Technologies Research Center (UTRC), providing global leadership for United Technologies Corporation's (UTC) central research organization. Under his leadership, UTRC developed a broad portfolio of advanced manufacturing technologies for the UTC business units and established the corporation's Additive Manufacturing Center of Excellence. Prior to joining UTRC, Dr. Parekh served as deputy director of Georgia Tech Research Institute and associate vice provost for research at the university. A fellow of the American Institute of Aeronautics and Astronautics, he is also a member of the Connecticut Academy of Science and Engineering. He earned a doctorate in mechanical engineering and master's degrees in mechanical and electrical engineering from Stanford University, as well as a bachelor's degree in mechanical engineering from Virginia Tech.