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Convergent Manufacturing

A Future of Additive, Subtractive, and Transformative Manufacturing

Linda Casola, *Rapporteur*

National Materials and Manufacturing Board

Division on Engineering and Physical Sciences

Proceedings of a Workshop

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Cover: The high-intensity electrical arc in the image stands for transformation in the similar way that convergent manufacturing is often described as the future of additive, subtractive, and transformative manufacturing. The arc and the image were generated algorithmically with a process that adds and subtracts three-dimensional parts to ultimately create the final image. Artist Erik Svedberg.

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Acknowledgment of Reviewers

This Proceedings of a Workshop 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 proceedings as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

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

Stephan Biller, NAE,[1] Advanced Manufacturing International, Inc.,
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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the content of the proceedings nor did they see the final draft before its release. The review of this proceedings was overseen by Dianne Chong, NAE, Boeing Research and Technology (retired).

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She was responsible for making certain that an independent examination of this proceedings 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 rapporteur and the National Academies.

Contents

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Introduction

The National Materials and Manufacturing Board of the National Academies of Sciences, Engineering, and Medicine hosted a 3-day workshop event to explore research and development (R&D) opportunities and challenges for convergent manufacturing. A convergent manufacturing platform is defined as a system that synergistically combines heterogeneous materials and processes (e.g., additive, subtractive, and transformative) in one platform. The platform is equipped with unprecedented modularity, flexibility, connectivity, reconfigurability, portability, and customization capabilities. The result is one manufacturing platform that is easily reconfigured to output new functional devices and complex components for systems.[1] This manufacturing system also converges the integration of physical components and digital models along with sensor networks for process monitoring and production.

Sponsored by the U.S. Department of Defense, the three workshops in the series were held virtually on November 15, 2021; November 19, 2021; and November 22, 2021 (see Box 1.1 for the statement of task, and see the Appendix for the workshop agendas). The workshop series focused on the following three overarching topics: (1) key areas for R&D investments that will enable the readiness and commercial development of convergent manufacturing; (2) application areas for convergent manufacturing, with an emphasis on future Army and related civilian applications; and (3) approaches for the design of a convergent manufacturing platform.

[1] Convergence in a unified manufacturing platform enables progress beyond Industry 4.0, with the use of both digital and physical footprints as expanded on in Chapter 2.

BOX 1.1
Statement of Task

The National Academies of Sciences, Engineering, and Medicine shall appoint an ad hoc planning committee to organize a workshop, that is open to the public, and that addresses selected issues associated with research and development leading to convergent manufacturing capability for heterogeneous materials, processes, and systems. In particular, the workshop will focus on three topical areas, as follows:

1. Key subject areas for R&D investments that will enable the readiness and commercial development of convergent manufacturing capabilities in the United States;
2. Potential application areas for convergent manufacturing, with an emphasis on future Army, and related civilian, applications;
3. Approaches for designing a convergent manufacturing platform.

The workshop will use a mix of individual presentations, panels, and question-and-answer sessions to develop an understanding of the relevant issues. An individually authored Workshop Proceedings will be prepared by a designated rapporteur.

Workshop speakers and participants convened from academia, federal agencies, and industry to discuss state-of-the-art materials design and manufacturing techniques as well as innovative potential applications, with particular attention to resilient design and multifunctional materials (Workshop 1); process hybridization in one platform (Workshop 2); and systems and part design at the point of need as well as issues related to the supply chain and sustainability (Workshop 3).

This proceedings is a factual summary of what occurred during the workshop series. The planning committee's role was limited to organizing and convening the workshops. The views expressed in this proceedings are those of the individual workshop participants and do not necessarily represent the views of the participants as a whole, the planning committee, or the National Academies of Sciences, Engineering, and Medicine.

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Resilient Design and Multifunctional Materials

Workshop Co-Chair Ajay Malshe, the R. Eugene and Susie E. Goodson Distinguished Professor of Mechanical Engineering at Purdue University, welcomed panelists and participants to the first day of the workshop series, which was motivated in part by the National Academies of Sciences, Engineering, and Medicine's publication *Fostering the Culture of Convergence in Research* (NASEM, 2019) and the notion that the future of combat is an asymmetric techno-socio-economic problem, solutions for which seek convergence. He highlighted ongoing nationwide initiatives to develop a convergent manufacturing platform and described a vision for the future to deliver agile, resilient, and versatile advanced solutions in a unified manufacturing platform for the mission, equipped with the convergence of designs, materials, tools, and processes to augment soldiers' functionality for combat and to reduce dependency on supply chains for critical materials and their applications. Traditional manufacturing processes are discretized in terms of their applicability and material-specific process optimization; have limited adaptability in terms of materials and design configurations; and require assembly, finishing, and packaging with separate sequential processing steps, increasing overall cost and turnaround time for logistics (see Bapat et al., forthcoming). Therefore, he asserted that the vision for the future could be achieved with convergence by hybridization in manufacturing to deliver at the point of need.

Malshe defined convergent manufacturing as a unified manufacturing system platform that converges heterogeneous interfaces in design, materials, processes (e.g., additive, subtractive, and transformative), and diagnostics with physical sensor data and digital models as inputs to produce functional devices, components, and complete systems as outputs at the point of need. Key attributes of such a platform include modularity, flexibility, connectivity, reconfigurability, portability, and customization. He emphasized that convergence in a unified manufacturing platform enables progress beyond Industry 4.0,[1] with the use of digital and physical footprints in designs from nature, heterogeneous critical materials[2] for multifunctionality, manufacturing tools for resilience, manufacturing processes for agility, and a sensor network for detection of critical interfaces (see Malshe et al., 2021). He stressed that these critical interfaces—for example, physical–digital interfaces,[3] design for manufacturing, and heterogeneous material interfaces[4]—cannot be removed and need to be managed carefully.

Malshe encouraged panelists and participants to consider the following three questions throughout the workshop series: (1) What is your vision of convergent manufacturing, according to your expertise and experience? (2) What are the knowledge gaps for science, engineering, and implementation of convergent manufacturing? (3) What are one or two "moonshot" projects for convergent manufacturing?

DEFENSE TECHNOLOGY

Maj. Gen. Darren L. Werner, Commanding General,
U.S. Army Tank-automotive and Armaments Command (TACOM),
Army Materiel Command

Keynote speaker Maj. Gen. Werner explained that TACOM synchronizes, integrates, and delivers soldier and ground systems and readiness solutions to ensure that the Army is equipped appropriately. TACOM's mission emphasizes *the sustainment* of equipment after it has been developed, produced, acquired, and fielded. When the U.S. Department of Defense's (DoD's) National Defense Strategy was released in 2018, the United States was "emerging from a period of strategic atrophy," in which its competitive military advantage had been eroding.

[1] Known as "Industry 4.0," the Fourth Industrial Revolution is characterized by the application of information and communication technologies to industry. It builds on the developments of the Third Industrial Revolution that began in the 1970s in the 20th century through partial automation using memory-programmable controls and computers.

[2] "Critical materials" here is intended as the materials that can produce the wanted multifunctionality.

[3] Physical–digital interfaces are, for example, the sensors that detect the properties of a material and any defects that occur in the material and communicate that information to the computational model for adjustments in the manufacturing process. In a convergent platform, these are intrinsic to the platform operating and cannot be removed, they must instead be carefully managed.

[4] Heterogeneous material interfaces will occur in the product being manufactured when the materials are changed from one composition to another and are an intrinsic fact of the change itself and cannot be removed, they must be managed.

During the same year, the Department of the Army released its Army Additive Manufacturing Campaign Plan, which developed an overarching strategy and provided a framework to operationalize the full potential of an additive manufacturing capability that is synchronized and integrated across the enterprise and has the potential to enhance mission readiness from the tactical point of need—to improve production, maintenance, and sustainment within the organic industrial base[5] (i.e., "from the foxhole to the factory") and to support modernization efforts through advanced science and technology development to make better materials. He remarked that the Army is on the verge of a transformation as it reimagines the sustainment of current and next-generation platforms for future operations (e.g., acquisition processes, location of pre-positioned forward stocks, forward repair activities, maintenance connectivity and self-diagnosis, prognostics and predictive maintenance, new approaches such as additive manufacturing, and agility in part development and production).

Reflecting on innovative efforts to institutionalize additive manufacturing, Maj. Gen. Werner mentioned the Army's recognition that the evolution from traditional manufacturing (which operates in separate siloes according to manufacturing method and material) to convergent manufacturing (which combines virtual manufacturing, manufacturing processes, process monitoring and control, and heterogeneous materials in one platform to yield functional devices and components) is under way. He emphasized the value of employing new technologies to deliver enhanced capabilities quickly to soldiers. Convergent manufacturing allows for greater flexibility in part quantity and availability on the shelf and in the field as well as improvements in part characteristics to make them available, durable, and better performing in adverse situations. Convergent manufacturing is a key objective for the Army over the next 15 years, which could be realized with the ongoing automation of traditional manufacturing industrial practices and by combining multiple technologies into a single robust and agile manufacturing capability. He asserted that with the convergence of digital and physical manufacturing domains, integration of traditional manufacturing and hybrid manufacturing, advanced manufacturing, intelligent design philosophies, improved digital enterprise, virtual manufacturing, automation, and improved quality inspection, systems could be more capable and available to address multidomain objectives.

Maj. Gen. Werner posited that the Army of 2028 will be ready to deploy, fight, and win decisively against any adversary, any time, and any place in a joint multi-domain, high-intensity conflict. Employing modernized systems (e.g., manned and unmanned ground combat vehicles, aircraft sustainment systems, and weapons

[5] The Army Organic Industrial Base (AOIB), a subset of the larger defense industrial base, is composed of resource providers, acquisition and sustainment planners, and manufacturing and maintenance performers.

coupled with robust combined arms formations and tactics based on the Army's strategic doctrine) and engaging exceptional leaders and soldiers could help the Army to achieve this vision. He stressed that the Army's efforts should be integrated across the domains, with a balanced focus on completing current missions and modernizing for the future. Readiness—including for supply availability, equipment materials, and data—ensures that the industrial base can execute safe, reliable, repeatable, and effective solutions.

Maj. Gen. Werner noted that the Army is shaping convergent manufacturing to support a multidomain framework with continued research and design philosophies that enable the manufacturing of complex shapes and functional devices; a focus on mission tailorability and mass customization of future systems; continued investment in and development of digital manufacturing and advanced manufacturing technologies; implementation of tools that allow for production of what is needed, where it is needed, and when it is needed; provision of new technologies that allow for improved fabrication at the point of need for soldiers; and transition of new technologies to the organic industrial base.

TACOM set the following two strategic goals to support the Army's 2018 Additive Manufacturing Campaign Plan: (1) augment supply chain responsiveness in the strategic support area now to produce parts used in the organic industrial base and (2) empower forward[6] advanced manufacturing capability of the future Army to produce limited-use field parts at the tactical point of need in the operational and tactical support area as technology develops, reducing the sustainment tail[7] while increasing readiness. TACOM developed the following three lines of effort to achieve these objectives:

1. *Component echelon*—the main effort in which the demand signal is associated with the part, and the end state is augmenting the DoD supply chain based on current need.
2. *System echelon*—a supporting effort in which the part has historical demand but is not currently on backorder status, and the end state is to qualify, store, and be prepared to deliver the part.
3. *Program echelon*—a supporting effort that includes program executive office engagement, contract language, and new programs that identify parts to leverage advanced manufacturing capability today; the end state is to support modernization and future transition to sustainment requirements.

These efforts are driving TACOM and Army Materiel Command forward in the strategy for convergent manufacturing. Maj. Gen. Werner pointed out that there is

[6] The word "forward" is used here to indicate the capability to be deployed at the point of need.
[7] Tail here being the supporting logistics for the effort.

significant opportunity to experiment, evaluate, and determine how best to deliver readiness to the Army using advanced manufacturing and additive manufacturing. Advanced manufacturing and convergent manufacturing are critical to the strategic effort to modernize the organic industrial base for sustainment of current and future Army platforms. The organic industrial base is challenged to continuously modernize and flex to support manufacturing processes—scale is an imperative part of this "critical path," he continued.

TACOM has several sites generating lessons learned related to readiness. As certification, qualification, and production efforts expand, it will be possible to integrate additive and advanced manufacturing and technical data requirements into future systems and production lines at all TACOM arsenals and depots. Maj. Gen. Werner envisioned that the Red River Army Depot, which serves as an Army Center of Industrial and Technical Excellence, could one day print parts on-demand to sustain a re-manufacturing line—the potential impact on the TACOM portfolio would be substantial, from water and fuel systems, to cannon tubes, to combat vehicles, to the tactical fleet. As the Army modernizes and sustains its legacy fleets, it is crucial that the industrial base is empowered to provide fluid and adaptable manufacturing methods, which could be achieved by applying creative and critical thinking to all processes and promoting new partnerships and enduring relationships. He said that doing this efficiently and effectively requires understanding Army operational requirements and synchronizing capabilities and resources to develop and deliver flexible and responsive support. Although this concept is simple, it is very difficult to execute. One approach would be to leverage advanced technologies across the entire Army organic industrial base to complement traditional manufacturing when the need arises. The Army would continue its effort to develop and integrate new manufacturing capabilities as well as to modernize its organic industrial base—Army Materiel Command plans to invest $5.2 billion over the next 15 years to modernize depots, manufacturing capabilities, physical and network infrastructure, and supply chain and distribution systems.

In closing, Maj. Gen. Werner commented that TACOM's most valuable asset is the tens of thousands of people who support its arsenals and depots as well as manage the supply chain. TACOM strives to build an environment where soldiers and Army civilians are empowered to be creative as well as to develop competent leaders with the skills to foster the enduring interagency relationships that are essential to wise decision making for future operations. TACOM continues to add new skillsets (e.g., data scientists, computer programmers, researchers) to complement its current team.

Question and Answer Session

Workshop Co-Chair and Session Moderator Tom Kurfess, Chief Manufacturing Officer, Manufacturing Demonstration Facility, Oak Ridge National Laboratory, asked about approaches that should be considered for convergent manufacturing. Maj. Gen. Werner replied that Detroit Arsenal is located in the heart of advanced and convergent manufacturing and the mecca of thought on the integration of technologies into manufacturing processes; both small and large businesses are actively fusing different capabilities. Because additive manufacturing is complementary to the Army's existing manufacturing processes, the Army has been leveraging it for prototyping (but not yet for production). Engineers have re-engineered older systems and programs using only additive manufacturing to improve output. Engineers are also developing new ways to better produce parts and systems in combat platforms and to use industrial control networks and technology to evaluate quality from the beginning of the production process to identify and eliminate flaws early in the manufacturing process. That level of capability has not yet been achieved in the organic industrial base, he explained. Other technologies, such as electrochemical machining, electrochemical deposition, and cold spray, are being applied in new ways for the defense industry. He emphasized that connecting machines is a top priority, as industrial control networks provide deeper understanding and better results.

Compiling several participants' questions, Kurfess inquired about the role of the digital thread[8] in enabling advanced capabilities. Maj. Gen. Werner suggested first developing acquisition strategies and contracts that allow the Army to access technical data that enable the integration of part manufacturing in forward locations. Next, it is important to identify which technical data are needed to create digital threads for particular parts so as to maintain a cost-effective process. He described an initial program with an infantry combat vehicle (M113) as a platform to develop a digital twin[9]; the goal is to better define what portions of the M113 should have evolutionary technical data developed and integrated into the future acquisition plan. A digital thread enables data sharing across industrial operations and sustainment operations at the tactical and operational levels. The ideal scenario, he continued, would be to have a new piece of equipment that comes with technical data, and those data are developed into a digital thread that is stored in an

[8] "Digital thread" is defined as "the use of digital tools and representations for design, evaluation, and life cycle management." The term digital thread was first used in the Global Horizons 2013 report by the USAF Global Science and Technology Vision Task Force

[9] A "digital twin" is a virtual representation that serves as the real-time digital counterpart of a physical object or process. Though the concept originated earlier (attributed to Michael Grieves, then of the University of Michigan, in 2002) the first practical definition of digital twin originated from NASA in an attempt to improve physical model simulation of spacecraft in 2010.

accessible central repository, making it possible to produce parts and afford repair. The digital twin of the M113 is a foundational experiment to collect data, analyze them against demand history for M113 parts, and better understand packages within a combat system for which technical data are needed from the acquisition of the first piece of equipment. Kurfess acknowledged that the digital thread enables rapid movement of new technologies into operations.

PANEL 1: MULTIFUNCTIONAL MATERIALS DESIGN

Charles Kuehmann, Vice President of Materials Engineering, Tesla/SpaceX

Kuehmann explained that despite the existence of an advanced design toolbox to develop multifunctional materials, a question remains about which materials to design, with consideration for the following hierarchy: (1) the materials genome, the building blocks of physics and the fundamental principles that define materials; (2) computational materials design, by which it is possible to gain computational control over materials and to develop feature-specific or application-specific materials to advance systems; and (3) integrated computational materials engineering, which integrates the previous techniques with computer-aided engineering and process simulation tools to design location-specific properties or for further optimization of material properties for specific applications. He described the following ideal scenario for design: the best part is no part, and the best process is no process, which reduces the cost, weight, time to buy, and engineering effort of design to zero. Tesla/SpaceX uses the following five-step process for design:

1. What are the requirements for the design? Requirements define what a design is and does; if the requirements are wrong, the wrong item will be designed. And because requirements are typically incorrect, it is important to identify the right question at the beginning of the process.
2. Can the part be deleted?
3. If the part cannot be deleted, how can it be simplified to its essential features?
4. Can the way the part is made be accelerated?
5. Can automation be used to keep the process moving smoothly?

Kuehmann detailed the process by which aerospace systems are designed, starting with systems engineering, which develops through various system and component design efforts into an implementation in hardware and software. Next, a verification process leads to an operational system. Learning occurs throughout, and the design is reiterated, which is a time-consuming process that creates challenges in implementing fundamental solutions to problems. He noted that it is critical that this V-shaped development process is compressed into a very fast combined build and test and design system to speed the pace of verification learning, iterate design, and validate at the operational level. In contrast, in the traditional V-shaped development curve there is often a need during the second verification leg of the "V" to return to the first leg and tune the system or component design. This creates multiple loops or iterations of redesign that are costly and takes away valuable time.

Processing, structure, properties, and performance comprise a manufacturing-driven paradigm, Kuehmann continued. In the design sequence, those steps are reversed, with consideration for performance at the start, followed by the development of material properties, which determine the structure, which leads to the selection of the processing step. He stressed that these steps cannot occur independently; performance and processing are part of the requirements, and it is important to determine what is needed from structures and properties to create the design. For example, because the Tesla Model 3 contained more than 400 individual parts assembled in the body line, plus a battery pack, a simplified design was needed for the Tesla Model Y. The new design includes one structure for the rear and one for the front, as well as a structural battery pack to take crash loads from the front to the rear and from side to side. This body system has only three major components, so it can be made much more quickly and efficiently from design to implementation; the Model Y also has 10 percent mass reduction, 14 percent increase in range, and more than 370 fewer parts in the body than the Model 3. A casting alloy, which could be made with high castability and enough strength for the structural aspects without allowing for heat treat or any subsequent processes, enabled this simplified design—the Model Y casting is 40 percent less expensive with 79 fewer parts. This new design also impacts the manufacturing facility, with 55 percent reduction in investment per gigawatt hour of battery pack capacity and 35 percent reduction in the floor space of the facility.

Julia R. Greer, Ruben F. and Donna Mettler Professor of Materials Science, Mechanics, and Medical Engineering, California Institute of Technology

Greer posed a question to the audience about how they like their materials—with multifunctionality and reconfigurability or just lightweight—comparing this "materials by design" concept to the age-old, now customizable question, "How do you like your coffee?" She emphasized that processes for manufacturing strong and heavy materials as well as those for manufacturing lightweight and weak materials are well established; however, it is important to consider how to make materials that are simultaneously lightweight and mechanically resilient. To achieve this, she proposed applying the concept of architecture to materials design. For example, although the Eiffel Tower is twice as tall as the Great Pyramid of Giza, it weighs three orders of magnitude less; the Eiffel Tower uses substantially less material, and both structures are still standing.

Greer described the previous decade's research on nickel microlattices, which made clear that to achieve both lightweight and mechanical resilience, it was essential to move three more orders of magnitude down to nano-architected materials—that is, where basic building blocks of components are at the length scales where the nanosize effect contributes to the overall properties of materials. It is possible to construct a three-dimensional (3D) network out of nanoscale building blocks to induce new, unusual properties (i.e., the emergence of photonic bandgap) and combinations of properties (i.e., lightweight and mechanical strength/stiffness). The properties of these "structural metamaterials" can no longer be described fully from either the material or the structural perspectives. The size effect gives rise to unique properties on the mechanical side; for example, the "smaller is stronger" size effect indicates that common metals in their single crystalline form (e.g., nickel, copper) can become as strong as steel, owing to size reduction. When using a different technique (e.g., thin film deposition), the effect on the same metals is reversed to "smaller is weaker." For metallic glasses that are put in tension at room temperature, smaller becomes more ductile; for ceramics, which do not typically remain intact with the application of extreme tensile stress, smaller is tougher at the nanoscale. She underscored that these varied effects only emerge at the nanoscale.

The next step, Greer continued, is to harness these beneficial size effects and proliferate them onto larger scales. For example, inherently brittle materials such as alumina, glassy carbon, and other ceramics, when sculpted even into complex 3D shapes with nano- and micro-sized thicknesses and dimensions, are able to deform and fully recover their shape after being deformed under complex stress states, without permanent damage. It is possible to build different relative densities and designs to induce different deformation trajectories into materials, reinforcing that size effect manifests itself significantly (see Meza et al., 2014, 2015; Portela et al., 2020). Hollow nanolattices enable venturing into the material property space of light weight and resilience. The approach of combined architecture with the emergence of nano- and micro-size effect in materials presents the opportunity to create new material classes through additive manufacturing. Nano-architected materials also offer the novel capability of impact resilience (see Portela et al., 2021). For example, when carbon nanolattices are subjected to impact, whatever is underneath is protected. This technique is also amenable to custom resin synthesis.

Greer outlined several other applications, including the use of additive manufacturing for nano-photonics; vat polymerization for a hydrogel infusion additive manufacturing process to swell in metal ions from their salts and convert printed metal oxides to metals; biomolecular surface functionalization to target agents for chemotherapy; the use of machine learning processes to create bio-scaffold design to mimic a biological or engineered feature and to predict anisotropic stiffness; and the creation of safer and lighter lithium-ion batteries via the use of architected electrodes. She stressed the importance of scaling-up the production and fabrication of nano-architected materials, as several opportunities and properties have not yet been leveraged in the commercial world. The creative use of (1) architecture, (2) nanomaterials, and (3) atomic arrangements as "tuning knobs" in material design enables the creation of new material classes, with decoupled properties that have always been linked before, and offers extremely lightweight options.

Wei Chen, Wilson-Cook Professor in Engineering Design,
Northwestern University

Chen remarked that multifunctional materials represent the future, owing to their superior performance. Most existing systems are designed by trial and error or are based on engineers' intuition; instead, it is important to develop efficient and intelligent computational design methods to automate the design process of these heterogeneous materials.

Chen highlighted research under way in Northwestern's IDEAL Lab. One project focuses on multifunctional materials design with a data-centric framework, which combines data from computer simulations and experiments (see Iyer et al., 2020). An example is the design of multifunctional dielectric materials, which have a wide range of applications including power lines to carry electricity. Multifunctionality is cast as a multicriteria optimization problem (e.g., storage, insulation, endurance), and the design scope covers the qualitative design decisions (e.g., what polymer to use, what surface treatment to use) and the quantitative representation (e.g., machine learning to extract descriptors around complex morphology). Computer simulation and machine learning are used to build a model to predict each property, and experimental data are used to calibrate and validate this model. Another project studies data-driven design of heterogeneous material systems (see Wang et al., 2021). Data are used to model inputs such as material type and architecture, and a novel machine learning technique allows mixed variables (i.e., quantitative and qualitative) to build a continuous Gaussian process model that can be integrated into upper-scale topology optimization. This approach makes it possible to create multiscale topology optimization–designed heterogeneous systems using a computation demand similar to single-scale topology optimization because the material law is surrogated by machine learning, and using two different materials with different architectures increases displacement by 167 percent in a compliant mechanism example.

Chen described several challenges in the computational design of multifunctional systems, including the "curse of dimensionality," which could be addressed with methods that can search the entire design space (i.e., material, architecture, and manufacturing process). Another challenge is the barrier to applying design methods caused by nonlinear behavior (e.g., accuracy and cost trade-off, lack of analytical gradient for optimization). Furthermore, multistable systems have nondifferentiable behavior, which makes automated design optimization methods problematic. Lastly, most multifunctional systems are also multiphysics systems, which creates challenges in analysis and optimization. She noted that future directions and moonshot ideas from the research perspective, in which the materials, mechanics, manufacturing, and design communities would work together, include predicting the process-structure-property-performance-function relationship across multiple scales with uncertainty quantification; using supercomputing and artificial intelligence (AI) techniques for fast 3D design integration and exploration; creating a multiscale design framework for heterogeneous systems to exploit hybrid manufacturing capability; and integrating manufacturing process impact into topology optimization.

LaShanda Korley, Distinguished Professor,
Departments of Materials Science and Engineering and Chemical and Biomolecular Engineering, University of Delaware

Korley discussed the convergence of molecular design, assembly, and manufacturing through a bio-inspired lens, with particular emphasis on how molecular design of functional materials enables strategic property development. She described spider silk as one of the most "elegant" examples of convergent manufacturing in nature. The diversity of the mechanical function achieved in spider silk is due to slight modifications in its peptide sequence, which lead to variations in the hierarchical assembly, all of which are facilitated by what occurs in its "manufacturing vehicle" (the spinneret). The toughness of the material is driven by the interplay of the chemical diversity (with glycine and alanine) and chain interactions (hydrogen bonding, which leads to self-assembled structures) provided on-demand by the spider. She pointed out that different spiders have different mechanical properties and structural pieces that create different materials—for example, brown recluse spiders have flat ribbons instead of cylindrical filaments, which gives rise to more adhesive material properties. The spider demonstrates that it is possible to use molecular design to challenge the probing of interfacial interactions and to increase energy efficiency (see Chan et al., 2020; Gosline et al., 1999).

In an effort to expand the tool set for advanced manufacturing, Korley's research group is working on the control of hierarchy in systems—design pathways include taking block copolymers that can segregate on their own into a variety of structures, generating elastomeric species, and using cross-linking. It is possible to use the overlay of covalent and dynamic interactions in these systems to explore how both secondary structure and organizational features give rise to unique properties. By tuning (whether there are small bits of peptitic ordering in the system or there is a change in the secondary structure by shifting from beta sheet ordering to alpha helix ordering), it is possible to manipulate hierarchy using the interplay of different design pathways coupled with manufacturing strategies. Comparing the secondary structure of these materials systems, which can be modulated by the solvent in which the materials are formed, it is possible to make a bi-layer material that can form a helical structure when exposed to a specific environmental condition (e.g., through water). Nature provides a variety of ways to merge manufacturing pathways and molecular design—for example, pinecones have layered material property and complex materials design at the interface, which allows opening and closing in response to humidity. She highlighted a "forest of opportunities" to use templates to drive organization, with the ability to create on-demand, responsive types of systems, using environmental conditions to tailor properties. Focusing on the modularity of building blocks could enhance efficiency, she continued, and using different pathways could customize material properties for a holistic convergent manufacturing approach.

Question and Answer Session

Moderator Christina Baker, Director of Additive Manufacturing, PPG Industries, asked how students could best prepare for future work in convergent manufacturing as well as what critical research gaps remain to achieve multifunctional convergent hybrid manufacturing. Kuehmann emphasized that to push back against design requirements, one would need a broad understanding of how systems work; therefore, students should seek fundamental knowledge in a broad range of systems (i.e., materials students would take mechanical design classes). Chen acknowledged the value of developing a systems view but noted that this may be difficult to achieve in the classroom. She championed project-based learning; for example, Northwestern University offers an interdisciplinary doctoral cluster program. Korley mentioned several opportunities for students to explore beyond their discipline-specific boundaries—for example, university interdisciplinary programs, the National Science Foundation's Research Experiences for Undergraduates, and other internships. She stressed that convergent manufacturing is about establishing a common language and set of tools to communicate in a way that moves the field forward and makes it possible to experience different aspects of the manufacturing chain.

Baker wondered about other challenges for multifunctional materials design. Chen affirmed that developing a common language with shared terminology is key to enabling communication across disciplines. Kuehmann added that in terms of multifunctionality, system design is reflective of an institution's organizing principles; for example, product interfaces often represent institutional interfaces that create inherent boundaries. However, the goal for multifunctional materials design is to erase these interfaces and improve product performance. Korley said that each aspect of the manufacturing process is often viewed as a discrete unit, with the product design the last to be considered. Instead, it is important to integrate product design early in the process: thinking from a systems perspective and including different types of materials leads to progress.

Baker asked the panelists about the potential for integrating natural resources into convergent manufacturing. Korley advocated for taking advantage of advances in catalytic technology and new synthesizing schemes that start with natural materials to create specific building blocks, which could be added to the existing value chain as building blocks for new materials that capture many of the properties and add functionality and sustainability. Baker also inquired about the potential for integrating nanoscale additive manufacturing into larger-scale additive manufacturing, and Greer described this integration of nanoscale additive manufacturing as a real challenge. Greer went on to also state that additive-manufactured materials are not well understood in terms of the properties they could enable and how they should be inspected. Thus, according to Greer, the most important aspects missing from additive manufacturing are in situ diagnostics (i.e., the ability to diagnose whether the part being produced will have the desired quality, and the ability to make those decisions in real time) and more data for machine learning. Although it is very expensive to evaluate different length scales from the nano scale and up, she continued, it is imperative to do so during the research stage—in situ diagnostic capabilities are invaluable.

Baker asked how economic decisions converge with the timing of product launches and performance expectations in the corporate decision-making process, especially in light of divergent safety considerations and cost expectations. Kuehmann noted that SpaceX and Tesla derive high-level metrics by which to measure trade-offs for engineering and manufacturing decisions. For example, Tesla is considering how quickly to replace the existing carbon-producing internal combustion engine vehicle fleet, which is an optimization problem of accelerating sustainable energy.

Baker posed a question about key challenges regarding scalability and integration—for instance, although many innovative early-stage technologies exist, it remains to be seen how they will transition into the real world. Chen explained that while data are part of the solution to the scalability problem, they are also part of the challenge, owing to the difficulty in identifying the most useful and high-quality data for which machine learning, dimension reduction, and other technologies can be applied. She portrayed design synthesis as a multiscale problem with the potential to develop algorithms that could break barriers and enable scaling. Kuehmann added that concurrent design and integration enable quicker delivery than sequential activities and reduce overall program risk. Malshe asked about the balance of top-down (system level) and bottom-up (engineering level) approaches for scalability. Kuehmann responded that Tesla/SpaceX maintains systems thinking throughout any engineering activity; when systems-level thinking permeates, an opportunity for true integration emerges.

Baker invited panelists to share additional moonshots for multifunctional materials capabilities. Greer suggested developing a model that captures complexity and physics with economically feasible computational resources. A true moonshot is the ability to enter a desired strength and weight ratio into a kiosk that would provide options on-demand for materials, including costs and properties. Kuehmann remarked that it would be beneficial to have an integration system that generates a representation of system-level performance and manufacturing to simplify trade-offs.

PANEL 2: HETEROGENEOUS MATERIALS DESIGN

Carolyn Duran, Vice President, Data Center and AI Group, Intel Corporation

Duran explained that many of the challenges for devices made by heterogeneous materials and design are similar to those that relate to the desire to shrink device sizes in accordance with Moore's Law with the goal to create more purpose-built products that optimize for use cases and allow for restructuring, reframing, recycling, and reusing materials. She shared the following three perspectives on convergent manufacturing and heterogeneous materials interfaces: (1) At the microscale level (e.g., semiconductor manufacturing), scaling leads to interfaces dominating the materials properties; it is important to eliminate unnecessary interfaces from the scaling to reduce the number of defects, provide the best properties, and improve product performance. It is vital to consider how to achieve that with disparate materials via in situ processing. (2) At the mid-scale level (e.g., hybrid bonding of units from different manufacturers), miniaturization is enabled, device performance improves, and the hybrid bonding allows disparate silicon types to be integrated. (3) At the macroscale level, it is critical to adapt products that are already in the field via repurposing or repairing.

Abhir Adhate, Product Director, Modeling & Simulations, Sentient Science

Adhate emphasized the value of rapid and accurate material microstructural tools for heterogeneous materials development and design. Additive manufacturing techniques allow for the embedding of heterogeneous materials in components in new and interesting ways. It is important to understand the evolution of microstructure in order to understand part performance, he continued, especially in terms of part quality (i.e., how microstructure evolves after different manufacturing operations). The ability to virtually test components with heterogeneous materials will thus be key to lowering costs and understanding part function. For example, cloud computing lowers barriers to entry for essential high-performance computing, especially for smaller organizations. To develop microstructure models, he indicated that an understanding of machine materials is needed via access to machine application programming interfaces (APIs) as well as material and machine data. Convergent platforms rely on models as part of quality assurance, and he stressed that understanding the intended microstructure at the interfaces of heterogeneous materials is critical for quality assurance. To achieve agile, versatile, and resilient manufacturing capabilities at the point of need, convergent manufacturing platforms would need in situ monitoring and defect correction capabilities, which require the ability to quickly develop material models, share material models seamlessly, and maintain open access to machine APIs.

Vinayak Dravid, Abraham Harris Professor of Materials Science and Engineering, Northwestern University

Dravid described energy, sustainability (of both material and financial resources), and the environment as non-colinear points that merge to create a stable plane for growth and societal progress. Therefore, when trying to advance a technology, it is critical to balance and articulate a tangible value proposition for all three segments. He championed nanoscale approaches to gigaton challenges, for example by leveraging convergent manufacturing for environmental remediation. Any science or technology that addresses gigaton challenges has to satisfy a series of convergence issues, with consideration for efficiency, effectiveness, the economy, eco-friendliness, and engineering and ergonomic compatibility. Highlighting the value of environmental remediation, he detailed the use of OHM (oleophilic, hydrophobic, and multifunctional) technology to leverage discarded waste sponges for use as substrates to create functional materials with only the addition of a coating (see Figure 2.1). When that technology is exposed to air, water, and soil as a way to attract pollutants, the pollutants are captured for reuse. This reusability cycle, in which the pollutant is removed, recovered, reused, repurposed, and recycled into a new product, could be expanded; he emphasized the importance of a life cycle analysis of a technology from birth to burial.

Kimani Toussaint, Professor and Senior Associate Dean, School of Engineering, Brown University

Toussaint highlighted the benefits of leveraging convergence to democratize biomanufacturing. He asserted that biology thrives on heterogeneity, which exists in composition and structure spanning multiple hierarchical (spatial) scales to introduce a variety of functionalities. It is critical to understand the structure

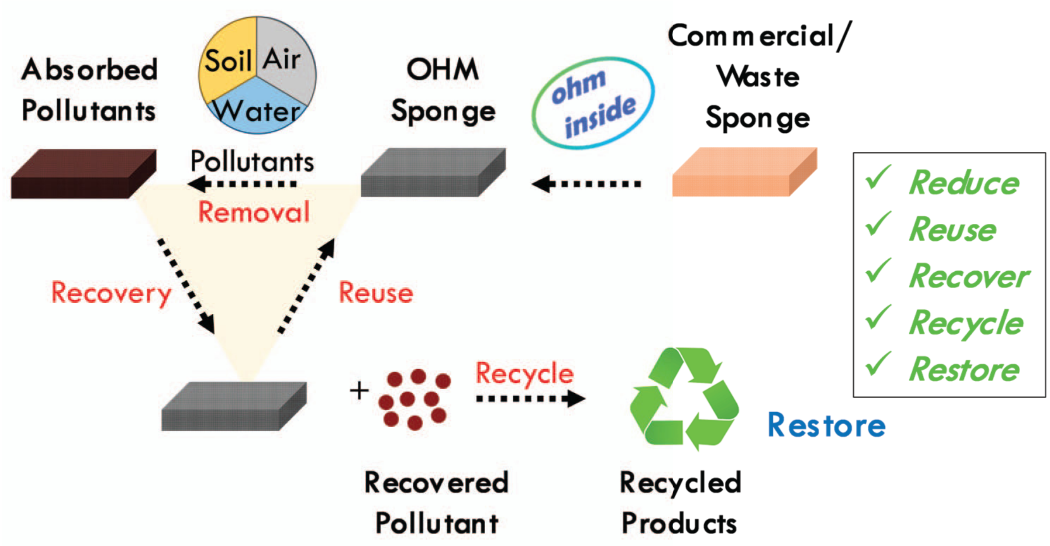

FIGURE 2.1 OHM (oleophilic, hydrophobic, and multifunctional) technology—using "waste" to "clean" waste. SOURCE: Vinayak Dravid, Northwestern University, presentation to the workshop, November 15, 2021.

function relationship, especially to replicate systems. For example, it is possible to perturb the molecular constituents of a collagen molecule—by removing the amino acid that affects the flexibility of the molecule, or modifying the amino acid sequence, in which case the system could lead to brittle bone disease. Interfaces in biological systems are especially important for replication. Complex biological systems have structural variation dependent upon the location (e.g., collagen fibers organize themselves very differently in the lungs than in the liver) or the severity of disease, as well as variation in composition in terms of functionalities.

Toussaint described a cross-disciplinary collaboration to capture a small slice of lung tissue, create a digital copy, replicate it, and feed it into a design and modeling process, which is informed by a materials database (see Figure 2.2). The initial product created via two-photon lithography undergoes advanced metrology and biological validation before machine learning is applied to compare the new product to the original system. Data obtained from this smart manufacturing platform could be uploaded to a data repository, leading to the democratization of the biomanufacturing process in which a variety of researchers and institutions could participate in the overall enterprise.

In closing, Toussaint shared knowledge gaps and technological needs for the future: (1) small footprint, ultrafast lasers with dynamic wavefront shaping capabilities; (2) multiscale and multiphysics modeling for complex, heterogeneous biomaterials; and (3) new biomaterials, and biocompatible and water soluble photoinitiators.

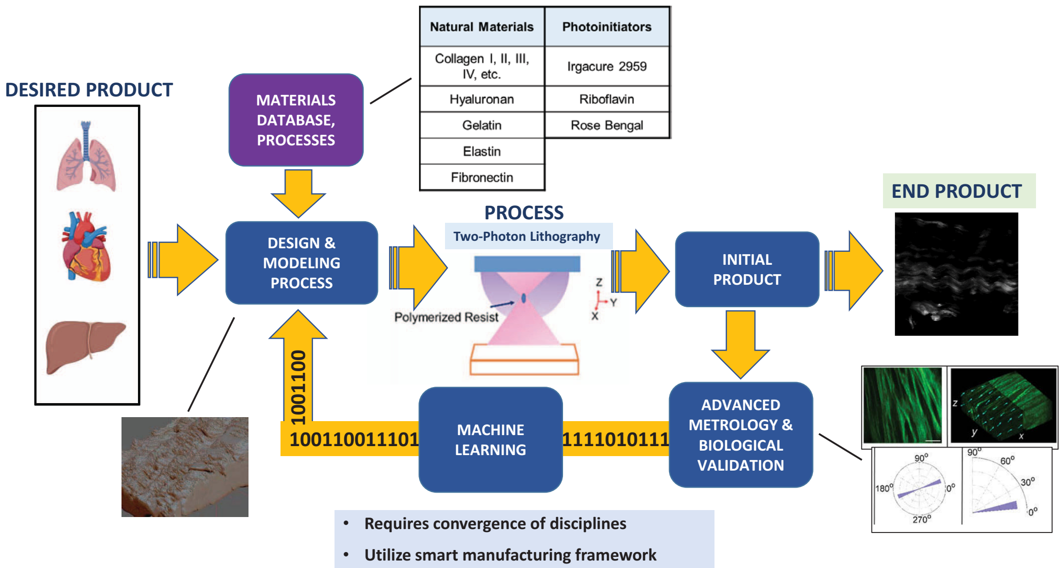

FIGURE 2.2 Framework for manufacturing heterogeneous biomaterials. SOURCES: Kimani Toussaint, Brown University, presentation to the workshop, November 15, 2021. Image in lower right corner from W. Lee, A. Ostadi Moghaddam, S. Shen, H. Phillips, B.L. McFarlin, A.J. Wagoner Johnson, and K.C. Toussaint, 2021, An optomechanogram for assessment of the structural and mechanical properties of tissues, *Scientific Reports* 11(1):324, https://doi.org/10.1038/s41598-020-79602-6, Copyright © 2021 The Authors, licensed under a Creative Commons Attribution 4.0 International License.

Question and Answer Session

Moderator Jian Cao, Cardiss Collins Professor and Founding Director of the Northwestern Initiative for Manufacturing Science and Innovation, Northwestern University, observed "point of need" as a common thread among all the panelists' presentations in this workshop, particularly in relation to repurposing, detection and repair, surface interaction, democratization of biomanufacturing processes, and supply chain agility. She asked about the barriers at the point of need as well as the system-level implementation of technology needed to overcome them. Duran replied that predictive understanding would help to anticipate and avoid failure so as to provide uninterrupted service and reduce the need for reactive repairs. Predictive understanding could be realized through a study of telemetry, diagnostics, and predictive behavior as well as modeling to optimize and reveal trends prior to failure. Adhate said that although AI and machine learning techniques are emerging to address this issue, physics is needed to understand how materials interact in different environments and under different modes of operation. Duran added that when a company does not service the end user, it is challenging to make predictions without knowing how a product may be used in the field.

Cao invited panelists to discuss additional knowledge gaps for convergence at the heterogeneous interface. Dravid remarked that there is a gap between laboratory excellence and field deployment, where the scale is much larger, particularly for issues related to energy and the environment. If it is not possible to demonstrate a proof of concept at an intermediate scale, it is difficult to make a case for it downstream. Adhate acknowledged this "valley of death" in technology development when attempting to scale concepts from the laboratory. Duran added that it is difficult, even in industry, to secure expensive pieces of equipment for testing at an intermediate scale, and Dravid observed that this issue is complicated by the fact that large companies tend to be risk averse. Toussaint commented that from an experimentalist's perspective, data are paramount. Efforts to build smart platforms for better decision making are under way, but there has been less effort to create databases that capture work from the discovery process. He proposed that data collected during field experiments be placed in a repository and shared in an open-source intelligent manufacturing system as a way to leverage and converge the findings of different experts. He requested more attention toward the discovery process, as well as incentives to share data. Cao supported the sharing of knowledge accumulated in laboratories and on manufacturing floors instead of continuing to publish only the "good data." Adhate highlighted the benefit of a common ontology to enable this level of data discovery and sharing. Cao wondered why a common ontology has not yet been established, and Adhate pointed out that with so many experts in niche areas, it is difficult for people to agree on terminology. Duran posited that it is difficult to develop systems-level perspectives without an integrator to connect siloes of expertise. Cao posed a question about how industry's hesitancy to share materials data could inhibit progress. Dravid suggested an intermediate approach that would include the sharing of some data that are separated from more confidential in-house innovation data, and Adhate championed Toussaint's suggestion of developing a database with varied levels of sharing and access.

Cao inquired as to whether convergent manufacturing could be leveraged to minimize the use of dangerous or scarce materials. Duran suggested borrowing materials for use cases and returning them for reuse. This approach would offer the benefits of modularity without the detriments of additional interfaces—it minimizes the total consumption of dangerous or scarce materials by recovering them for safe reuse. Cao wondered what manufacturing methods could be used to design material with a heterogeneous interface to enable easy separation for later reuse. Dravid responded that affordability and impact are critical; the economics and social implications of material have to be considered, as environmental laws vary by country. Duran noted that building systems with flexibility often increases complexity and cost, but a balance between simplicity and flexibility is important. Toussaint explained that specific applications for and specific aspects of material properties determine how information is distributed. For example, a substitute material could be used to copy the overall structure of a malignant tissue and digitize the information for distribution. There is no one-size-fits-all solution, which reinforces the value of a well-analyzed database to make smarter decisions about how to better use materials. Dravid added that distributed solutions depend on local scenarios; instead of seeking perfection, the goal should be to develop solutions that are "good enough," and Adhate remarked that this decision relates to the appropriateness of the requirements. Cao asked the panelists how Scope 3 relates to borrowing materials and carbon dioxide (CO_2) emissions. Duran said that it is important for industries to take Scope 3 emissions into account to move closer to full life cycle analyses and circular economies, but she cautioned against unintended consequences, such as the recapture of borrowed materials increasing cost. Dravid highlighted not only the cost of purchase but also the cost of ownership; CO_2 is only one of many impacts that should be considered. Adhate suggested developing interchangeable models and building metamodels of a particular product to identify the CO_2 emissions from a life cycle.

Cao posed a question about affordable materials that could provide significant advantages over current aerospace materials, and Dravid replied that it is possible to develop a more affordable substrate and a surface-based solution. Toussaint noted that it is important to consider the scope of metamaterials and the issue of functionality (e.g., it is possible to print a substitute tissue that does not look like the heart but functions like the heart), which is another area in which a common language developed by experts from various fields would be beneficial. Cao presented a related question about the potential for functional metrology. Adhate responded that evaluating part performance in terms of what is allowable instead of what is safe is a very different way for engineers to think about design, and Dravid pointed out the benefits of designing holistically around the core technology.

Cao questioned how to expand convergent manufacturing. Adhate suggested open machine APIs and a common language between them to enable convergence. Dravid stressed the need for better workforce development to address gaps in manufacturing, with a value chain of talent at both the college and community college levels. Duran pointed out that because people generally fear change, it is important to demystify the notion of convergent manufacturing. Toussaint commented that as new disciplines emerge, more crosstalk would be beneficial. He proposed that postsecondary institutions update their paradigm for education to a "convergent education model" that emphasizes a common lexicon, teamwork, and problem-solving across traditional disciplinary boundaries. Dravid encouraged the professional societies to offer cross-training (e.g., bootcamps), and Toussaint emphasized the need for incentives to shift the university approach to evaluation to place value on cross-disciplinary training.

Cao observed that an objective of the Materials Genome Initiative is more rapid materials development, and she inquired about industry's progress. Duran described the goal to reach a point in which models are trusted enough to eliminate some of the test cases. New capabilities have begun to enable this progress, but she asserted that more work in experimentation and production would be beneficial, and predictive modeling is critical. Cao wondered about the availability of appropriate design software for convergent manufacturing. Adhate highlighted sectors of academia that are experimenting with design software that incorporates heterogeneity, density, and energy materials, although this software is not widely available to engineers. He added that most computer-aided design software only assumes uniform material properties—a gap that should be addressed.

Cao asked about the challenges of processing multiple materials within a single system, and Dravid used electron microscopy as an example and discussed the dichotomy between hard (e.g., metals) and soft (e.g., polymer) interfaces while examining the interface. He noted that although soft interfaces are dominated by more damage by the electron beam, it is important to find a common denominator between the two materials to extract information about the material interface such as using adaptive sampling for the soft material as not to damage it. Cao wondered if there are parallels between previous approaches to semiconductor manufacturing and current approaches to convergent manufacturing. Duran explained that the semiconductor industry solves for defects to eliminate interfaces and obtains a bulk material property at a small volume that is not dominated by surface effects. Although that is not the process that would be used in convergent manufacturing, if the objective is modularity, one could quickly treat the interface and use it in its intended state—a similar approach despite the difference in problem statements. Dravid pointed out that the semiconductor industry has been dominated by flaw intolerance, but the new paradigm for convergent manufacturing emphasizes adapting flaws and finding ways to circumvent them. Cao asked if there are bio-inspired processes most suitable for convergent manufacturing, and Toussaint referred to areas of biomimetics that have been adapted—for example, functionalizing surfaces through patterning for self-cleaning materials.

GROUP QUESTION AND ANSWER SESSION: SCIENCE, ENGINEERING, AND APPLICATION GAPS

\Moderator Sandra DeVincent Wolf, Senior Director of Research Partnerships, Carnegie Mellon University, explained that in a systems-engineering approach for manufacturing at the point of need, materials, processes, and performance requirements are evaluated simultaneously, along with the consideration for the production or repair of something at or near the point of need. In addition to the previously mentioned scalability challenges (e.g., data collection, a usable database, characterization and inspection, evaluation at length scales, in situ diagnostics), she wondered about other gaps as well as how to best invest in research and development. Dravid reiterated the need to consider the technology's impacts on the environment and the local society during the design stage. Duran remarked that more systems-level thinking would balance siloed expertise. To achieve this, the future workforce would be trained to think differently and be rewarded accordingly. Korley and Adhate restated their support for the generation of a common language that encourages communication across the full system to facilitate convergent manufacturing. Kurfess highlighted the opportunity to develop augmented intelligence tools for "human cognitive offloading"—that is, the human focuses on creativity and innovation, while the tools complete more mundane tasks. Toussaint noted that as manufacturing matures, it will be important to think about design in terms of meeting the end user's needs (i.e., bespoke versus mass manufacturing). He cautioned that rigid definitions for concepts such as "scalability," for example, could constrain one's ability to rethink the framework for manufacturing.

Wolf invited the panelists to discuss gaps specifically related to design software. Adhate replied that for any design or simulation software to be useful, it should calibrate directly to data. Kurfess noted that interesting concepts are emerging around relatively inexpensive cloud-based computing capabilities: clouds can operate on Chromebooks, which increases access, especially for middle and high school students. Adhate explained that Sentient Science relies on software-as-a-service and runs on Amazon Web Services, the costs for which are steadily decreasing. As these tools become more affordable and students are able to use them, he continued, better training would be worthwhile.

Wolf observed the collective desire for a usable, curated materials database. While initiatives are under way, many challenges remain to enable data sharing. Assuming that a database with significant cybersecurity and sufficient knowledge of how to format data to be searchable and usable could be developed, she asked whether organizations would trust that database enough to contribute to it. Adhate responded that it would depend on how the organization could extract value from the material data. Toussaint pointed out that there are ways to limit the amount of (or anonymize) data in the database. A key motivator is whether people who contribute data receive something in return, such as access to other data. Duran described the Semiconductor Research Corporation, which provides a precompetitive space where people actively share *fundamental* research. Challenges arise in other situations when there is a specific application to a product, as industry tends only to publish things that are *not* working.

Wolf posed a question about the roles of the digital twin and digitization in supporting the evolution of manufacturing capabilities. Adhate remarked that the digital twin is most useful when good telemetry from the field can support sustainment. Progress is still needed to connect the digital twin to customer requirements, material selection, and material foundries. Dravid outlined the challenge of the digital divide when designing technology, as not everyone has access to digital information.

Wolf asked about other research opportunities to advance both materials and the study of materials design, and Korley highlighted an opportunity to integrate product design earlier in the materials design process. Duran said that because unintended consequences and trade-offs are often not well understood, better modeling, clearer assumptions, and a better understanding of key metrics are important as well as flexibility to balance trade-offs to develop the right material. Kurfess noted that complexity expands significantly with trade-offs; although AI offers some solutions, the human will always play an important role in optimization. He mentioned the culture shift required to realize a significant opportunity for workforce development and tool development—not just for high-level engineers but also for users on the manufacturing floor. Malshe described this as the true democratization of manufacturing.

Wolf questioned how to achieve the full potential of hybrid and multifunctional materials for convergent manufacturing. Dravid expressed his desire for accelerated testing (i.e., how the material behaves) and for increased attention to the *local* supply chain when developing solutions (e.g., adaptive sampling and adaptive supply chain). Korley advocated for taking advantage of natural materials in different locales to facilitate access, decrease costs, and enable functionality. Adhate emphasized that undergraduate and graduate programs should prepare engineers with the right design mentality[10] to effectively exploit heterogeneous and multifunctional materials. Toussaint commented that data have to be extracted at multiple scales in a variety of environments and then fused, and he suggested rediscovering the types of metrics and measures needed at these various scales and the types of metrology platforms required to extract these data. Dravid added that the life cycle analysis, including the impacts of the technology, have to be explicit from the design stage.

DAY 1 SUMMARY

Malshe provided an overview of key themes from the first day of the workshop series, noting that

1. Convergence is motivated by the aspiration to manufacture parts that are both simple and powerful.
2. Convergence by hybridization, hierarchy, and heterogeneity is critical, as is the transition to accepting greater risk of challenging ourselves to work with the added complexity and opportunity heterogeneity gives.

[10] An openness to the possibilities available using the more complex behavior in heterogeneous materials as compared to homogeneous materials.

3. That progressing beyond the boundaries of Industry 4.0 requires extensive community involvement to distribute information at the point of need and to make manufacturing equitable (i.e., accessible to all), which is key to the nation's economic well-being and security.

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3

Process Hybridization in One Platform

Opening the second day of the workshop series, Workshop Co-Chair Tom Kurfess, Chief Manufacturing Officer, Manufacturing Demonstration Facility, Oak Ridge National Laboratory, welcomed panelists and participants and posed three key questions for discussion: (1) What is your vision of convergent manufacturing, according to your expertise and experience? (2) What are knowledge gaps for science, engineering, and implementation of convergent manufacturing? (3) What are one or two "moonshot" projects for convergent manufacturing?

Introducing the theme of the keynote presentation, he noted that democratization of innovation aims to move innovation from the smallest enterprise to production and operations, and ultimately to the population.

DEMOCRATIZATION OF INNOVATION

Tracy Frost, Director, Office of the Secretary of Defense Manufacturing Technology

Keynote speaker Frost explained that merging different materials, processes, and systems requires collaboration among several communities, many of which are accustomed to working in siloes. This convergence could lead to opportunities to democratize innovation. However, she described an ongoing challenge with scale-up and manufacturing, particularly among small businesses that lack access to capital-intensive facilities. The U.S. Department of Defense's (DoD's) initiative to address this barrier and support the democratization of manufacturing innovation is the Manufacturing USA Innovation Institutes (MIIs). Recommended by the President's Council of Advisors on Science and Technology, this initiative began in 2010–2011 after one-third of the manufacturing workforce had been lost, the manufacturing share of the gross domestic product had declined to 12 percent, and 85 percent of the textile industry workforce had been lost—creating a national economy and security issue. The framework for the MII program emphasizes public–private partnership (i.e., a whole-of-nation effort), a model that has been sustained for a decade. The three main pillars of the MII framework are (1) advancing research and technology (i.e., partnering with industry in applied research and industrially relevant manufacturing technologies); (2) securing human capital (i.e., developing manufacturing-specific education and workforce development resources to ensure that innovative technology is manufacturable); and (3) establishing and growing regional manufacturing hubs and ecosystems for long-term, national impact.

Frost noted that the first institute that was stood up—America Makes in Youngstown, Ohio—focused on additive manufacturing. Eight additional institutes have launched, the most recent of which focuses on bio-industrial manufacturing for non-medical products—BioMADE in Saint Paul, Minnesota. Although each institute has a headquarters, all have satellites and a broad presence across the United States: the institutes have more than 1,500 members across 49 states, the District of Columbia, and Puerto Rico. These industry-led, public–private partnerships have significant stakeholder commitments, with $1.5 billion invested from the federal government and more than $2 billion invested from private entities and states. She outlined the objective of the MII program to create enduring resources for these advanced manufacturing stakeholders across the nation.

Frost remarked that the MII model is intended to bridge the "valley of death," where technology cannot be scaled up or adopted in the United States, or where funding ceases and technology stalls. She described key tenets of the MII model, the mission for which is to catalyze the establishment, effective operation, and integration of industry-led, public–private research partnerships that connect and develop people, ideas, and technology to accelerate the transition of new capabilities into defense products and systems. The MII model also focuses on industry-led, DoD-informed technical roadmapping of priorities. Joint roadmapping activities include all stakeholders across the institutes, which contributes to better, faster benefits. All members are invited to be involved in topic development and to lead or participate in a project, with particular emphasis on small- and medium-sized industry,[1] where much innovation occurs but does not become adopted broadly.

Frost emphasized that when manufacturing capabilities are too expensive and inaccessible to small- and medium-sized businesses, the pipeline of good ideas

[1] The United States considers small- and medium-sized industry to include firms with fewer than 500 employees. Small firms are generally those with fewer than 50 employees.

and the possibility to leverage manufacturing capabilities decreases. She stressed that the MII model provides opportunities for small- and medium-sized businesses to participate in projects with and leverage technologies from large manufacturers: more than 50 percent of the current membership is small- and medium-sized businesses. She shared a success story from AIM Photonics, which provides a state-of-the-art fabrication, packaging, and testing capability that is accessible for small- and medium-sized companies, academia, and government. AIM Photonics supports rapid, low-cost development with the provision of process design kits (PDKs) and multi-project wafers (MPWs). AIM Photonics PDKs include standard component libraries, are available in common electronics/photonics software platforms, support fabless design models, and facilitate entry for new designers and small businesses. PDKs have basic components, packaging, and modeling information to create and run a design through AIM's foundry, reducing both design time and cost and increasing first-run success. MPWs, which allow companies to buy a piece of a wafer instead of a whole wafer, also lower cost and increase accessibility for small businesses.

Turning to a discussion of the MII pillar on securing human capital, Frost highlighted the value of education and workforce development. She explained that people often focus on pursuing science, technology, engineering, and mathematics education at the K–12 level, but reskilling and upskilling the existing workforce is equally important, for everyone from skilled technicians to PhDs. She advocated for developing more training opportunities, certificates, apprenticeships, and internships for technicians in particular. The 20 percent of MII members who are from academia help drive curriculum development as well as maintain existing pathways or offer alternative pathways to delivering education. She presented several examples of MII efforts in education and workforce development. First, Advanced Functional Fabrics of America embedded research fellows at defense facilities, providing cross-training opportunities. Second, AIM Photonics has developed online and in-person training courses. Third, BioFabUSA, which focuses on regenerative medicine (an area not often accessible to young students), developed games to engage middle and high school students in understanding biofabrication. Fourth, Advanced Robotics for Manufacturing (ARM) helped DoD to determine robotic workforce needs, training, and salary; as a result, ARM, in partnership with JROBOT, drafted three recommendations for robotic workforce positions.

Frost underscored the need to ensure that taxpayer dollars are used and leveraged for the right investments in these industry-led institutes. Although this is a national effort, she continued, there is an expectation to transition MII technologies to DoD to strengthen the military and better protect warfighters. For instance, Light Innovation for Tomorrow (LIFT) began working with Ricardo Defense Systems in 2017 to retrofit Humvees with antilock brake and electronic stability control systems, reducing rollovers by 74 percent. In March 2021, the

Army provided a contract for $89 million to Ricardo to develop 9,500 kits to retrofit additional Humvees over the next 3 years. Another example is NextFlex, which is working with Sentinel to develop a wearable atmospheric chemical sensor for personnel working in hazardous environments. Both MII partnerships demonstrate the relevance of innovations to many commercial and military applications.

Frost said that the MII program has become a long-term initiative owing to its success in expanding both the use of technologies and the ability of small- and medium-sized businesses and individuals to enter previously inaccessible spaces (i.e., democratizing innovation). Noting that institute assessments are conducted every 5 years, she expressed her hope that advanced manufacturing technologies would become fully adopted as traditional technologies.

Question and Answer Session

Workshop Co-Chair and Session Moderator Ajay Malshe, R. Eugene and Susie E. Goodson Distinguished Professor of Mechanical Engineering, Purdue University, echoed Frost's assertions about the value of significant investments in and community collaboration for technology development. He reiterated that the future of combat is an asymmetric techno-socio-economic problem, and future solutions seek convergence of length scales, heterogeneous materials, and top-down and bottom-up processes in one platform (e.g., in a backpack, Humvee, or base station) to augment soldiers' functionality and to reduce dependency on supply chains for critical materials and applications at the point of need. He invited Frost to share her initial commentary on the three key workshop questions. She replied that her team continues to advocate for institutes to work together on convergent manufacturing because siloed efforts are ineffective: public–private partnerships enable innovation. Although 16 institutes span the federal agencies, she continued, more could be needed in the future.

PANEL 3: HYBRID MANUFACTURING PROCESSES

Michael Sealy, Associate Professor of Mechanical Engineering, Purdue University

Sealy noted his interest in hybridization as a means to solve problems related to degradable implants, as well as those related to the food chain, supply chain, wearable structures, and lightweight structures. For example, when it costs $9,000/kg to launch something into space but only $5/kg for an airplane to fly from one city to another, the urgent need for lightweight structures as well as remote manufacturing (i.e., the ability to produce anything anywhere, whether in space or in a deployment zone) becomes evident.

Sealy described his research in hybrid additive manufacturing processes and defined convergent manufacturing by hybridization as having three components—hybrid additive manufacturing processes; hybrid additive manufacturing material, structure, and function; and hybrid additive manufacturing machines. He mentioned that in 2005, the research landscape for hybrid additive manufacturing was sparse, with only 5 key groups active in the area. By 2015, there were 11, and in 2021, there were more than 25—an exponential growth in the number of papers and the number of universities and investigators working in this space.

Sealy explained that traditional manufacturing platforms focus on producing surface integrity, where each manufacturing process can make unique changes to a part. With hybrid additive manufacturing, however, it is possible to combine manufacturing processes (e.g., deep rolling, milling, peening) to make changes layer by layer and to print the desired mechanical properties. He referred to this ability to make local changes with global implications as "glocal" integrity—that is, cumulative and evolving surface integrity and properties across multiple scales to achieve heterogeneous changes (see Sealy et al., 2018, 2019).

Sealy presented three knowledge gaps in convergent manufacturing: (1) Understanding thermal cancellation of residual stresses from applied heat flux on a previously peened layer as well as mechanical cancellation of compressive residual stress by new laser shock peening in a previously peened layer, for which more advanced computational tools are needed (see Madireddy et al., 2019; Sealy et al., 2019, 2020). (2) Moving toward more advanced solutions and identifying *one* solution for a given problem (e.g., using more advanced design tools to avoid simple fixed interval solutions). (3) Enabling *anyone* to measure changes from convergent manufacturing processes by bulk wave ultrasound (see Avegnon et al., 2021; Sotelo et al., 2020). Although an advanced degree or access to unique equipment is currently needed to take such measurements, the future could offer a convergent manufacturing measurement tool that could be plugged into an iPhone, revealing the microstructure of and the residual stress on a part. Sharing his moonshot for an intelligent manufacturing process that is accessible to all, he stressed that software should enable anyone to produce complex solutions for fatigue and corrosion problems; accessibility, understandability, and usability lead to true democratization.

Aaron Stebner, Associate Professor of Mechanical Engineering and Materials Science, Georgia Institute of Technology

Stebner explained that cooperative additive and subtractive tools improve precision, but the combination of tools increases challenges in build path planning. He discussed initial approaches that combined large-scale additive processes with computer numerical control machining processes to help with dimensional tolerance control as larger structures were built, and described the current movement toward integration that is now being explored beyond simply additive and machining technologies.

Stebner noted that dividing tasks among multiple tools could increase cyber-physical security. He presented work from the Colorado School of Mines ADAPT (Alliance for the Development of Additive Processing Technologies) Research Center to integrate a femtosecond laser with a carbon dioxide (CO_2) laser in a laser powder bed system machine. It was possible to use ablative surface machining from the femtosecond laser to achieve three different surface textures, two different surface finishes, and structured surfaces (see Worts et al., 2019). This technology has implications for defense—for example, using ablative machining while building a part that, when held up to light, reveals an optical barcode. This provides an anticounterfeiting capability, where the plan for the placement of the barcodes is in the femtosecond laser, not part of the build file for the base part itself. An added benefit, he continued, is that 10 percent of the light from the femtosecond image can be used for real-time imaging and feedback control. The Colorado School of Mines is now working with Georgia Tech to add interferometry—enabling surface roughness measurement of the additive plus machine surfaces.

Stebner said that near-term goals for hybrid manufacturing include moving beyond the paradigm of two tools/processes and one material. He described three new tools at Georgia Tech: a machining tool, a powder-blown laser deposition tool with different nozzle shapes, and a wire feed tool, which together make it possible to build faster cores of parts with wire; apply different surface coatings, different materials, or finer finishes with a powder tool; and have the machining capability to help with subtractive tasks and improve surface finishes in critical places, all iteratively in one environment while parts are built. He emphasized that hybrid processes and hybrid human–artificial intelligence (AI) cooperation would help realize the benefits and abilities for these controls, and added that it is critical to be able to characterize, measure, and qualify, as well as to integrate recycling.

Stebner mentioned previous work to replace and improve door hinges on armored vehicles when breaking in the field. After several design iterations, the hinge became 35 percent lighter, more instruments could be added to the vehicle, the hinge became much stronger, the part count was reduced from seven to one, and destructive testing was completed to generate qualification data (see Gallmeyer et al., 2019). His near-term moonshot for hinges that break in the field is to be able to feed a broken hinge into a machine and print a new one with an improved design that corrects the problem. This would require recycling, analyzing data, and qualifying implications of the new part on-demand at the point of need, an approach that integrates manufacturing processes, data informatics, human cooperation, resource utilization, and sustainability.

Brian Paul, Professor of Manufacturing Engineering, Oregon State University

Paul discussed some of the polymetal[2] additive manufacturing work he and his team have been engaged in since 2016, including a partnership within the RAPID (Rapid Advancement in Process Intensification Deployment) Institute, a Manufacturing USA Institute, involving Oregon State University, Pacific Northwest National Laboratory, STARS Technology Corporation, and Southern California Gas Company. He described an advanced thermochemical platform that turns natural/renewable natural gas into hydrogen for fuel cells. As a result, compact chemical plants are placed in a distributed manner, adjacent to the point of use, and the natural gas infrastructure is used to deliver methane to the plants at a low cost. Toyota and other automobile manufacturers have introduced fuel cell vehicles into the California market, but owing to the high cost of centralized hydrogen production plus distribution to filling stations, the price of hydrogen at the "pump" is currently too high to accelerate adoption. Through the RAPID partnership, additive manufacturing vendors were found capable of producing new compact microchannel reactor components economically, which is enabling an initial demonstration for fuel cell buses in California in 2022.

Paul noted that polymetal additive manufacturing could further extend the ability to miniaturize these reactor components through the use of thermally enhanced pins within the microchannels to direct heat transfer vertically between heat transfer channels while minimizing axial (i.e., lateral) heat loss. Polymetal techniques can further be used to lightweight high temperature reactor components by enabling the doping of metal alloys to produce metal matrix composites possessing higher creep resistance at equivalent density. His moonshot is to integrate a capacitive sensor into future flow components for measuring flow-induced vibrations to avoid high cycle fatigue. He stressed that all of these innovations require the ability to tailor existing alloys or grade between multiple materials within a single build.

Paul showed that his research on polymetal additive manufacturing demonstrates that it is possible to build high-quality metal matrix composites such as oxide dispersion–strengthened stainless steel. Furthermore, he and his colleagues have developed "programmable" alloys with the means to locally dope the microstructure at a voxel level, opening the means for product designers to specify different material properties within a single component (see Paul et al., 2020). He added that programmable alloys illuminate the challenges associated with differences in the way materials scientists and engineers think. For example, consider the grading between two metal alloys: materials scientists think in terms of gold standards such

[2] In chemistry or mining, polymetal or polymetallic is a substance composed of a combination of different metals.

as X-ray fluorescence as a means to validate the evolving microstructure. Engineers think in terms of indirect methods such as melt pool morphology as a means for process control and part certification. Much work is needed to develop process control methods that can reliably predict the composition and microstructure of components on a voxel-by-voxel basis during economical production. Advances are happening in the machine tool supply chain to make this a reality. Meltio, a small company formed between a U.S. technology startup and a Spanish three-dimensional printing equipment distributor, is selling laser-based directed energy deposition equipment with simultaneous powder-fed and wire-fed capabilities, which Paul and his team are showing capable of delivering programmable alloys. These capabilities are important for navigating the deleterious phases and residual stresses that can make it difficult to place two alloys (e.g., Inconel 625 and GRCop 42) side by side, producing intermediate transition layers to take advantage of the 13× difference in thermal conductivity within components, such as rocket nozzles and chemical reactor vessels.

In closing, Paul described four key knowledge gaps:

1. Exploiting voxel-level properties within design methodologies (including AI-assisted design tools), characterizing graded materials, and predicting microstructure based on process conditions;
2. Decoupling the mixing of alloys and phases within weld pools/beads from process parameters, creating composition tolerances for specifying local material properties and graded transitions, controlling voxel size while changing composition, and estimating high temperature material properties needed for process models;
3. Improving process control and data to support part certification; and
4. Enabling electromechanical integration.

He championed moonshots in the following two areas, which could be attainable with increased investment: (1) Chemical reactors—thermal circuits to direct the flow of exergy between exothermic and endothermic events as well as integrated catalyst scaffolds and catalyst loading. (2) Electromechanical systems—the programming of conductive and dielectric materials during a component build to enable the integration of sensing for equipment health monitoring in space, nuclear, aerospace, and defense applications.

Mary Clare McCorry, Director of Technology and Process Development, Advanced Regenerative Manufacturing Institute (ARMI), BioFabUSA

McCorry outlined the biological considerations for hybrid manufacturing, emphasizing that biology makes a system more complicated, with concern for how all of its components are interacting. ARMI's goal is to protect and restore capabilities to warfighters by creating technologies that regenerate instead of only treat. ARMI is focusing on engineered tissue technologies that could restore form, function, and appearance to wounded warfighters—for example, restoring skeletal muscle function when there is muscle loss or engineering a custom-fit bone to replace a damaged bone. Another area of interest is restoring function of damaged nerves, with consideration for long-term effects of warfighting. For instance, there are efforts to address the osteoarthritis that often emerges among discharged warfighters after years of strain in the field. There is also work in small-size disease models with miniature tissues to develop personalized medicine approaches or to better screen drugs used for treatment.

McCorry stressed that the structure and mechanical performance of tissues are as important as the materials themselves. Cells are critical because they are the "tools" used in the manufacturing process to generate tissue; therefore, it is important to consider how cells will interact with and respond to materials, regarding both biological and mechanical characteristics. A tissue-engineered medical product has a triad of materials: cells, signaling factors, and scaffolds. She explained that many manufacturing approaches for generating cells, tissues, and organs are manual-intensive (e.g., sterile rooms, culture hoods, operators with pipettes). Now, there is a shift toward scalable, modular, automated, and closed (SMAC) manufacturing, but the steps of the manufacturing process remain siloed (i.e., tissue harvest and cell banking, expansion of culture, cell harvest and wash, scaffold fabrication, tissue assembly and maturation, preservation and packaging, and transport and logistics). A key challenge is shipping, especially in the transplant industry, which requires short time scales to deliver live tissue. In the case of personalized medicine, she continued, materials have to be tracked throughout the manufacturing process to ensure that the right product is delivered to the right patient.

McCorry's moonshot is to simplify the process so that it is more accessible, to be able to deploy in remote environments, to develop consistent and quality products, to create autonomous and closed processes, to enable predictive understanding, to engage in informed decision making, and to create flexible processes and personalized medicine. These improvements require measurement system optimization, implementation of process analytic technologies, development of predictive models, technology integration, and implementation and application of AI and modeling.

Question and Answer Session

Cambre Kelly, Vice President of Research and Technology, restor3d, Inc., observed common themes across the panel discussion, including the need to program heterogeneous materials and the importance of developing inspection and monitoring techniques. Serving as discussion moderator, Sudarsan Rachuri, Technology Manager, Advanced Manufacturing Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, posed a question about moving from hybrid manufacturing to the convergence of different technologies at different scales. Sealy highlighted two areas that would benefit substantially from multiscale convergent manufacturing: tissue engineering and cellular-based food (i.e., integrating cellular behavior on scaffolds to achieve the desired taste, texture, and form of food). He added that convergent manufacturing is complex in that it requires multiple materials across multiple scales, processes, and systems. Stebner referenced the National Academies' decadal survey for materials and manufacturing, which prioritized the movement from serial development cycles to continuously connected development (NASEM, 2019). As a result, convergent manufacturing relies on computing, data management, data connection, and mapping among different types of data and players in the supply chain. It is also critical to remove siloes in areas of expertise. He noted that because human minds think serially, parallel computing or computing with a graphics processing unit, which are *not* limited to that type of thinking, are important. He proposed that automation be used at the point of data curation, allowing humans to focus on abstract thought, extrapolation, and understanding complex relationships. A convergence of physics, science, engineering, computing, and social implications is key, he continued, because technologies are irrelevant if societies do not adopt them. Paul remarked that the design of hybrid manufacturing machine tools extends from an understanding of the physics that must be governed in the context of a manufacturing process. Thus, he suggested that "manufacturing process design" precede machine tool design and become part of a common engineering lexicon as a means for achieving manufacturing innovation. A key question remains about the best pathway to achieve the desired microstructure needed to produce tailored material properties within parts. The value of tailoring material properties can only be leveraged in regulated industries through the development of process control capable of supporting component certification. Although metrology is available for enabling dimensional control, he continued, further research is needed to reveal how best to enable microstructural control including ways to measure compositional tolerance. He advocated for more interaction across disciplines to think about problems from different perspectives, which could lead to the creation of new platforms to develop diverse products and capabilities.

Rachuri asked McCorry if SMAC manufacturing is a precursor to convergent manufacturing. She described SMAC as a good place to begin and outlined a roadmapping exercise that was used to better understand ARMI members' thoughts about the current state of manufacturing. It became clear that no one had thought about manufacturing from the start; because the process is so complex, they relied on the way that they manufactured during the innovation stage, which requires much flexibility. Operators were both performing manual steps and interacting with the U.S. Food and Drug Administration, which created anxiety about making changes in the manufacturing process that could affect the final product. McCorry's team has been interacting with these companies early in their manufacturing processes to help develop methods that they can grow with as they begin to scale to meet clinical demand. She emphasized the importance of predictive models for scaling—much of the time, it is not possible to know how materials and cells will behave, so it is useful to predict performance at all scales.

Malshe wondered how to converge disciplinary siloes with the point of need so that linear thinking becomes spherical thinking. Paul said that convergent manufacturing involves "superprocesses" involving many separate traditional processes for which new design methodologies are critical. He suggested formulating the requirements before designing the process: What is the desired product? What is the annual production quantity? What material systems are needed? Stebner noted that during the pandemic, commercial supply chains were not robust enough to make personal protective equipment and respirators, but universities and individuals with printers could enter this supply chain and meet it at the point of need. This demonstrates the usefulness of a flexible supply chain to optimize at the point of need, although challenges arise in how to govern, certify, and ensure quality and data security. He added that military deployments and space missions also demonstrate the importance of the point of need, where the options are to wait 5 months for a capability to arrive or use what is available.

Rachuri inquired about the educational training needed to participate in convergent manufacturing. Sealy explained that although most universities have secured a metal additive manufacturing system over the past 5 years, it is too complex and unsafe for many at the bachelor's level to use, which raises questions about how students will be trained to do metal additive manufacturing. To expand convergent manufacturing, he continued, more accessible and lower cost systems would lead to increased educational opportunities at the undergraduate level and make it less difficult to hire people with metal additive manufacturing skillsets. He asserted that a diversity in backgrounds and experiences among experts is essential to further convergent manufacturing. McCorry echoed the notion that there is significant demand for education and workforce development. Although advanced degrees are important for manufacturing, technicians would also benefit from more and better training. Her team is engaged in efforts to excite K–12 students about the opportunities in manufacturing careers, as well as efforts to reskill technicians. Because manufacturing tools are being continuously developed, she noted that it is difficult to determine what skillsets are needed, and hiring qualified people remains a challenge throughout the ecosystem.

In closing, Rachuri invited the panelists to share their key takeaways from the session. Paul commented that with so much open space for tailoring material properties, engineers need to grow in their knowledge of materials science and material design. The required culture change emphasizes the need for cross-disciplinary education to address this gap. Focusing on the importance of process control for tailoring microstructures within components, he cautioned against underestimating the challenges of developing software to implement process control. Stebner said that AI and machine learning can tackle any problem with statistical relationships and enough samples taken to estimate those statistics, and he pointed out a lack of evaluation tools for hybrid additive manufacturing. He posited that better statistical models would lead to the scaling of information value versus information speed. In the near term, he suggested increased attention to information fusion, verification, validation, and uncertainty quantification. Sealy remarked on the opportunity to use AI and machine learning to help solve optimization problems in hybrid additive manufacturing, although this process has to become simple enough that an advanced degree is not needed. McCorry championed the value of the convergence of minds, as well as standards and control of data to enable distributed manufacturing.

PANEL 4: DESIGN AND MODELING OF HYBRID MANUFACTURING PROCESSES

Julie Chen, Vice Chancellor for Research and Innovation, University of Massachusetts Lowell

Chen emphasized that funding for fundamental research and development has encouraged the creation and evolution of models amidst the modification of materials and the emergence of more complex structures. As these models continue to evolve, AI and machine learning play an important role; for example, additive manufacturing processes and materials combinations are becoming so complex that machine learning coupled with physics-based models offers a means to optimize and move beyond the make-and-break process and product development stage. She described the complexity of a current Army Research Laboratory–funded project, which has a plastics engineer, a mechanical engineer, and a computer scientist working together to develop a model and process for one manufacturing capability.

Chen highlighted the Fabric Discovery Center at the University of Massachusetts Lowell, which is supported by the Commonwealth of Massachusetts as well as three Manufacturing USA Institutes (Advanced Functional Fabrics of America, Flexible Hybrid Electronics, and ARM), to demonstrate the value of collaboration in the creation of products or systems. Despite the Center's strong modeling capability to make an organic photovoltaic fiber and weave that fiber into a fabric that could be put into a soldier's uniform, this process is complicated when there is a photovoltaic fiber that needs to be connected to power the device for the soldier. Noting a gap in the development of modeling capabilities at the systems level, she explained that less funding has been available for connectors and system-level work (especially how to model behavior after developing a product)—and few of the sensors created in the laboratory are ever used in the field. She added that it is important to consider how to create the smallest unit that could be accessible for warfighters in the field. While it is possible to additively manufacture a semiconductor chip, it would not be very efficient; the alternative would be to have access to many chips and sensors and use additive manufacturing for the connections and packaging in the field.

Chen suggested the following discussion topics on the challenges for design and modeling of hybrid systems: (1) interconnects, interfaces, packaging, and mixed materials; (2) standards, test methods, and material databases; and (3) workforce development. She said that manufacturing has a reputation of not being a desirable field because people only think of "dirty and dangerous" manufacturing from many decades ago, and technicians through PhDs are in demand, including a broader and more diverse population within those fields.

Mark Benedict, Computational Materials Scientist and Program Manager in the Propulsion, Structures, and Industrial Technologies Branch, Manufacturing Technology Division, Materials and Manufacturing Directorate, Air Force Research Laboratory (AFRL)

Benedict explained that most manufacturing for the Air Force has to be qualified for air worthiness, which is a rigorous process related to stability, producibility, characterization, predictability, and maintainability. Modeling and advanced design have the potential to accelerate the acceptance of advanced manufacturing concepts, he continued, particularly in convergent manufacturing.

Benedict described DoD's opportunities in convergent manufacturing related to (1) persistent design, (2) qualification and certification for a unique part, and (3) iterative codesign. First, he reflected on his experience supporting many legacy applications for which the original design data were from the distant past or were lost. When so few data are available to replace a part, inferences have to be made and different advanced techniques used to create new parts. As almost every aspect of the design process becomes digital, persistent design is possible; however, each expert has a modeling stack that does not integrate well and does not outlive the production of the part. To achieve persistent design, he said that data should be co-located so that designs can live in the future and become live entities that can be updated and modified, instead of being frozen or forgotten. Persistent design thus requires coding existing knowledge in the design space into models that can live for significant periods of time.

Second, questions remain about how to best qualify and certify a unique part (i.e., a lot size of 1). Predictability is key, Benedict continued, and modeling is integral to accepting the risk of the use of that part. A stack of models (e.g., microstructure models, process models, performance models) could be brought to bear to bring knowledge and insight into the potential quality of the part. His moonshot is to have flexible convergent processes that respond to a perceived operational need with a new and novel solution, accept the risk of use on the first part produced, and allow that to change as the mission evolves.

Third, Benedict discussed the concept of iterative codesign, which does not yet exist for multiple processes. He described an opportunity to make near-term investments that would significantly impact convergent manufacturing: the processes would be aware of the needs of what precedes and will follow them, and an iterative process would occur to determine the best article to produce at any one stage in the process to reduce total system delivery time, to increase quality, or to reduce the cost of the item being produced.

Paul Witherell, Mechanical Engineer, Measurement Science for Additive Manufacturing Program, Systems Integration Division, Engineering Laboratory, National Institute of Standards and Technology

Witherell offered a systems perspective of design and modeling for hybrid manufacturing processes. He explained that systems integration activities have long benefitted from and contributed to maturing design, modeling, and simulation capabilities (e.g., virtual to virtual and virtual to physical). The evolution of systems integration can be characterized by the technology, the application, and the problem: technology acts as a driver for requirements, applications act as a driver for scoping domain needs, and problems evolve with new technologies and applications. Key characteristics of hybrid manufacturing through a systems perspective could include increased use of autonomy as well as multiple scales, materials, lasers, and machines.

Witherell turned to a discussion of systems technologies and applications in hybrid manufacturing. As technologies continue to advance, hybrid enablers include new laser systems and other processing technologies, advanced sensors and sensor networks, new automation capabilities, new materials, faster communication with improved wireless access, improved computational capabilities, new information paradigms, and new data analytics. These technology advancements lead to new systems challenges such as increased on-demand data access and storage; real-time system-to-system communication; real-time network (re)configurations; real-time data analysis with explainable results; varying data structures with increased data heterogeneity; and increased redundancies in instructions, observations, and behaviors. The desired platform characteristics to overcome these challenges include local, edge, and cloud support; on-demand access to relevant data; transfer learning capabilities; data compression;

information security; established baseline truths; a unifying data structure for disparate data sources to capture convergence; and a semantically unifiable structure.

As technology matures, digitization progresses, and new applications emerge, Witherell continued, hybrid enablers include new tooling requirements; new machine-to-machine interactions; integrated inspection; new (multi)material delivery and removal systems; scaling of processes/deposition rates in real time; process monitoring, diagnostics, and feedback systems; and accounting for the human-in-the-loop. These emerging application areas present new systems challenges, such as real-time, system-to-system communication; process interruption and control; machine health and prognostics monitoring and communication for machine, build, and facility; awareness between systems' behaviors; and local and global response control to changing behaviors. Desired platform characteristics include data and decision convergence support, real-time automatic reconfigurability (virtual and physical), well-characterized and integrated behavior models, integrated safety features, integrated security features, and standards-based communication between systems.

Witherell emphasized that advanced hybrid manufacturing systems extend beyond the additive and subtractive. Advanced hybrid manufacturing systems create unique systems challenges, which can be overcome by solving evolving systems problems: these problems become increasingly complicated as the components of the system continue to increase in size, complexity, and scope while increased demands are placed on control. He stressed that modeling and simulation are key enablers and benefactors, and are necessary for problem formulation and resolutions. Modeling and simulation solve systems problems through activities such as supporting systems integration, developing systems interfaces, enabling communication between systems, understanding and facilitating system scaling, performing system optimization, defining system structure, understanding and predicting systems behavior, and assessing system performance. He added that verification, validation, and uncertainty quantification are critical.

John Keogh, Director of Engineering, LIFT

Keogh explained that technology used for instruments such as spectrometers and radio telescopes demands a multidisciplinary approach toward hybrid systems. A synthesis among various disciplines' capabilities forms an overall functioning system that could do something more complex than what the individual components could do. His vision of convergent manufacturing includes materials processes (i.e., additive, subtractive, metamorphic, or transformative), the digital systems that integrate them, and the workforce—convergent manufacturing requires accurate and careful problem definition *before* identifying the materials processes, digital systems, and talent, which is a task on which industry could improve.

Keogh shared his overall approach to design and modeling for hybrid manufacturing processes. Problem definition is typically a synthesis between physical systems (the "napkin sketch" to begin to design the machinery or capability) and virtual systems (the modeling and simulation, which is a significant knowledge gap). Simulation requirements are then defined for the process and the material, and a preliminary digital thread is developed. The next steps are to monitor key metrics, manage and interrogate data, perform virtual commissioning to optimize and simulate the hybrid process, iterate (i.e., alternate between the physical and the virtual until a solution to address the original problem statement emerges), and either build the physical system or continue to iterate on the digital twin to improve function. He reiterated that a holistic approach toward hybrid manufacturing integrates many disciplines to solve a specific problem.

Keogh asserted that the successful execution of hybrid manufacturing revolves around people (see Figure 3.1). He suggested continuous and repeated movement through the following cycle to optimize parameters toward certification: a model or a digital twin, process parameters that interface with the physical process to drive the system, in-process monitoring, big data, machine learning and AI, simulation

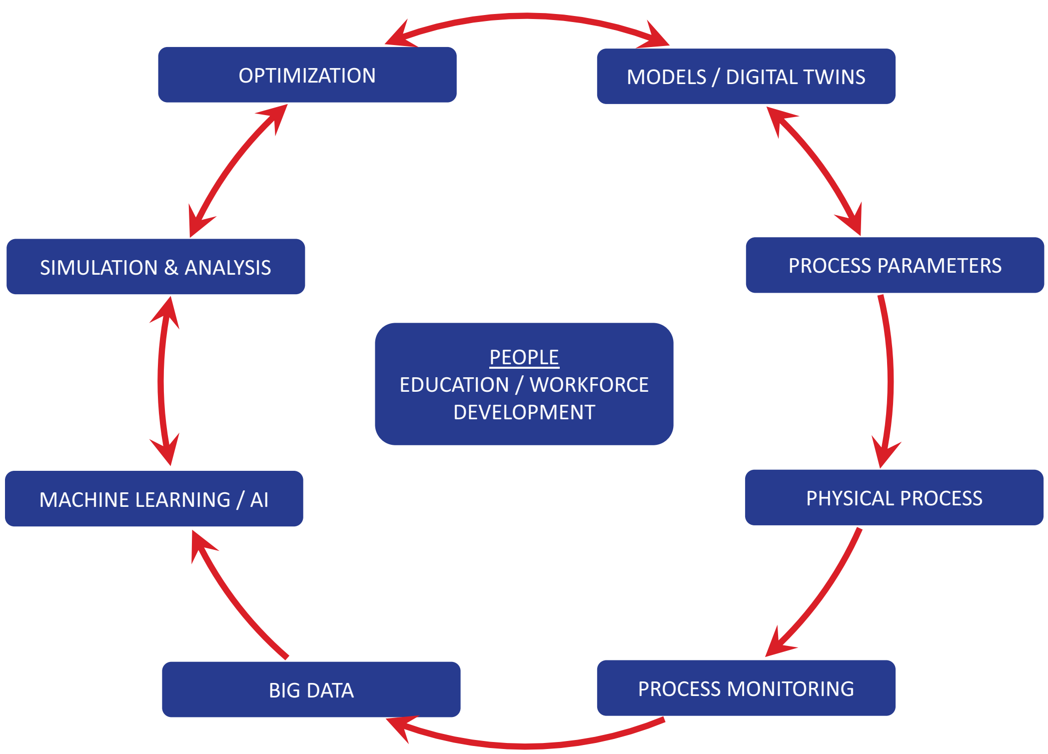

FIGURE 3.1 Execution of hybrid manufacturing. SOURCE: John Keogh, LIFT, presentation to the workshop, November 19, 2021.

and analysis, and optimization. Education and workforce development are critical, as each node demands competent personnel.

Keogh described a current LIFT hybrid manufacturing cell with an additive/subtractive approach that is working toward monitoring thermal and melt pool data, torch parameters, and machining chatter, and feeding those data back through a centralized data hub that is interrogated with machine learning algorithms to improve function. Moonshot projects include any synthesis of additive, subtractive, or metamorphic capabilities to control the thermal history and microstructure of components, which could provide information on the properties that could be yielded and subsequent performance. He mentioned other innovative work under way to achieve a software- or process-agnostic approach toward a fully integrated tool chain for computational materials engineering—a middleware wrapper that could accurately and thoughtfully pass data between various software packages to move across the chemistry-process-microstructure-properties-performance continuum would be very impactful.

Question and Answer Session

Serving as session moderator, Kelly reiterated that problem definition continues to be challenging, especially given the number of disparate fields with different vocabulary, tool kits, and understanding. She asked about best practices to define explicit requirements and problems, as well as about tactical approaches to improve education and workforce development so that the next generation is ready to define problems clearly from multiple angles. Keogh observed that problem definition is situationally dependent, but, in general, a clear approach to the problem requires understanding system nuances and asking a wide range of questions. Chen remarked that researchers are often unaware of DoD's problems; increased communication between those researchers and people in the field would help better define problems. In terms of education, students become more excited and engaged when they are presented with real-world problems. Kelly expressed her support for problem-based learning, which is also a step toward creating better requirements from the early stages of a project. Benedict championed persistent design and noted that model-based definition for requirements (instead of fixed requirements) allows some flexibility in creating a system or component. Witherell emphasized the need to understand the problem for which a digital twin is being developed. Clearly articulating the problem makes it possible to capture and communicate the right information and to focus on solving one problem instead of trying to address everything at once or nothing at all. Modeling and simulation are key to solving specific problems, he continued, but a problem has to first be formulated in a way that a machine can understand.

Malshe wondered whether mechanical modeling could be an effective on-site tool to augment a soldier's ability to quickly respond to an emerging situation.

He also asked if a digital twin could integrate in real time with little latency so that modeling databases could drive processes to respond at the point of need. Keogh remarked that although it depends on the intention and the situation, accurate programming of decision-making algorithms is essential. The automation of modeling and simulation is limited computationally and in terms of the ability to capture human decision-making processes. He said that a well-refined decision tree is still a distant goal. Benedict noted that some real-time capabilities supported by cloud computing resources are available, although not yet on the battlefield. He envisioned a future state with large computational resources and edge devices or wearables that can interrogate the environment and receive decision support using modeling and manufacturing knowledge. Chen endorsed the notion of decision *support*, which provides guidance so that the human does not have to sort through a large volume of information and can focus on what is most important. Malshe highlighted the opportunities to unite modeling talent and knowledge in real time for systems-level decision making at the point of need via convergent manufacturing. Witherell reiterated that the digital twin is also situational, because changing environments affect decision making. Thus, one could sensor surroundings, model them, and embed them in the simulation to help inform appropriate behavior and determine corrective action.

Kelly asked how to reframe the design and modeling of hybrid systems when targeting specialized applications (e.g., a lot size of 1). Benedict replied that AFRL is working on advanced demonstration concepts that embrace risk and allow for novel approaches (e.g., modularity, a Lego-like approach to manufacturing). The goal is to open the design space to embrace variability in the available manufacturing process and materials as well as the perceived need; however, tools do not communicate well with each other, which creates a challenge. Witherell noted that if the goal is reconfiguration, the first step is to consider how the available material could be repurposed to provide a different function. The introduction of hybrid processes offers new options, so different levels of composability and modularity have to be considered. Keogh supported having a well-developed modeling and simulation cycle and history coupled to the manufacturing process, as well as certifying the process itself, to advance toward non-destructive certification or qualification of components in low batch numbers. Chen suggested thinking about how to create an opportunity for many types of companies and researchers to offer new ideas to solve the same problem; making it easier to exchange different variations on a particular theme will encourage more creative and innovative problem solving.

Kelly invited the panelists to share their key takeaways from the session. Chen asserted that workforce development is a top priority. It is also important to understand multiprocessing, multifunctional, and multimaterial systems (i.e., how the part is made and how it connects to the rest of the system). She pointed out that university funding often does not support an across-the-system perspective even though manufacturing is a systems problem, and suggested that universities exert more effort toward the systems approach and eliminating siloes between disciplines. Keogh noted the lack of connection between industry requirements and what is being taught in the university classroom. He also supported more multidisciplinary education to better understand hybrid systems and the future of advanced manufacturing. Benedict explained that design fulfills a requirement, and modeling informs the risk of achieving that requirement; risk acceptance is key to moving faster. He advocated for a new phase of manufacturing, in which the voice at the point of need is amplified: the flight line knows what it needs and what risks it is willing to take, which should be communicated to the manufacturing floor. Witherell highlighted the important role of standards for systems with many moving parts, although specific hybrid manufacturing standards have not yet been developed. Kelly added that standards around a data management strategy would also be valuable.

GROUP QUESTION AND ANSWER SESSION: SCIENCE, ENGINEERING, AND APPLICATION GAPS

Moderator Amy Peterson, Associate Professor of Plastics Engineering, University of Massachusetts Lowell, asked the panelists to discuss successes in and areas for improvement with democratization of innovation. Sealy responded that lowering the cost of equipment would improve democratization of convergent manufacturing and serve as an important step in building the workforce. Benedict commented that making design tools more accessible and affordable allows people to become more comfortable with them. He reiterated that standards are the next step and advocated for government investment in those standards. Witherell added that standards development and participation enable a shift in mindset toward democratization. Chen acknowledged the benefit of more people at different levels of the workforce learning how to use tools, especially via retraining in small businesses. Acquiring lower-cost tools is important, she continued, but meanwhile people should have the opportunity to engage with more expensive tools on a trial basis (e.g., a company that is experimenting and is not ready to convert to new equipment). McCorry mentioned regional hubs that create opportunities for people to test out equipment. She also noted that when the Manufacturing USA Institutes were launched, a standards coordinating body was formed, which accelerated timelines for the development of new standards in regenerative medicine. She asserted that more standards for integration would be useful. Keogh posited that democratization of equipment and software is key for hybrid or advanced manufacturing—for example, plug-and-play capabilities and better education on integration. Because the high cost of and limited access to software continue to present challenges for those in the manufacturing space, particularly the small- and medium-sized companies, he proposed developing better partnerships with software providers and perhaps offering trials of software packages.

Peterson posed a question about a moonshot related to iterative codesign. Benedict described a 20-year vision for an all-electric air vehicle with an aggressive price target. A smaller moonshot would be a design that could host a modest payload for a certain distance with a fixed cost target, realized with trade-offs between exquisite design and affordability. Most of the cost savings are in the integration of manufacturing processes. Peterson also asked whether intelligent manufacturing processes could create material substitutions to avoid the use of harmful chemicals. Keogh gave two examples of emerging approaches toward mitigating hexavalent chromium pollution: (1) the application of cold spray for thin layer deposition and cladding with metallic chromium, and (2) the use of ionic liquids that allow the use of various chemical forms of non-hexavalent chromium for electromechanical deposition. He championed applying historical knowledge to contemporary problems to achieve cutting-edge manufacturing. Benedict discussed a mirror system being designed by Raytheon with advanced manufacturing to topologically optimize additive designs with a conventional aluminum. Although the result creates a modest penalty for performance, other trades can be made to offset it. While this project demonstrates that it is possible to displace an unwanted material, he cautioned that sometimes displacing the material is not the best approach. Witherell added that the digitalization of manufacturing makes it possible to choose functionally graded materials and design at the microscale to achieve results at the mesoscale and macroscale.

Peterson inquired as to whether convergent manufacturing takes the full life cycle into consideration or if there is a risk that one-off designs are going in the opposite direction. Stebner explained that this question is being explored in the Advanced Manufacturing Pilot Facility at Georgia Tech, where they consider recycling integral to the characterization, the feedstock, and the widget. The difficulty with one-offs is qualification, and a challenge with convergence is doing certification and qualification simultaneously across disciplines, materials, parts, and build paths. He said that thought leaders and innovators at the top level as well as regional depots and small businesses that excel at the point of need could push the field in new, convergent directions. McCorry noted that three-dimensional printing and additive manufacturing are being used to create personal therapeutics that are being filed as one-offs for particular patients, even though the same manufacturing approach is used every time. At some point, she continued, the therapeutic should not be considered a one-off, and the *material* should be qualified to accelerate approvals and avoid the need to run a full clinical study for each *use* of the material.

Peterson wondered about international efforts in convergent manufacturing. Witherell replied that the international community has excelled in collaboration and cooperation on standards development. He referenced an agreement between

ASTM and the International Organization for Standardization on additive manufacturing, but international standards for convergent and hybrid manufacturing are not as mature. He emphasized the need for investment in new applications for existing technologies. Sealy added that the earliest patents for hybrid additive manufacturing processes emerged from China and the United Kingdom, many of which were driven by aerospace applications. He mentioned that some of the oldest work was published internationally and funded by the military overseas—the United States is lagging.

In closing, Peterson posed a question about strategies to increase the appeal of manufacturing careers among a broader community. Chen emphasized that manufacturing is not only the act of making something but also the pathway to solving challenging technical problems. Keogh stressed that manufacturing offers much opportunity for professional growth, intellectual engagement, and reward.

DAY 2 SUMMARY

Malshe challenged future innovators to be inspired by the opportunity to improve people's lives. At the conclusion of the day's panel discussions, he identified the following as gaps and opportunities for convergent manufacturing:

1. Facilities could connect to achieve and surpass Industry 5.0.[3]
2. The workforce could be trained with experiential learning that is driven by problems, not disciplines.
3. Because the point of need demands functions, siloes could be removed and features and functions could be converged.
4. Modeling could augment soldiers in the field in real time who are making and rationalizing decisions.
5. Low-cost material could be used for high-value functions, increasing accessibility and affordability.
6. Removing a manufacturing factory is a significant step toward democratization (e.g., Mother Nature manufactures without a traditional factory).
7. Existing facilities could reduce barriers to access and create opportunities for equitable manufacturing.
8. Social scientists, economists, and anthropologists could be part of the conversation about democratizing manufacturing, which is not only a technology problem but also a policy problem.

[3] Industry 5.0 is a new production model where the focus lies on the interaction between humans and machines. Industry 5.0 takes the next step, which involves leveraging the collaboration between increasingly powerful and accurate machinery and the unique creative potential of the human being.

Kurfess suggested that these long-term goals could be achieved by leveraging human resources in conjunction with generative design, as well as by leveraging computing capabilities. He emphasized that there is a plethora of paths to the future.

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4

System and Supply Chain: Looking Beyond Industry 4.0

Opening the final day of the workshop series, Workshop Co-Chair Ajay Malshe, R. Eugene and Susie E. Goodson Distinguished Professor of Mechanical Engineering, Purdue University, explained that manufacturing touches every gadget, gadgets touch digits, and digits touch almost every part of society across the world. Because the digital divide furthers the techno-socio-economic divide, he asserted that manufacturing inequities would need immediate attention if social equity is to be achieved. He noted that Industry 1.0[1] created a significant number of job opportunities (and thus the beginning of democratization). During the peak of Industry 2.0,[2] however, there were catastrophic losses in manufacturing jobs, (and thus an increase in manufacturing productivity, and an increase in energy demands and manufacturing).

Malshe remarked that Industry 4.0[3] introduced competition between humans and machines. He described current disparities in technology access across the United States—the cost of inequity is substantial. Although there are a tremendous number of gadgets available, many people cannot afford these products, with the

[1] The First Industrial Revolution began in the 18th century through the use of steam power and mechanization of production.

[2] The Second Industrial Revolution began in the 19th century through the discovery of electricity and assembly line production.

[3] The Fourth Industrial Revolution is characterized by the application of information and communication technologies to industry and is also known as "Industry 4.0." It builds on the developments of the Third Industrial Revolution that began in the 1970s in the 20th century through partial automation using memory-programmable controls and computers.

average earnings in the United States in 2018 at ~$36,000 per capita (Malshe and Bapat, 2020). If the community enables accessible and affordable innovation and manufacturing opportunities, he continued, a society that is technologically, sociologically, and economically equitable could emerge. To achieve this state, he advocated for manufacturing convergence driven by problems at system-of-systems levels. He stressed the value of thinking spherically to extend beyond Industry 4.0 and championed the convergence of length scales, heterogeneous materials, and top-down and bottom-up processes in one platform to augment soldiers' functionality for the future of combat and to reduce dependency on supply chains for critical materials and applications at the point of need.

Malshe invited workshop panelists and participants to once again reflect on three key questions: (1) What is your vision of convergent manufacturing, according to your expertise and experience? (2) What are the knowledge gaps for science, engineering, and implementation of convergent manufacturing? (3) What are one or two "moonshot" projects for convergent manufacturing?

EQUITY

Lonnie J. Love, Corporate Fellow, Energy & Transportation Science Division, Oak Ridge National Laboratory

Keynote speaker Love discussed emerging science and technology (S&T) opportunities that align with the goal to democratize manufacturing. He described his work with additive carbon fiber and composites, machine tools, robotics, and automation in Oak Ridge National Laboratory's Manufacturing Demonstration Facility (MDF), where he has observed synergies among government, industry, and academia. Seventy percent of the equipment placed in this facility is provided at no cost by the companies working with MDF. MDF also works with more than 50 universities. This local ecosystem has generated new technologies and business models; the next step is to expand so that similar types of research facilities could be leveraged across the United States.

Love highlighted several opportunities over the next 15–20 years, particularly for the democratization of energy. The United States has consumed ~100 quadrillion British Thermal Units (BTUs) per year for the past 7–8 years,[4] but its output has increased over that time period; in other words, energy efficiency and productivity are increasing while energy consumption remains relatively flat. With ~22 quadrillion carbon-based BTUs going to the grid, the goal is to eliminate as many carbon-based sources as possible. The automotive industry in particular

[4] Lawrence Livermore National Laboratory, "2019 Energy Flow Chart," https://flowcharts.llnl.gov/content/assets/docs/2019_United-States_Energy.pdf.

consumes ~26 quadrillion BTUs of carbon-based sources (mostly petroleum, some natural gas and biomass); consequently, the government and industry hope to electrify much of the transportation sector over the next 15 years. Because only ~0.03 quadrillion BTUs currently come from the grid to electric vehicles, he continued, it is important to consider the impact that offsetting carbon-based sources with electric sources will have on energy production and energy transmission—transferring from petroleum-based to electric sources would cause strains on but also create opportunities for the grid. In the manufacturing industry, ~22 quadrillion BTUs are from carbon-based sources (natural gas and petroleum) and ~10 quadrillion BTUs are from buildings (residential and commercial); thus, there are significant opportunities to manufacture new materials and for new manufacturing processes and applications as the United States moves away from carbon-based sources for energy. Noting that there are ~67 quadrillion BTUs of waste heat from energy production to energy utilization, he mentioned additional opportunities for recovering waste heat and increasing efficiency of processes, both of which are connected to manufacturing.

Love explained that the 20th century energy landscape emphasized scaling through consolidation. For example, scaling production of electricity meant that a few large power plants were needed instead of many small power plants, which sent power over larger distances and contributed to the growth of the United States over the past 100 years. He stressed that only a few entrepreneurs created this vast energy landscape from production, to transmission, to utilization. One hundred thirty years later, a new and hopefully more equitable paradigm is emerging via "Build Back Better," with the potential for everyone to be involved in energy production, transmission, and utilization. Although large-scale production in the 20th century drove the migration of manufacturing to low-wage nations, Love envisioned a scenario to create equitable manufacturing for the 21st century by locally sourcing and manufacturing materials with a local workforce for local customers—a scenario that could also be applied to energy production.

Love remarked that only ~15 percent of the energy landscape is non-carbon-based. Rapidly weaning off of carbon-based sources would require enormous innovations in production, transmission, and utilization of energy, all of which are manufacturing challenges. Advancements in manufacturing could enable cost-effective, small, modular sources of distributed energy production (e.g., small head hydro; small, local solar or wind sources; and small, modular nuclear reactors). Without having to transmit over a large distance, cost of entry would be reduced for companies, making it easier for new companies to break into the energy sector and for new businesses to be created. To increase the size of the grid in the coming years, he asserted that distributed energy production and local power transmission via microgrids (to increase flexibility and resiliency) are key. This would enable everyone to participate, with each community having its own microgrid.

Love turned to a discussion of S&T manufacturing challenges related to production. Henry Ford's concept of scaling manufacturing with the assembly line demonstrated that the supply chain could provide components to a centralized assembly facility, have a production line that could produce hundreds of thousands of vehicles per year, and distribute the vehicles to dealerships throughout the nation and eventually the world. This process is still used today, although it is now highly automated. However, he pointed out that this is a difficult ecosystem for new companies to enter: not many have access to the billions of dollars needed for an automotive assembly plant. Nevertheless, with the construction of microfactories to print vehicles, it is possible to break into the industry with millions of dollars instead of billions. This approach, which also applies for printing tools and furniture, offers lower cost and increased flexibility. He reiterated the value of looking locally instead of globally to develop new business models through advancements in manufacturing.

Love outlined S&T opportunities to address challenges in infrastructure, as the grid is expected to expand by 75 percent over the next 20–30 years. He referenced Uber, the world's largest taxi company that does not own any vehicles, as an example of how to democratize an industry with an innovative business model.[5] Hence, he returned to his key question: what if we could democratize energy? If every car produces a few hundred kilowatts of energy, but the cars are only used for a small portion of the day, what if those cars could be portable energy sources and connected to the grid instead of only being used for mobility? He posited that cars could become sources of income in terms of energy production.

Love also described S&T manufacturing challenges and opportunities for processes and materials. Welding, for example, is energy-intensive, as is additive manufacturing. He explained that most industrial printers consume ~100 kwh/kg, whereas a desktop printer consumes ~5 kwh/kg, owing to the difference in the oven used to control the residual stress. Transforming from a neat polymer to a carbon fiber–reinforced material eliminates the need for the oven and substantially reduces energy intensity for large-scale printing. He emphasized that these significant changes in energy intensity emerged simply by creating innovative solutions for the process and materials.

Love underscored that the United States is a wasteful society, especially in terms of composites. Instead of discarding those materials and making new materials, he proposed viewing "waste" as a source of revenue by creating value-added products—additional S&T would make it possible to extract and repurpose these materials. Biomaterials in particular offer an opportunity to reduce energy intensity. He mentioned work with the University of Maine to replace carbon fiber (which is energy intensive) with other types of materials (e.g., bamboo) and achieve

[5] Note that Uber is a ride-sharing platform.

similar performance with several applications (e.g., building materials, molds for marine applications, precast concrete structures, wind energy, infrastructure such as utility poles, and tooling). There are additional opportunities to transform energy-intensive industries to more clean and productive industries via waste heat recovery, moving from coal and natural gas to electrical sources, electrolysis and electrodialysis, and microwave and radio frequency processing, for example. He stressed that looking holistically at materials and manufacturing processes to develop new applications reduces costs, creates more environmentally friendly options, and reduces the amount of energy needed for manufacturing.

Love expressed excitement about additional opportunities in large-scale metal printing. The United States experienced a migration of its foundries to other countries, and because it will be difficult to get those industries back, he advocated for the development of a microfoundry. For example, the MedUSA system has multiple robots working collaboratively to grow large steel structures. This fairly energy-intensive approach could be further improved with local processing. He reiterated that more people could participate in business models through advancements in these technologies (i.e., democratization). Focusing on local manufacturing and energy production enables greater resiliency, security, and equity.

Question and Answer Session

Workshop Co-Chair and Session Moderator Tom Kurfess, Chief Manufacturing Officer, MDF, Oak Ridge National Laboratory, noted that even when shifting to a local model, the shipping of raw materials presents challenges. Love described his work with a global injection mold company that makes water bottles, whose facilities in China are being re-shored. Given that the volume of plastic in the bottles is 99 percent air, the greatest volume of import was Chinese air. By having raw materials shipped instead, the material that could be transported in the same volume compared to before increased. He commented on the importance of building business models around the local ecosystem. Kurfess observed that many small enterprises are integrated appropriately with a secure digital thread to address similar challenges.

PANEL 5: SYSTEMS AND PART DESIGN AT THE POINT OF NEED

Scott Reese, Executive Vice President of Product Development and Manufacturing Solutions, Autodesk

Reese explained that although more products are available than ever (~30,000 new product introductions per year), the majority of products fail to meet their objectives (~70 percent do not hit profit targets). Productivity gains in manufacturing are also at an all-time low (~3 percent globally), and it is becoming more difficult to find advanced talent to fill manufacturing jobs (2.1 million remain unfilled) (see Conference Board, 2021; Deloitte, 2021; and Nielsen, 2019). He suggested that the best way to address these issues is to develop a different way to work.

Reese asserted that a linear manufacturing process amidst a proliferation of proprietary data is not agile. As the market demands more innovative products as well as more products manufactured at the point of need, these linear approaches to manufacturing will continue to create challenges. He observed that much data are lost when moving from design to engineering, and workflows are disconnected; this creates inefficiencies and late product delivery, with a less-than-optimized end result.

To achieve the agility necessary to manufacture at the point of need, Reese advocated for convergence of product conception, design, and manufacture into one set of processes. To do this, he continued, the data have to be in the cloud, and the capabilities have to be connected—with mass customization, digital collaboration among engineering and manufacturing teams and customers, and hybrid and additive manufacturing with capabilities to distribute around the world.

Lisa Strama, President and Chief Executive Officer,
National Center for Manufacturing Sciences

Strama noted that the National Center for Manufacturing Sciences was established to increase U.S. competitiveness by accelerating and transitioning innovation. It engages both vertically within a supply chain and horizontally to identify and fill gaps by adopting and adapting technology from one industry to the next. It has an extensive network of thousands of academic, industry, and other partners.

With consideration for systems and design at the point of need, Strama continued, it is important to rethink the traditional manufacturing process, which is primarily sequential with 15–20 steps per part. The equipment and tooling required to process a part could be in the dozens, depending on the complexity of that part, and the process is multidisciplinary (e.g., mechanical, electrical, software). To achieve design at the point of need, this single thread could be reimagined by combining assembly and test into a new process order. Instead of concurrent engineering and manufacturing, she advocated for distributed manufacturing processes with different handling and environmental factors. The point of need also requires the ability to design for maintenance and sustainment and to address these aspects early in the design process. This further redefines the technical baseline to include system margins for accepting fielded part repairs and the necessary trades to be made in the repair and dispositioning process. Routing of parts also introduces new external challenges to a process that was previously controlled internally. She asserted that traditional "make, buy, and source" adopts a wider landscape beyond the four walls of the factory, which leads to more complex security concerns, depending on the type of handoffs made throughout the process.

Strama indicated that the incorporation of the Internet of Things and predictive data analytics is crucial to upfront decision making. Collective intelligence (i.e., factory location and support; requirements, equipment needs, and maintenance; processing times; first-time-through-test yields; and consideration of lost lead time) across all disciplines becomes integral to visualize and virtualize the design process, manufacturing, and the point of need. Establishing a digital thread with full traceability is also essential for maintaining quality controls of the process. However, simplifying a manufacturing process does not guarantee a shorter lead time. She noted that the first-time-through-test yields should drive what, how, and where manufacturing occurs, and being able to predict those is critical in the process. The result could be (1) longer lead times due to the handoffs and increasing costs, owing to the new manufacturing and test required to support the product; and (2) lower yields if increased transportation, handling, or packaging requirements are necessary. With the total cost of the product in mind, it is important to ensure that data are being added to models throughout the process and captured in a digital thread. She suggested including inspection criteria and quality control measures in the model to virtualize and verify across the entire process, while considering the total cost, first-time-through-test yield, and lead time.

Glaucio Paulino, Margareta Engman Augustine Professor of Engineering, Princeton University

Paulino discussed part design at the point of need via multiscale topology optimization for convergent manufacturing. He shared an image of a part (a canopy) designed with topology optimization at different scales, from the microscale, to the mesoscale, to the macroscale. The part has different microstructures that transition in a functionally graded fashion to a face-*x* microstructure (see Sanders et al., 2021). He asserted that topology optimization and its applications are pervasive. Other places where it has been applied include the use of topology optimization in the Airbus A380 aircraft to create a new wing design and the use of topology optimization in the biomedical field to design the scaffold that is implanted into cancer patients.

Paulino emphasized that the selection of different microstructures and different tools leads to varied designs and has a significant influence on functionality. Compatible microstructures are important for manufacturing—for example, a gap in thickness would be incompatible. He and his colleagues designed mathematical techniques that make it possible to transition in a functionally graded fashion from one microstructure to another. Different representations show multimaterial topology optimization data for three-dimensional (3D) printing with continuous microstructural embedding (see Figure 4.1). He explained that although there are

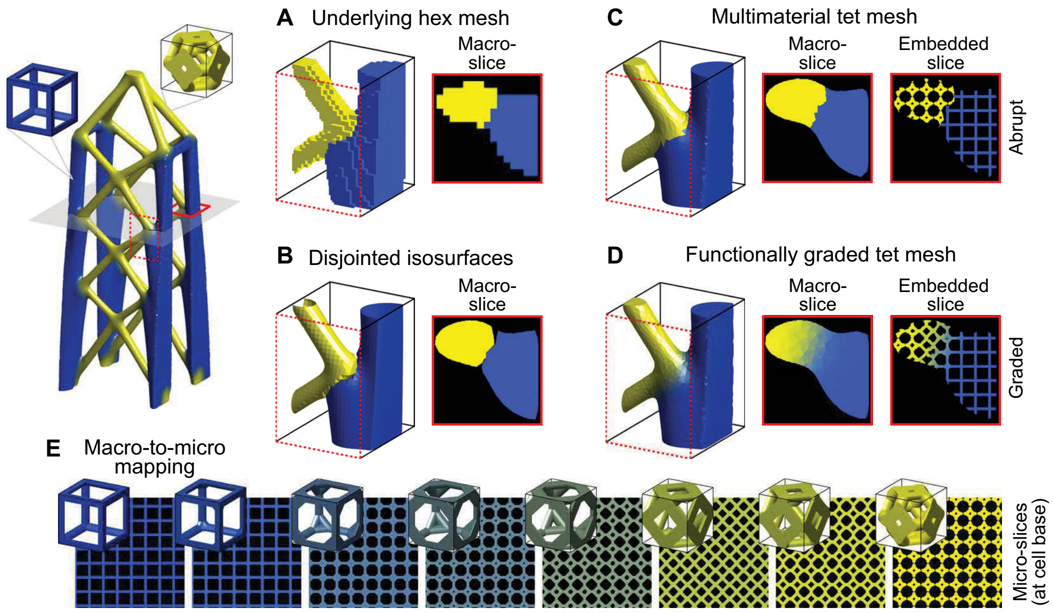

FIGURE 4.1 Continuous microstructure embedding. SOURCES: Glaucio Paulino, Princeton University, presentation to the workshop, November 22, 2021, from E.D. Sanders, A. Pereira, and G.H. Paulino, 2021, Optimal and continuous multilattice embedding, *Science Advances* 7(16), doi: 10.1126/sciadv.abf4838, Copyright © 2021 The Authors, distributed under a Creative Commons Attribution NonCommercial License 4.0.

several approaches to achieve this, one possibility is the use of a functionally graded tetrahedral mesh, which leads to the creation of a functionally graded embedded slice. Macro-to-micro mapping is done via micro slices to allow the printing of exquisite structures and microstructures. It is possible to see transitions between two different regions, for example from a center-*x* to a face-*x* microstructure. Returning to the discussion of the canopy designed with topology optimization, he noted that the material was optimized at the micro-level and the structure was optimized at the macro-level—different microstructural configurations lead to the design of a unique part, and different transitions at different locations reveal the complexity of a design.

Nancy Currie-Gregg, Deputy Director and Chief Technology Officer, George H.W. Bush Combat Development Complex, Texas A&M University

Currie-Gregg discussed systems and part design at the point of need. For remote missions, whether in space or on the future battlefield, supply chain functionality can mean the difference between mission success and failure. Therefore, the ability to perform system and part design at the point of need is a critical element in resilient system engineering for future military operations, which involve constantly evolving threats, increasing complexity of systems and operations, rapid response and high operations tempo, and significant geographical scale of operations. She stressed that research and development (R&D) efforts for new technologies and capabilities would support design at the point of need—this requires an agile, mission-oriented approach to research and innovation with partnerships among academia, government, and industry, as well as continued, frequent involvement of and feedback from military stakeholders.

Currie-Gregg described several relevant manufacturing challenges: the diversity of required skills at the point of need (i.e., design engineering, convergent manufacturing, and maintenance of the manufacturing equipment); initial and continued training of military and civilian personnel; technical protection of designs, manufacturing processes, and equipment and assets; reliability, safety, and security of the materials and of the manufacturing equipment and software; and system engineering practices (i.e., verification of as-built systems and parts, and safety/reliability assessments).

Question and Answer Session

Moderator Craig Arnold, Professor of Mechanical and Aerospace Engineering, Director of the Princeton Institute for the Science and Technology of Materials, Princeton University, wondered how key knowledge gaps could be targeted. To address the complexity of manufacturing at the point of need, Reese first underscored the benefits of embracing new technologies and finding new ways to work. Convergent manufacturing relies on computation for building tools and human cognition for completing tasks in which humans have an advantage over machines. He said that it is incumbent upon companies to provide the appropriate training and reskilling to enable their employees to develop this new mindset and bridge the knowledge gaps. Strama explained that factory technicians are often multidisciplined quasi-engineers who can troubleshoot issues with manufacturing equipment and software before engaging a systems engineer. It is important to recognize that the majority of the workforce that fields and repairs hardware are these multidisciplinary technicians. Thus, she said that both engineers and technicians should be engaged in learning new, convergent methods for design. She advocated for a paradigm shift, including an apprenticeship that offers real-world experience and provides a new type of credential (between a technical certificate and an engineering degree) to the workforce that converges technologies. Paulino noted that exploring the capabilities of well-combined, topology-optimized design and additive manufacturing enables unprecedented innovation. For example, when topology optimization was used in the design of the Airbus A380, savings of hundreds of kilograms for each wing were realized. Topology optimization provides a means to do additive manufacturing to optimize at the material level, at different length scales, and for different functionalities. Currie-Gregg added telemanufacturing to the list of important knowledge gaps. She acknowledged the value of hiring multidisciplinary technicians; however, that is not a feasible solution at the soldier level. She encouraged an innovative approach that uses remote support for design or manufacturing parts at the point of need.

Arnold asked how quality control could be implemented to validate parts made in the field. Strama suggested the use of the digital twin; people in the field as well as their perspectives, environments, and missions could be incorporated in the model for the digital twin to help assess the appropriate trades and determine the best way forward. Reese commented that a manufacturer should be involved throughout the process. Consumers expect products to improve over time and self-heal; if not, they will not buy them and the manufacturer will fail.

Arnold questioned how software or scientists in general handles materials with unknown or evolving properties. Paulino replied that controlling microstructure by means of geometry and porosity creates material representations with different functionalities and properties. If the geometry is explored further at different scales, unique multifunctional material properties could emerge. For example, printing with ceramics is challenging because they break, but microscopic coatings make ceramics ductile and flexible. He asserted that this exploration of new materials with better functionality could lead to better integration into a system or part based on desired objectives. Arnold inquired about how systems would need to evolve to manage multimaterial hybrid structures. Currie-Gregg championed the systems engineering approach, because differences between materials could cause unforeseen failures in a system. To ensure quality control, reliability, and safety of the equipment manufactured in situ, she suggested that point-of-need manufacturing be focused on the augmentation of a capability to promote mission success. Soldiers would have the core capabilities of those systems through traditional means, but when faced with unforeseen challenges and hazards, equipment, additional supplies, and support systems could be manufactured in-situ to increase the viability of mission success. Strama stressed the value of both systems engineering and collective intelligence. Historically, software was run independently and converged later in the process, and flaws were not identified until the final integration and test. Instead, she proposed virtually verifying the software into the entire system early in the process, and then verifying and using collective intelligence to read it back into the previous design processes. Reese pointed out that topology optimization could begin to address this problem. He anticipated that, in 10 years, computers will be used very differently than they are now: engineers will be declaring functional requirements and leveraging compute algorithms to determine the best geometry and material instead of drawing designs. Once human guessing is removed from the process, the need for quality control would decrease, essentially inverting the way that products are designed, engineered, and manufactured.

Arnold highlighted the need for the generation, analysis, and sharing of data; he wondered how to overcome security concerns and maintain manufacturing leadership in the United States. Currie-Gregg remarked that cybersecurity is critical for manufacturing at the point of need; a force could interrupt the supply chain by disrupting data streams, and ultimately disrupt operational capabilities. She suggested new methods to secure large amounts of data—when industry is creating systems for military applications, data have to be more readily available across a wider array of individuals to support those systems in situ and to manufacture components to interface with those systems. Paulino recognized industry's concern for intellectual property but championed the value of data sharing. Advances in data science and machine learning lead to breakthroughs in industry and to solutions for complex problems. He mentioned a program on machine learning for topology optimization: a new system was created where the training of the network was separate from the computations. The more extensive the training library becomes, the better the capability to do intricate designs with minimal resources. This approach could help to avoid the intellectual property issue between academia and industry. For non-military systems, Reese advocated for a shift from closed and proprietary to open and accessible. It is also important for companies to be clear about what they will and will not share instead of identifying everything as intellectual property, which leads to broken workflows and supply chains and creates challenges at the point of need. Strama added that to be successful in designing parts at the point of need, where equipment and resources are limited, constant collaboration with subject matter experts is critical. Models would benefit from more sophisticated antitampering methods, as well as from more information not only to verify for quality assurance and inspection but also to enable better sharing.

Arnold inquired about the best ways to determine risk thresholds for applications. Currie-Gregg proposed using digital twins and simulation models to evaluate operational capabilities and the resiliency, reliability, and safety of systems. This would have to be done concurrently with manufacturing to keep up with the tempo of operations. She emphasized how important it is to increase the probability of soldier success in field operations by supplying at the point of need and decreasing concern about system failure.

Before concluding the discussion, Arnold invited the panelists to share their moonshots for convergent manufacturing. Strama proposed reversing the traditional manufacturing process by reengineering a mechanical rendering of the finished product, going from the components to the systems view and then from the systems to the components view, and infusing knowledge into the design process. Reese described his work with the Jet Propulsion Laboratory in which a computer designed a lunar lander using a "generative design" process: the humans defined the problem and the computer generated the geometry. Paulino proposed taking topology optimization to the next level—for example, is it possible to have properties change spontaneously, to engineer bandgaps by design, or to have materials with topological protection? Currie-Gregg described the need for "design by operators," because asking operators for feedback at the end of the process is not effective. She also suggested a paradigm shift for college-level and community college–level education: applied training should occur in middle and high school because the majority of operators do not spend 4 years in a postsecondary institution. Kurfess emphasized that the human will continue to play an important role in the vast design space, and advanced tools (with the right education and training to use them) will allow humans to explore complex options.

PANEL 6: SUPPLY CHAIN AND SUSTAINABILITY

Erica Fuchs, Professor, Engineering and Public Policy, Carnegie Mellon University

Fuchs provided an overview of an initiative at Carnegie Mellon University on a national strategy for technology. Participants include more than 15 faculty members, whose expertise spans specific technical domains (e.g., semiconductors, energy storage, tool development, data analytics) and areas related to trade, innovation, energy, and policy. She explained that since World War II, U.S. national security and prosperity in a global economy have relied on domestic technical and manufacturing superiority in key technologies. Access to certain supplies and their intermediate inputs can likewise be essential.

Reflecting on a paper from the Council on Foreign Relations about innovation and national security,[6] Fuchs pointed out that the United States lacks data, an intellectual foundation, and a policy roadmap—there is no agreement on what a critical technology is or where to invest once critical technologies have been identified. She noted that approaches in the 1980s and 1990s under the Defense Authorization Act were unsuccessful: long lists of critical technologies were compiled, but none made their way into policy. She has observed bipartisan interest in investing in infrastructure as well as in science and critical technologies, and although most agencies are siloed, technology and large investment decisions would be crosscutting. Thus, the moonshot is to create the intellectual foundation, data, and analytical tools to support the government in designing critical technology, supply chain, and infrastructure strategies that help ensure technology leadership and product access to protect the nation's objectives for security, prosperity, and social welfare.

[6] Council on Foreign Relations, "Innovation and National Security: Keeping Our Edge," updated September 2019, https://www.cfr.org/report/keeping-our-edge.

Fuchs emphasized that real-time situational awareness of domestic and international technology and production is lacking but could be attained with modern data and analytics tools that transform capabilities to connect with Tier 2 and Tier 3 suppliers. She proposed using machine learning and natural language processing tools, in particular, to leverage available data for technological development. However, building real-time situational awareness is insufficient; it is also critical to identify innovations that transform the geopolitical landscape (e.g., redesigning semiconductors and porting them onto different nodes to leverage underutilized production capacity in the world). She said that it is crucial to develop a forward-looking strategy—matching techno-economic tools with supply chain analytics and machine learning and natural language processing—that invests in the innovation that will allow the United States to lead in the future.

Fuchs remarked that, currently, it is difficult to share data and coordinate across individual agencies. She highlighted the value of policy packages and institutional reform that would enable investments across missions. Combining deep engineering expertise with analytic expertise (in operations research and machine learning) and policy expertise could be revolutionary. She asserted that leveraging behavioral science, machine learning, and technical expertise in a way that scales the knowledge to accelerate the commercialization of new advanced materials and processes will be critical in helping innovations transform the geopolitical landscape faster.

Alex King, Professor Emeritus, Materials Science and Engineering, Iowa State University

King explained that a critical mineral or material is defined as having two important features: (1) importance to a particular application (e.g., clean energy) and (2) supply risk (i.e., if a material has significant supply risk but there is no demand, or if a material is vitally important but has no significant supply risk, there is no concern; if a material is vitally important and has significant supply risk, this is problematic) (see NRC, 2008). In 2010, it became apparent that supplies of certain rare-earth elements were in question, owing to increased demand for high-strength magnets for energy conversion and because the rare-earth elements were being sourced almost exclusively from China, which had recently announced export restrictions.

In 2011, King continued, the U.S. Department of Energy (DOE) issued its second iteration of *Critical Materials Strategy*, which identified five rare-earth elements (neodymium, dysprosium, terbium, europium, and yttrium) as critical materials—not yet in crisis but threatened with a crisis. *Critical Materials Strategy* advocated for (1) developing resources that diversify the supply of critical materials; (2) developing substitutes for critical materials; and/or (3) driving reuse, recycling, and efficient use of materials in manufacturing (DOE, 2011). Every 3 years, the

White House's National Science and Technology Council publishes a list of critical materials, which now includes ~50 elements and minerals. King indicated that the five-fold increase in the number of critical materials arises in part owing to the "awareness effect," in which once a problem is identified, everything becomes a critical material. However, he pointed out that there are also real effects. For example, the world's first cell phones required ~35 elements while, five decades later, modern cell phones require ~70 elements; as more elements are used in ever-advancing technologies, more materials are considered essential, and their supply chains may be subject to risk. He shared a timeline from the British Geological Survey's Analysis of Critical Materials, which reviews the degree of supply risk for several at-risk elements. Only two (out of ~26) elements saw their supply risks decline between 2011 and 2015. This demonstrates that more elements are being used and that every element is experiencing an increased level of supply risk, owing primarily to the reliance on fewer sources for elements.

King noted that DOE's strategy of providing alternative materials, alternative sources, or more recycling has not been effective in the majority of historical or current cases. In comparison with man-made technologies, however, the biota of planet Earth are robust against materials criticality because all of their functions and capabilities are provided by fewer than 30 elements, all of which are plentiful (see King, 2020). He emphasized that if fewer elements are used to manufacture products, lower risk is incurred because there are fewer supply chains that need to be managed. If lighter and more readily available elements are used, there is less risk in each supply chain. His moonshot is to reduce the bill of materials for every product engaged in distributed manufacturing. To make products at the point of need where supplies of different materials may be limited, he said that designs should rely on the smallest possible number of elements. He championed Paulino's work on achieving different properties from the same material using 3D manufacturing to produce different microstructural architectures.

Shreyes Melkote, Morris M. Bryan, Jr. Professor in Mechanical Engineering, Georgia Institute of Technology

Melkote discussed the convergence of different physics to transform raw material into finished products that provide desired functionality at the point of need. He described critical needs to realize this vision of convergent manufacturing: plug-and-play system integration capability (i.e., use of additive and subtractive processes and other surface modification technologies to achieve the desired transformation); sustainable materials and energy sources at the point of need (i.e., the ability to use substitute/recycled materials in the field); know-how "on-demand" to operate convergent manufacturing platforms (i.e., human knowledge, data-driven knowledge, model-based knowledge systems, and autonomy); operational resiliency (i.e., rapid reconfigurability of a platform with different physics and the ability to operate in extreme environments); capabilities that enable rapid inspection and certification of products in the field; and training to support a talent pipeline of soldiers, technicians, and engineers who have the knowledge and capabilities to operate complex systems.

Melkote also outlined key knowledge and capability gaps for convergent manufacturing platforms: capability to predict convergent/hybrid process performance (i.e., multiphysics interactions at different length and time scales during processing as well as process-structure-property relationships); process planning tools for convergent/hybrid processes; leverage of sensing and control algorithms for process autonomy; knowledge of potential product performance for substitute and recycled materials; and a secure digital thread to enable the supply of information and knowledge at the point of need.

John Vickers, Principal Technologist, Space Technology Mission Directorate, National Aeronautics and Space Administration (NASA)

Vickers pointed out that much of NASA's technology development is similar to that of the U.S. Department of Defense, for which partnerships with other government agencies, industry, and academia are important. He described a recently released strategy for on-orbit servicing, assembly, and manufacturing (OSAM) for the space superhighway as well as a new Office of Science and Technology Policy and National Space Council interagency working group on OSAM, which serves to coordinate U.S. efforts in R&D as well as policy and regulation for this novel activity. OSAM is the cornerstone technology for creating regional hubs, which are intended to support space logistics, to host payloads, and to provide services. Individual in-space capabilities have their own important convergence, but they also have next-level dependent convergent technologies such as autonomy, artificial intelligence (AI), robotics, and additive manufacturing. He alluded to an upcoming critical design review of a 3D printed 10-m composite beam operating in-orbit, which will deploy a solar array from a satellite. This will be launched in 2023, but in the future, the goal is to move to the 100-m scale, with the aforementioned convergent technologies playing a key role.

Vickers identified in-space manufacturing as a moonshot capability with the potential to initiate a new industrial revolution. A key question remains about how to operate, maintain, and repair systems when not in physical proximity to them. He emphasized the need for an approach, such as a digital twin, to manage convergence. The digital twin could be more than just a bridge between the physical and the virtual worlds, as much more work can be conducted in the virtual space than in the past.

Vickers discussed the phases of the metal additive manufacturing process, noting that NASA spends billions of dollars on an experimental certification process for safety-critical aerospace metal parts. He proposed replacing much of the expensive testing with the digital twin, computational modeling and simulation, and other convergent technologies, such as in-situ monitoring and control, as a way to reduce both time and cost. He remarked that NASA has prioritized additive technology, especially for rocket propulsion systems, and is benefitting from cost and schedule reductions as well as speed increases; but these benefits are significantly negated by the experimental trial and error and inspection processes. Thus, he highlighted in-space manufacturing, digital twin, and digital certification as areas of opportunity.

Question and Answer Session

Moderator Chris Saldana, Ring Family Professor, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, pointed out that logistics are different in a convergent manufacturing system and wondered what tools would best support analyses for future technologies. Fuchs described three capability categories for tools: (1) increasing real-time situational awareness (i.e., machine learning and natural language processing will not reveal which critical technology would help, but they would help identify Tier 2 and Tier 3 suppliers not visible in the supply chain), (2) identifying innovations in which to invest to transform geopolitics (e.g., economics and supply chain, including the capability of firms to pivot instead of stockpiling, and technoeconomic modeling, which is forward looking), and (3) accelerating commercialization of those innovations (i.e., automating manual tasks with machine learning and natural language processing and letting experts focus on creativity and innovation).

Saldana questioned whether manufacturing readiness level is an effective measure for critical manufacturing technologies that should be developed in the future. Melkote replied that if speed is the goal, the traditional systems used to gauge readiness (i.e., technology readiness level, manufacturing readiness level) are ineffective. For example, transitioning manufacturing technology development from the laboratory to production could take 5–10 years. He emphasized the value of rethinking the minimum capability desired and how to achieve that in terms of function. It is also important to understand the capabilities of available manufacturing methods. Technology readiness level and manufacturing readiness level are important checks and balances for safety-critical systems, but if the focus is functionality at the point of need, it is more effective to focus on the minimum capability requirements. King added that technology readiness levels are useful in some cases but misleading in others. For some technologies, it takes a long time to introduce substitute materials owing to the need for qualification of the material or the process. Technology readiness levels reveal how far a path is progressing, he continued, not whether the path is best.

Saldana asked how material criticality analyses are conducted today as well as how to build systems that could perform such analyses. King noted that because the two axes of a critical materials analysis do not have universal metrics, materials are deemed critical fundamentally on the basis of "expert opinion," and analyses are often misleading; for example, rare-earth elements were understood to be critical for wind energy, yet the vast majority of land-based U.S. and European wind turbines do not use significant amounts of rare-earth elements, owing to technology substitution rather than materials substitution—an approach not considered in DOE's *Critical Materials Strategy*. Furthermore, materials criticality analyses are not true risk analyses, which would provide a direct measure of what should be spent to mitigate a problem. The criticality analysis would be useful in highlighting materials that are critical, he continued, but if half of the chemical elements have already been identified as critical then the prioritization is not clear enough to guide mitigation efforts.

Saldana inquired about how to build risk assessment into new technologies. Vickers responded that although technology readiness level and manufacturing readiness level are used routinely at NASA, neither is much more sophisticated than a checklist. Instead, risk analysis, probabilistics, and data analytics tools would better determine product effectiveness and optimality of a design. Risk analysis is a routine approach that NASA takes for safety-critical processes, but a paradigm shift is needed, in which available tools are further integrated. The more distributed and complex the supply chain, he added, the greater the need for sophisticated virtual techniques to precede physical production.

In closing, Saldana invited the panelists to share their moonshots. Fuchs asserted that the United States would benefit from an innovative critical technology analytics program that reports to mission central, is strategic and forward looking, draws data from across agencies, leverages expertise across the nation, and creates public–private partnerships. King suggested reducing risk by reducing the number of supply chains that have to be managed for any manufacturing process, perhaps by half. Melkote noted that machine learning, AI, and digital twin capabilities could address the design-to-manufacturing translation problem. Vickers emphasized that intelligent manufacturing is the moonshot for space.

GROUP QUESTION AND ANSWER SESSION: SCIENCE, ENGINEERING, AND APPLICATION GAPS

Moderator Francisco Medina, Associate Professor of Mechanical Engineering, The University of Texas at El Paso, posed a question about how convergent manufacturing could make better use of recycled materials. King responded that although there are niche cases in which recycling is successful, recycling is often not an effective approach to solving the critical materials problem, in part owing to the power of primary suppliers. If one starts collecting and recycling materials and offers those recycled materials to manufacturers, they have relationships with primary suppliers who will then raise their price as a result. Furthermore, as more material is manufactured and used, the demand for material increases exponentially; if material demand doubles every year and the product has a 2-year lifespan, four times as much will be needed in 2 years, while the amount available to recycle is only one-quarter of what is needed. He emphasized that recycling can neither keep pace with the expanding market nor become the majority supplier, which exacerbates the primary supplier monopoly problem.

Medina asked what resources could be reused in space for convergent manufacturing. Vickers noted that restocking is a significant problem the farther away one is from Earth. Approximately ~40,000 lb. of repair parts and supplies for the International Space Station are kept in low-Earth orbit, ~80 percent of which are unlikely to be used. Therefore, the ability to manufacture in situ will be critical. Resources are available from both the Moon and Mars, and studies are under way to determine the potential for extracting alloys for 3D printing and manufacturing; using bulk materials for the construction of landing pads; and extracting consumables (e.g., oxygen) for fuel and human consumption. He advocated for leveraging more virtual capabilities, owing to the high cost of traveling to the lunar surface for demonstration.

Medina inquired about strategies for success in convergent manufacturing. Fuchs observed that "convergent manufacturing" has several definitions; in this context, she suggested federal funding that is integrated throughout the life cycle of the material (i.e., from discovery, to commercialization, to production, to learning from the products, to reuse). Machine learning offers continual feedback to the discovery process, which makes it possible to leverage information to innovate, learn, and accelerate. Melkote defined convergent manufacturing as employing transformative capabilities to convert raw materials to finished products in a single platform. Since there are many unknowns, he continued, resources should be used to develop test beds to examine variations of convergent manufacturing, to reveal challenges, and to present new visions for convergent manufacturing.

Medina posed a question about potential challenges in the shipping of raw materials. King referenced recent problems in the Port of Los Angeles and emphasized that any supply chain that covers a significant distance across the world is a potential weakness. The farther something has to be shipped, the more difficult it becomes, which is an important consideration for space, especially in terms of risk assessment. He cautioned against the use of a single supplier. Medina presented a question about space mining for critical materials that could be used on Earth. Vickers explained that the materials would have to be incredibly valuable to engage in such a difficult process with such a long, complex supply chain. King added that if mining the ocean floor was too difficult, mining asteroids in space would have significantly more technical challenges.

Medina wondered about the appropriate size (e.g., container or backpack) of the system for convergent manufacturing. Vickers explained that although there are likely many applications for a backpack or a truck in a forward location, one example of a practical convergent manufacturing process is in situ monitoring and control for additive systems to predict properties downstream of additive parts. King suggested reframing the question to determine the right size for the system: What is the most important component or device that could be approached through convergent manufacturing? In other words, he proposed identifying desired capabilities of the finished product and allowing those to determine the type of system. Kurfess added that the size of the system is dependent on the product (e.g., food versus metals) and the energy source needed.

DAY 3 SUMMARY

Malshe commented on the need to redefine "intelligence" in any discussion on convergent manufacturing and introduced the concept of "frugal manufacturing," where less is more, as both intelligent and equitable. He summarized three themes from the workshop series:

1. Converging designs, materials, and manufacturing processes at the user end—how can low-quality and fewer materials as well as resource-constrained processes be used to deliver high-value functions for accessibility and affordability?
2. Converging interfaces for plug-and-play and reliable systems—what are critical interfaces that could converge to manufacture at the asymmetric point of need?
3. Converging skills and knowledge for the operator—how should mindsets be shifted so that thought processes are driven by problem solving for the mission and not structured by disciplines?

He emphasized the value of converging human intelligence, biological intelligence, and AI in a single platform. Kurfess highlighted the varied pathways to achieve convergent manufacturing as well as the flexibility to address materials, processing, and computing power challenges at the point of need. He indicated that the questions raised throughout the workshop about the future of convergent manufacturing are important for the U.S. economy; it is critical to evaluate manufacturing operations, determine how to create a more resilient supply chain, and leverage the defense and civilian industry and workforce to develop a strong manufacturing ecosystem.

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Appendix

Public Workshop Agendas

NOVEMBER 15, 2021

Virtual Workshop

10:00–10:30 Committee, speakers, and staff equipment check

10:30–10:40 Intro by Ajay Malshe, Purdue University

Defense Technology

10:40–11:15 Keynote
Commanding General Darren L. Werner, U.S. Army Tank-Automotive and Armaments Command, Army Materiel Command

Q&A led by Tom Kurfess, Oak Ridge National Laboratory

Panel 1—Multifunctional Materials Design

11:15–12:30	Introductions by Jian Cao, Northwestern University
	Charles Kuehmann, Tesla/SpaceX Julia Greer, Caltech Wei Chen, Northwestern University LaShanda Korley, University of Delaware
	Q&A led by Christina Baker, PPG Industries
12:30–1:00	Break

Panel 2—Heterogeneous Materials Design

1:00–2:15	Introductions by Christina Baker, PPG industries
	Carolyn Duran, Intel Abhir Adhate, Sentient Science Vinayak Dravid, Northwestern University Kimani Toussaint, Brown University
	Q&A led by Jian Cao, Northwestern University
2:15–2:45	Main Q&A session led by Sandra DeVincent Wolf, Carnegie Mellon University
2:45–3:00	Workshop summary led by Tom Kurfess, Oak Ridge National Laboratory
3:00	Adjourn for the Day

NOVEMBER 19, 2021

10:00–10:30	Committee, speakers, and staff equipment check
10:30–10:40	Intro by Tom Kurfess, Oak Ridge National Laboratory

Democratization of Innovation

10:40–11:15	Keynote Tracy Frost, *Director*, OSD ManTech and DoD Manufacturing USA Institutes Q&A led by Ajay Malshe, Purdue University

Panel 3—Hybrid Manufacturing Processes

11:15–12:30	Introductions by Cambre Kelly, restor3d, Inc. Michael Sealy, Purdue University Aaron Stebner, Georgia Institute of Technology Brian Paul, Oregon State University Mary Clare McCorry, ARMI BioFabUSA Q&A led by Sudarsan Rachuri, U.S. Department of Energy
12:30–1:00	Break

Panel 4—Design and Modeling of Hybrid Manufacturing Processes

1:00–2:15	Introductions by Sudarsan Rachuri, U.S. Department of Energy Julie Chen, University of Massachusetts Lowell Mark Benedict, AFRL Paul Witherell, NIST John Keogh, LIFT Q&A led by Cambre Kelly, restor3d, Inc.
2:15–2:45	Main Q&A session led by Amy Peterson, University of Massachusetts Lowell
2:45–3:00	Workshop summary led by Ajay Malshe, Purdue University
3:00	Adjourn

NOVEMBER 22, 2021

10:00–10:30 Committee, speakers, and staff equipment check

10:30–10:40 Intro by Ajay Malshe, Purdue University

Equity

10:40–11:15 Keynote
Lonnie Love, *Corporate Fellow,* Energy & Transportation Science Division, Oak Ridge National Laboratory

Q&A led by Tom Kurfess, Oak Ridge National Laboratory

Panel 5—Systems and Part Design at the Point of Need

11:15–12:30 Introductions by Chris Saldana, Georgia Institute of Technology

Scott Reese, Autodesk
Lisa Strama, National Center for Manufacturing Sciences
Glaucio Paulino, Princeton University
Nancy Currie-Gregg, Texas A&M University

Q&A led by Craig Arnold, Princeton University

12:30–1:00 Break

Panel 6—Supply Chain and Sustainability

1:00–2:15 Introductions by Craig Arnold, Princeton University

Erica Fuchs, Carnegie Mellon University
Alex King, Iowa State University
Shreyes Melkote, Georgia Institute of Technology
John Vickers, NASA

Q&A led by Chris Saldana, Georgia Institute of Technology

2:15–2:45 Main Q&A session led by Francisco Medina, The University of Texas at El Paso

2:45–3:00	Workshop summary led by Ajay Malshe, Purdue University, and Tom Kurfess, Oak Ridge National Laboratory
3:00	Adjourn