**Proceedings of the ASME 2019 14th International Manufacturing Science and Engineering Conference
MSEC2019
June 10-14, 2019, Erie, PA, USA**

MSEC2019-3032

CHALLENGES IN REPRESENTING MANUFACTURING PROCESSES FOR SYSTEMATIC SUSTAINABILITY ASSESSMENTS: WORKSHOP ON JUNE 21, 2018

Arvind Shankar Raman[1], Dustin Harper, and Karl R. Haapala
School of Mechanical, Industrial, and Manufacturing Engineering
Oregon State University
Corvallis, Oregon 97331, USA

Barbara S. Linke
Department of Mechanical and Aerospace Engineering
University of California Davis
Davis, California 95616, USA

William Z. Bernstein and KC Morris
Systems Integration Division
National Institute of Standards and Technology
Gaithersburg, Maryland 20899, USA

ABSTRACT

A workshop on Challenges in Representing Manufacturing Processes for Systematic Sustainability Assessments, jointly sponsored by the U.S. National Science Foundation, the U.S. National Institute of Standards and Technology, ASTM International, the American Society of Mechanical Engineers, and the Society of Manufacturing Engineers, was held in College Station, Texas on June 21, 2018. The goals of the workshop were to identify research needs supporting manufacturing process characterization, define limitations in associated education practices, and emphasize on challenges to be pursued by the advanced manufacturing research community. An important aspect surrounded the introduction and development of reusable abstractions of manufacturing processes (RAMP), which are standard representations of unit manufacturing processes to support the development of metrics, methods, and tools for the analysis of manufacturing processes and systems. This paper reports on the workshop activities and findings, which span the improvement of engineering education, the understanding of process physics and the influence of novel materials and manufacturing processes on energy and environmental impacts, and approaches for optimization and decision-making in the design of manufacturing systems. A nominal group technique was used to identify metrics, methods, and tools critical to advanced manufacturing industry as well as highlight the associated research challenges and barriers. Workshop outcomes provide a number of research directions that can be pursued to address the identified challenges and barriers.

Keywords: Unit Process Modeling, Advanced Manufacturing, Nanomanufacturing, Sustainable Manufacturing, Engineering Education

1. INTRODUCTION

The advanced manufacturing research community has been recently exploring wide-ranging issues attendant with additive manufacturing, bio-manufacturing, nanomanufacturing, and smart manufacturing, among other technical domains. However, the integration of findings across these domains, especially in support of sustainable manufacturing analysis, has become increasingly challenging due to the complexity of information and the domain expertise necessary for its interpretation [1]. Further, the reusability of results is inhibited by the lack of standard methods for interpretation, e.g., reproducing results from life cycle assessment (LCA) remains a challenge [2].

The pursuit of sustainable manufacturing requires balancing competing objectives, including cost, time, and environmental and social considerations. The complexity of modeling these objectives increases during the assessment of process-related manufacturing impacts. Assessing system-level sustainability performance is further complicated by the uncertain emergent properties of systems [3], but it is ultimately vital to comparing alternative designs of products and production systems for sustainable manufacturing. Standard approaches for acquiring and exchanging manufacturing process information will lead to more consistent process characterization and may contribute to a consolidated repository of process models for reuse across advanced manufacturing domains [4]. Improved process

[1] Contact author: shankara@oregonstate.edu

modeling (e.g., using data-driven and physics-based approaches), along with the ability to compose a variety of process models, will ensure more effective communication of computational analytics and may facilitate sharing of sustainability performance data [5].

Engaging industrial and academic researchers in presenting and discussing related work is critical for sharing best practices, exposing gaps in technical and educational research and practice, and developing new research agendas. To facilitate this, two workshops have been organized that focused on research to support modeling of manufacturing processes across production scales (e.g., discrete, batch, and continuous) using a variety of manufacturing methods (conventional manufacturing, nanoscale manufacturing, additive manufacturing, and others) applied in various fields (e.g., mechanical, electrical, chemical, nuclear, biochemical, and biological).

This paper presents motivations for the 2018 workshop, based on the prior 2017 workshop (Section 2). It summarizes the workshop activities (Sections 3-6) and presents an outlook for future directions the manufacturing research community might explore (Sections 7). A full workshop report is forthcoming.

2. PRIOR WORKSHOP OUTCOMES

A workshop on Formalizing Manufacturing Processes for Structured Sustainability Assessments, supported by the U.S. National Science Foundation (NSF), was held in conjunction with the 2017 ASME Manufacturing Science and Engineering Conference (MSEC) of the American Society of Mechanical Engineers (ASME) and the 45th North American Manufacturing Research Conference (NAMRC) of the Society of Manufacturing Engineers (SME) on June 7, 2017. The workshop was announced by the National Institute of Standards and Technology (NIST) in partnership with ASTM International, NSF, and ASME. The objectives of the workshop were to:

1. Model different unit manufacturing processes (UMPs);
2. Apply the new ASTM E3012-16 standard for various UMPs; and
3. Provide models suitable for system analysis based on the reusable standard format.

The workshop attracted several dozen participants from industry, academia, and government labs. Results from this workshop [1] highlighted the need for an open repository of process models. The workshop identified many emerging efforts including both standards and research, and outlined a vision for coalescing these efforts towards an open process model repository. In addition, lessons from the 2017 workshop led to proposed revisions of ASTM E3012-16 [6]. Experience through the workshop revealed a need for more rigorous definition of the concepts presented in the standard to support consistent application and implementation. In response to this need, E60.13, the ASTM subcommittee on Sustainable Manufacturing, is revising E3012 with a more robust information model. The forthcoming information model will facilitate more consistent characterizations of physical artifacts in production systems, leading to better reusability of models and reproducibility of environmental analyses.

Based on 2017 workshop results and findings from ongoing research, a 2018 workshop was planned to

1. Provide a venue for participants from industry, government labs, and academia to exhibit manufacturing process developments of their own interest;
2. Identify educational and research challenges and requirements relevant to manufacturing process model development and validation;
3. Expose the research community to developments in the recent standards for modeling manufacturing processes being proposed to the ASTM E60 subcommittee;
4. Identify candidate models to populate an extensible repository of reusable manufacturing process models;
5. Gather inputs on best practices for sharing, reusing, extending, and composing models of conventional and advanced manufacturing processes for characterizing manufacturing systems;
6. Develop a roadmap that defines key research gaps and strategies for addressing system-level modeling; and
7. Enable sharing of model development experiences for evaluating sustainability performance.

3. 2018 WORKSHOP OUTCOMES

The 2018 workshop, titled *Challenges in Representing Manufacturing Processes for Systematic Sustainability Assessments*, supported by NSF's Nanomanufacturing program, was held in conjunction with the 2018 ASME MSEC and the 46th SME NAMRC conferences on June 21, 2018 at Texas A&M University, College Station, TX, and sponsored by ASME, ASTM International, NIST, NSF, and also SME.

The workshop, comprised of two half-day sessions and an evening poster session, engaged the research community in discussions of emerging topics in advanced manufacturing, nanomanufacturing, sustainable manufacturing, and engineering education. The workshop hosted 46 student participants from the NIST RAMP Challenge competition [7], which included six teams of 23 student finalists. Also, there were two dozen participants from industry, academia, and government labs. As part of the workshop, undergraduate and graduate students were able to present their research in manufacturing process development, process modeling, and sustainability performance assessment.

Expected outcomes of the workshop were to identify needs for UMP characterization to support system-level sustainability assessment, to define limitations in associated engineering education and research practices, and to prioritize the challenges to be pursued by the advanced manufacturing research community to best meet industry needs in adopting and applying analytical methods for improving process and system performance. The workshop outcomes summarized in Section 7 were gathered through brainstorming discussions aimed at identifying the barriers and opportunities in several topics of relevance to advanced manufacturing research.

4. 2018 WORKSHOP OVERVIEW

The theme for the 2018 workshop was *Tracking Resources and Flows through the System*. The morning session began with presentations from a NIST-hosted challenge competition on modeling UMPs. After the student presentations, workshop organizers presented use cases of applications exploring unit process modeling and system composition, including those from industry, research, and educational settings, in the form of lightening talks (Section 5). A moderated discussion after the talks fielded audience comments and questions about the cases discussed and points made.

In the afternoon session, facilitated breakout conversations with the attendees were used to gather inputs on methods, issues, and challenges in sharing, reusing, extending, and composing process models for characterizing manufacturing systems, as well as strategies to overcome these challenges, including engineering curriculum development needs. Organizers applied a modified nominal group technique [8], which typically follows this flow: 1) Introduction; 2) Individual idea generation; 3) Idea sharing; 4) Group discussion; and 5) Voting and ranking of ideas. This approach effectively involved all participants, who arrived with varying levels of experience and perspectives on the topics.

Workshop participation was open to MSEC/NAMRC conference attendees with broad interests in teaching engineering students and conducting basic and applied research in manufacturing. Academic researchers with foci in advanced manufacturing, nanomanufacturing, and engineering education were particularly encouraged to attend. NIST RAMP Challenge participants were also encouraged to attend, since they had practical application knowledge based on their work completed for the competition. Section 5 summarizes the workshop lightening talks, which addressed the workshop theme.

5. SYNOPSIS OF THE LIGHTENING TALKS

The lightening talks were presented by workshop organizers and affiliated subject matter experts. Topics focused on various applications of advanced manufacturing technologies in industry and research. The talks centered around the goal of engaging the research community in discussions of emerging topics in advanced manufacturing, nanomanufacturing, sustainable manufacturing, and engineering education.

5.1 Nanomanufacturing

Khershed Cooper, a program director in the NSF Advanced Manufacturing program, defined nanomanufacturing as the fabrication of nano-scale building-blocks (nanomaterials, nanostructures), their assembly into higher-order structures, and the integration of these into larger scale systems with manipulation and control of matter at the nano-scale. Research challenges were noted in processes, metrics, precision, speed of production, unit processes, and integration and packaging. Nanomanufacturing processes should be controllable, reproducible, repeatable, and reliable. Production should be scalable, affordable, safe, have high yields and efficiency. Nano-products should be of high quality, durable, and exhibit desired performance and functionality. With these factors in mind, appropriate metrics to be evaluated can be determined, e.g., precision placement, feature size, and density.

Machine learning has an integral role in nanomanufacturing processes. For example, raw materials serve as an input for an advanced manufacturing system, which outputs meta-materials that exhibit both performance and quality characterized via *in situ* metrology. These characterizations are inputs to a machine learning node. Customer specifications are also an input to the machine learning node. Outputs of the machine learning node are tuned process parameters that feed back into the advanced manufacturing system for process optimization.

Next, Ajay Malshe, a professor of mechanical engineering at the University of Arkansas, outlined three main drivers for standardization in nanomanufacturing: efficiency, yield, and a diverse operating environment. It is important to maintain a business perspective on standardization by keeping factors such as return on investment (ROI) and productive yield in mind. Efficiency is important to business and should be thoroughly considered in developing standard nanomanufacturing methods.

Future nanomanufacturing research efforts are anticipated in three waves: 1) Nanoparticle-based production; 2) Nano-scale template-based production; and 3) True self-assembly for production. Two eminent objectives are 1) Repeatability, reliability, and reproducibility (3Rs), and 2) Product, productivity, and producibility (3Ps). In particular, nano-products should be scalable and minimize waste.

Current nanomanufacturing limitations can be seen through the lens of industry. One limitation is increasing stress levels in the research lab because of a dramatically changing *invention-to-product* life cycle. Further sources of limitations are the complex solutions required. There is a need to account for the frequency of products changing hands. Additionally, there is a missing link between research and industrial application, which could be mitigated by researchers addressing the industry needs. The overall vision for manufacturing science and engineering research is to support the development of the 3Rs and 3Ps for sustainable nano-manufactured products with ROI.

5.2 Systems integration: Additive manufacturing

Kevin Lyons, a senior research engineer in the NIST Systems Integration Division, presented on additive manufacturing and its components: part design using CAD tools, followed by CAD adjustments for additive manufacturing, part build, part post-processing, verification, and validation. Three main focus area in additive manufacturing include industry drivers, research challenges, and scientific and engineering approaches.

Limited connectivity exists between additive manufacturing lifecycle activities and supply chain activities. There is also a disconnect between additive manufacturing software tools, as well as limited process understanding and knowledge of design decision support [9]. The management and representation of additive manufacturing models and knowledge are isolated in industry, and data is generated individually and is costly through additive manufacturing lifecycle activities without coordination. Additionally, because of the heterogeneous nature of these models, it is difficult to combine these models.

The collection and curation of data remains a main research challenge for additive manufacturing. Further, the diversity of the additive manufacturing operating environment gives rise to some important questions, e.g., *How do researchers integrate across the various models while considering the inherent complexities, underlying assumptions, and constraints?* and *How will the models be coordinated?* Design for Additive Manufacturing (DfAM) [10] is an approach to characterize performance and life cycle considerations using design methods or tools for process optimization. Drivers of DfAM include providing manufacturers approaches to capture design rules for different additive manufacturing processes by using formal representations. Additionally, DfAM provides the architecture to derive design rules in a computer-interpretable way, allowing the effective exchange of additive manufacturing information.

5.3 Sustainable engineering education

Fazleena Badurdeen, a professor of mechanical engineering at the University of Kentucky, presented challenges in educating engineers about sustainable manufacturing. There is a need to demonstrate reduced negative environmental impact through sustainable manufacturing, offer improved energy and resource efficiency, provide operational safety, and improve personal health, all at the product, process, and systems levels. Throughout the lifecycle of the product, the 6Rs (reduce, recycle, reuse, recover, redesign, and remanufacture) are implemented at all points, such as redesign during product manufacturing [11].

Realizing sustainable manufacturing innovations requires developing an educated and skilled workforce. This idea falls in line with the United Nation's Sustainable Development Goal 4 (*Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all*) [12]. A lifecycle approach can be applied to recruit, reeducate, and retrain at all levels for building a workforce pipeline [13]. Additionally, a need for a multi-disciplinary approach, which incorporates convergent research and education, to address sustainable manufacturing challenges has to be emphasized. Various programs and funding opportunities can facilitate efforts to bolster sustainable manufacturing education. For example, the NSF Education and Human Resources (EHR) directorate sponsors programs such as the Research on Learning in Formal and Informal Settings. Programs such as these can promote activities that strengthen Science, Technology, Engineering, and Mathematics (STEM) education and prepare future STEM leaders for a rapidly developing work environment.

5.4 Unit Process Life Cycle Inventory (UPLCI)

Barbara Linke, an associate professor of mechanical engineering at the University of California Davis, presented on the Unit Process Lifecycle Inventory (UPLCI) method [14], which is entering its ninth year of development. UPLCI uses industrial information for a single manufacturing process (a machine) to estimate material inputs, energy use, material loss, and dependencies of process parameters with respect to product design. UPLCI is a multi-institutional effort by Katholieke Universiteit Leuven, Northeastern University, Oregon State University, Purdue University, University of California Davis, University of Michigan, University of Virginia, University of Wisconsin, and Wichita State University.

Creating a UPLCI follows a clear, easy-to-follow template, and has breadth to allow different materials and designs. UPLCI require about a month for development, suitable for graduate class project or part of thesis. Moreover, the Springer journal *Production Engineering,* sponsored by the German Academic Society for Production Engineering, now publishes UPLCI studies. The unit process is decomposed into physics-driven equations that describe the energy and material consumption. UPLCIs can be integrated together to evaluate a manufacturing line leading to a completed part or product. The UPLCI approach plans to develop life cycle inventories for around 100 varied manufacturing processes, of which 31 have been completed, with categories including heat treatment, surface finishing, joining, auxiliary, material conversion, and material reducing.

Another unit process inventory approach was created under the Cooperative Effort on Process Emissions in Manufacturing (CO2PE!) framework [15]. Challenges in UPLCI methods include data quality and availability, how to reduce complexity while remaining generic, managing empirical models, materials dependency, energy-dependence on machine set-up, and an unclear vision of whether auxiliary processes are to be included or not. As supporters of UPLCI continue to solve these problems, the demand for inventorying models will continue to increase.

The UPLCI method provides an appropriate means to identify sources of data, collect appropriate models to characterize manufacturing processes, and evaluate performance for general scenarios. However, the storage of UPLCI requires a formal representation to improve robustness. Relating UPLCI studies with ASTM E3012 is a promising approach forward [16].

5.5 Manufacturing process modeling standards

KC Morris, Information Modeling and Testing Group Leader from NIST's Engineering Laboratory and Arvind Shankar Raman, a graduate research assistant in mechanical engineering at Oregon State University, presented a standards-based methodology for extending manufacturing process models for sustainability assessment. They discussed the current lack of assessment tools, which presents analysis challenges. An operational deficiency of analysis applications to support system-, process-, and machine-level manufacturing decisions limits system analysis capabilities. Data collection and reporting has been one of the biggest challenges for manufacturers in pursuing sustainability assessment.

Efforts to characterize manufacturing processes, including UPLCI and CO2PE!, have focused on developing information models that are distinct and specific to processes of concern, sometimes making them limited in their extensibility to related processes. Often these models must be developed from scratch. A question to address becomes, *How do researchers develop methodologies that allow companies to collect, analyze, and disseminate data-driven conclusions about sustainability factors linked to unique manufacturing processes?*

To realize reusability and extensibility, developing models at the appropriate abstraction is critical. Appending an existing model with information about auxiliary systems, such as exhaust gas pressure control systems, monitoring equipment, and electric boosting systems, would constitute a high order variant of the manufacturing process considered [17]. Similarly, if properly developed, models should remain valid after removing information regarding a particular physical setup to be applied to alternative scenarios. For example, in the case of manual drilling, a robust abstraction would facilitate the characterization of multiple instances of drilling regardless of its functional manifestation, e.g., electric hand drilling or using a drill press.

Existing work can be expanded by characterizing data exchange information or linking variables, to facilitate composability. Additionally, an information exchange framework can be created that enables model composability for manufacturing system characterization. Information validation would be critical to its success. The end state of this work would be realizing the framework in commercial software applications.

5.6 Factory Optima: A web-based software

Alex Brodsky, a professor of computer science at George Mason University, presented on a web-based system for composition and analysis of manufacturing service networks based on a reusable model repository [18]. The architectural design allows for rapid software solution development for descriptive, diagnostic, predictive, and prescriptive analytics of dynamic production processes. This architecture emerged in response to the limitations of decision-making tools and models that enable smart manufacturing.

One such limitation is due to the fact that most analysis and optimizations tools are currently developed from scratch, which leads to high cost, long-duration development, and restricted extensibility. Additionally, numerous computational tools are designed to model individual activities, which require the use of specialized, low-level mathematical abstractions. This proposition for an architecture that addresses these limitations is unique in that the middleware layer was based on reusable, modular, and extensible knowledge bases. However, the architecture lacks systematic design of the unit manufacturing process models, which are based on linear functions as opposed to being physics-based, typically involving non-linear functions.

Factory Optima is a high-level system architecture based around a reusable model repository and the unity decision guidance management system (DGMS). The software framework and system enables composition, optimization, and trade-off analysis of manufacturing and contract service networks. This work is unique in its ability to perform tasks on arbitrary service networks without manually crafting optimization models. Industrial case studies are needed to further develop the architecture. In addition, stochastic optimization-based deterministic approximations, and model calibration and training will aid in improving the commercial utility of the tool.

6. BREAKOUT SESSION AND REFLECTION ACTIVITY

Parallel breakout discussions were facilitated by six subject matter experts (the workshop presenters and I.S. Jawahir, a professor of mechanical engineering at University of Kentucky). Discussions were guided by Karl Haapala, an associate professor of manufacturing engineering at Oregon State University, and focused on advanced discrete manufacturing processes, nanomanufacturing at scale, additive manufacturing, process-level sustainability assessment, system-level sustainability assessment, and engineering education in advanced manufacturing. Scribes captured the ideas generated during three timed sessions. These are summarized in Section 6.1.

Each group discussed challenges and opportunities related to metrics and indicators, models and algorithms, and tools and methods. The groups were prompted to progress through the discussion in three four-minute intervals. Participants distributed themselves among the six topic areas and were given 14 minutes per facilitated discussion round to brainstorm ideas related to the topic. The final two minutes of each round were allotted to reviewing the ideas that were shared and collected. The structure of this breakout session allowed for a continuous flow of perspectives and ideas that were guided toward identifying challenges and approaches to overcoming them for each topic.

The final stage of the afternoon workshop session involved an individual reflection activity, which posed two questions: *What do you see as the most pressing need for advanced manufacturing research or advanced manufacturing education?* and *What do you see as the key next step to be taken to address a pressing research or educational challenge in advanced manufacturing?* Participants recorded their individual responses to these questions on notecards, as described in Section 6.2.

6.1 Breakout session results

The breakout session consisted of small-group brainstorming along three subtopic lines: metrics and indicators, models and algorithms, and tools and methods. The results are reported along the same lines. Discussions revolved around challenges, barriers and solutions to overcome them.

Topic 1: Advancing discrete manufacturing processes

Metrics and Indicators: Challenges include product customization, standardization, and bolstering the flexibility of processes. One key barrier is to connect process level controls and system level metrics. Modeling interdisciplinary/dynamic processes can be extremely difficult.

Models and Algorithms: The complexities in model composition and optimization pose barriers to developing flexible models and algorithms. Participants identified a need to support related product categories with similar models across multiple enterprises. Additionally, transient analysis is required for developing robust models of complex systems, especially non-steady state manufacturing elements. Scheduling intricacies pose a challenge for modeling flexible discrete systems.

Tools and Methods: Participants noted that robots, which are widely used in discrete product manufacturing, can be extensively integrated to achieve process improvements. It was also established that machine learning classifications of problems is increasingly an important in advancing the understanding and optimizing the performance of discrete manufacturing processes.

Topic 2: Nanomanufacturing at scale

Metrics and Indicators: Participants identified some of the key metrics and indicators that need to be considered for nanomanufacturing as follows: fluid type, electron beam power, scan rate, beam diameter, material removal rate, structural resolution, feature size, tolerances, nanoparticles (e.g., silver), medium, roll-to-roll, roll speed, printing speed, ink spread, sintering conductivity, circuit device design, and reactor design.

Models and Algorithms: To model the metrics and indicators identified in the above, participants noted existing models and algorithms. Some of the current modeling categories include fluidic modeling, roll-to-roll modeling, circuit modeling, molecular dynamics, and density functional theory (DFT). Participants indicated that currently models or algorithms for other metrics and indicators of interest do not exists.

Tools and Methods: Participants indicated that some of the common tools for modeling and analyzing nanomanufacturing include MATLAB, scanning electron microscopes (SEM), transmission electron microscopes (TEM), computational fluid dynamics (CFD), finite element method (FEM), finite volume method (FVM). The UMP Builder based on ASTM E3012 [19] was also noted as an enabler of analysis. Key advancements in tools have been achieved using machine learning (for prediction), image processing, and fuzzy logic, with advancements in computing technology and an increase in usage of artificial intelligence techniques.

Topic 3: Additive manufacturing at scale

Metrics and Indicators: The participants identified some of the basic metrics for additive manufacturing: temperature, layer thickness, material uniformity, material density, extrusion rates, feed rates, internal geometries, product dimension constraints, melt pool geometries, and build time. More quality-oriented indicators identified were surface profile, accuracy, surface finish, repeatability, preventative maintenance, a need for post-processing operations, and control of multi-axis equipment.

Models and Algorithms: Some of the challenges identified were limitations to support structure optimization, design features, and fidelity of current models. A need exists for topology optimization and an expression of key performance indicators (KPIs) as a function of control parameters. Participants posited cloud-based process design is needed, by combining parameterized product design with process design.

Tools and Methods: The participants desired tools and methods which are able to provide information on selection of process, build orientation, material. Also the tools should be able to support metrology, in-process monitoring tools, quality, verification, validations, sustainable decision support tools, cross-validation tools, selection of models, cost models, and product design optimization methods.

Topic 4: Process level sustainability assessment

Metrics and Indicators: The participants indicated that metrics and indicators for sustainability at the process level include cost, environmental impact, energy, resources, waste minimization, safety, public policy, personal health, productivity and quality, all essentially addressing the three pillars of sustainability. At the process level, these metrics can be difficult to identify and quantify. Safety and public policy, for example, consider societal impacts, legislative and administrative issues, and ethics, which are difficult indicators to effectively assess.

Models and Algorithms: One of the key challenges identified by the participants is the limited models or algorithms that facilitate assessment of process-level sustainability metrics. Physics- and empirical-based methods were discussed, as well as predictive and optimization methods. In addition, participants identified process planning, sensors, and data-driven models as means to assess and improve process-level sustainability.

Tools and Methods: One important topic that emerged as a necessary element of effective sustainability assessment was education. A strong need for bolstering education was identified to address the growing demands and urgency of awareness and accurate sustainability assessment at the process level. Beyond education, the group identified training, skills, societal influence and behaviors as key tools and methods of importance regarding sustainability at the process level.

Topic 5: System level sustainability assessment

Metrics and Indicators: At the system level, lead time and resource availability appear to be metrics and indicators of worthy consideration, as well as material stability, resource availability, and reliability. Additionally, it is important to consider the interaction of multiple manufacturing processes involved at a system level, as one process usually is fed into the next, and the connection between those processes needs to be seamless to ensure more accurate assessment.

Models and Algorithms: For the systems level, it is important that models for risk assessment and for evaluating system dynamics are developed. Models describing manufacturing processes were found to have an important role in system-level sustainability assessment. Also, game theory can be applied iteratively to identify critical issues. Discussions also raised the point that network models should be developed, in addition to unit manufacturing process models.

Tools and Methods: Current challenges for modeling sustainability at the system level include how to collect and sort data. Methods for defining interactions of processes within the system would be helpful. Obtaining a system-level view is essential for the task of sustainability assessment. Participants identified the potential for application of machine learning in predictive modeling of systems level sustainability. Discussions also raised the idea of diagnostic problem identification through degradation classification.

Topic 6: Manufacturing engineering education

Metrics and Indicators: An indicator for education in advanced manufacturing is an identifiable increase in confidence in manufacturing classes. Participants also suggested that introducing students to advanced manufacturing at a young age (such as through the use of cartoons) would help increase their interests. A current indicator of weak advanced manufacturing education is the lack of sustainability studies in undergraduate studies. Overall, metrics for engineering education in advanced manufacturing are hard to define.

Models and Algorithms: Some of the models and algorithms associated with engineering education in advanced manufacturing include the applicability of sustainability in real life, easy to apply solutions and methods, and circular design. Additional models taught are design for x (DFx), end of life (EOL), and design for manufacturing (DFM) models (e.g., cost, feasibility, and material use). A robust advanced manufacturing curriculum should include systems engineering models.

Tools and Methods: The tools and methods for bolstering engineering education for advanced manufacturing largely include learning in groups and sharing knowledge. This includes overall manufacturing techniques that can be taught using in-house demonstrations. Basic technical skills to be taught include physics-based classes, which participants suggested being taught in conjunction with case studies and interactive in nature (i.e., labs associated with the material). To provoke students' thinking about sustainability earlier, the group recommended tracking sustainability in real life, and relating sustainability impacts to cost in industry. Hands-on exposure to learning the impacts of manufacturing and relating it to sustainability can be achieved using field trips to manufacturing facilities, for example.

6.2 Results from individual reflection

The answers to the first question (*What do you see as the most pressing need for advanced manufacturing research or advanced manufacturing education?*) were quite diverse, but can be grouped largely into the following categories:

1. Link between research and industry (24%)
2. Development of process models (20%)
3. Improvements in manufacturing education (20%)
4. Advancements in technology and methods of scalability (16%)
5. Encouragement of an interest in manufacturing (12%)
6. Validation of models (8%)

Based on these results, nearly a quarter of the participants thought a stronger link between research and industry was the most pressing need. This indicates a lack of research applications in industry, or at least perception of a lack thereof. The second category, development of process models, scored high as well, likely in response to the workshop discussions tailored toward addressing a need for more models to fill current characterization gaps. Somewhat surprisingly, however, validation of said models did not score as high, even though it was consistently presented as one of the more pressing needs throughout the workshop. This may be a result of an overlap between categories, as some responses qualified for a position in the "link between industry and research" category, but may have also referred to validation.

For the second question (*What do you see as the key next step to be taken to address a pressing research or educational challenge in advanced manufacturing?*), the same six categories were applicable to the responses, in a slightly different order:

1. Improvements in manufacturing education (39%)
2. Link between research and industry (17%)
3. Development of process models (13%)
4. Encouragement of an interest in manufacturing (13%)
5. Advancements in technology and methods of scalability (9%)
6. Validation of models (9%).

As demonstrated here, when posed with questions about the future of manufacturing, a large fraction of the participants regarded education as pivotal to its progression. This and the "encouraging an interest" category are closely related; together they assume a majority of responses to the second question. Based on these results, there is consensus that strengthening the advanced manufacturing community in both numbers and ability is crucial to addressing all the research and industry needs posed during the workshop.

7. FUTURE OUTLOOK

The outcomes of the workshop are expected to benefit research programs, for example, by advancing basic and applied research in topic areas such as sustainability of nanomanufacturing processes and nano-products, digitization of continuous and batch processes, development of physics-based models of manufacturing processes, and efficient process and system models for cloud (cyber) manufacturing. Based on the foregoing, the following research directions emerged:

a) Machine learning methods can support fundamental understanding of a variety of discrete manufacturing processes, e.g., nanomanufacturing, and system-level sustainable manufacturing analysis and optimization.
b) Bridging the gap between process-level controls and system-level metrics can enable deeper insight for discrete and bulk product manufacturing. A mapping of product categories that have similar models and can be used across multiple enterprises is also needed.
c) Transient analysis of complex manufacturing systems can lead to robust manufacturing process models.
d) Metrics and indicators for nanomanufacturing are plentiful and span process parameters, material properties, and part characteristics. They should be unified/harmonized to enable technology comparisons.
e) Scalability in nanomanufacturing needs to lead to reduced defects and defectives, improved metrology, and measurement of moving parts and assemblies.
f) Scalability of additive manufacturing requires material, geometry, and support structure optimization methods.
g) Additive manufacturing key performance indicators must be connected as a function of process controls.
h) In additive manufacturing, integration of *in situ* and out-of-process metrology, sustainability decision tools, model selection tools, cost models, and product design optimization tools, are all areas of research need.
i) Societal influences of sustainable manufacturing, e.g., stakeholder behavior, must be better understood.

j) Engineering education approaches are needed to address the growing urgency for accurate sustainability assessment at the process and system levels.
k) Systemic sustainable manufacturing requires insight from risk assessment and system dynamics methods.
l) Robust methods to characterize interactions of processes, activities, and decisions across a system are needed to advance systemic sustainable manufacturing.
m) Diagnostic problem identification can be aided through degradation classification of physical assets.
n) Developing and sharing metrics for improving the effectiveness of learning in advanced manufacturing should be a focus of engineering education research.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation (NSF) under Grant No. 1831141. The authors wish to thank the NSF for their generous support of this research. The authors also extend a warm thank you to the invited speakers, competitors, and supporters of the 2018 workshop.

DISCLAIMER

No endorsement of any commercial product by NIST is intended. Commercial materials are identified in this report to facilitate better understanding. Such identification does not imply endorsement by NIST nor does it imply the materials identified are necessarily the best available for the purpose.

REFERENCES

[1] Garetti, M., and Taisch, M., 2012, "Sustainable Manufacturing: Trends and Research Challenges," Prod. Plan. Control, 23(2–3), pp. 83–104.

[2] Kuczenski, B., Marvuglia, A., Astudillo, M. F., Ingwersen, W. W., Satterfield, M. B., Evers, D. P., Koffler, C., Navarrete, T., Amor, B., and Laurin, L., 2018, "LCA Capability Roadmap—Product System Model Description and Revision," Int. J. Life Cycle Assess., 23(8), pp. 1685–1692.

[3] Suh, S., and Qin, Y., 2017, "Pre-Calculated LCIs with Uncertainties Revisited," Int. J. Life Cycle Assess., 22(5), pp. 827–831.

[4] Bernstein, W. Z., Mani, M., Lyons, K. W., Morris, K. C., and Johansson, B., 2016, "An Open Web-Based Repository for Capturing Manufacturing Process Information," *Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, ASME, p. V004T05A028; 8 pages.

[5] Bernstein, W. Z., Bala Subramaniyan, A., Brodsky, A., Garretson, I. C., Haapala, K. R., Libes, D., Morris, K. C., Pan, R., Prabhu, V., Sarkar, A., Shankar Raman, A., and Wu, Z., 2018, "Research Directions for an Open Unit Manufacturing Process Repository: A Collaborative Vision," Manuf. Lett., 15, pp. 71–75.

[6] ASTM, 2016, "Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes (ASTM E3012)." Conshohocken, Pennsylvania, USA.

[7] Carlisle, M., 2018, "RAMP: Reusable Abstractions of Manufacturing Processes," NIST [Online]. Available: https://www.nist.gov/news-events/events/2018/01/ramp-reusable-abstractions-manufacturing-processes. [Accessed: 19-Nov-2018].

[8] Stewart, D. W., Shamdasani, P. N., and Rook, D., 2006, *Focus Groups: Theory and Practice*, SAGE Publications, Inc.

[9] Lu, Y., Witherell, P., Lopez, F., and Assouroko, I., 2016, "Digital Solutions for Integrated and Collaborative Additive Manufacturing," *Volume 1B: 36th Computers and Information in Engineering Conference*, ASME, Charlotte, North Carolina, USA, p. V01BT02A033.

[10] Kim, S., Rosen, D. W., Witherell, P., and Ko, H., 2018, "A Design for Additive Manufacturing Ontology to Support Manufacturability Analysis," *Volume 2A: 44th Design Automation Conference*, ASME, Quebec City, Quebec, Canada, p. V02AT03A036.

[11] Jawahir, I. S., and Bradley, R., 2016, "Technological Elements of Circular Economy and the Principles of 6R-Based Closed-Loop Material Flow in Sustainable Manufacturing," Procedia CIRP, 40, pp. 103–108.

[12] "Goal 4: Ensure Inclusive and Equitable Quality Education and Promote Lifelong Learning Opportunities for All — SDG Indicators" [Online]. Available: https://unstats.un.org/sdgs/report/2017/goal-04/. [Accessed: 19-Nov-2018].

[13] Badurdeen, F., and Jawahir, I. S., 2017, "Strategies for Value Creation Through Sustainable Manufacturing," Procedia Manuf., 8, pp. 20–27.

[14] Overcash, M., and Twomey, J., 2012, "Unit Process Life Cycle Inventory (UPLCI) – A Structured Framework to Complete Product Life Cycle Studies," *Leveraging Technology for a Sustainable World*, D.A. Dornfeld, and B.S. Linke, eds., Springer Berlin Heidelberg, pp. 1–4.

[15] Kellens, K., Dewulf, W., Overcash, M., Hauschild, M. Z., and Duflou, J. R., 2012, "Methodology for Systematic Analysis and Improvement of Manufacturing Unit Process Life Cycle Inventory (UPLCI) CO2PE! Initiative (Cooperative Effort on Process Emissions in Manufacturing). Part 1: Methodology Description," Int. J. Life Cycle Assess., 17(1), pp. 69–78.

[16] Brundage, M. P., Lechevalier, D., and Morris, K., 2018, "Towards Standards-Based Generation of Reusable Life Cycle Inventory Data Models for Manufacturing Processes," J. Manuf. Sci. Eng.

[17] Shankar Raman, A., Haapala, K. R., and Morris, K. C., 2018, "Towards a Standards-Based Methodology for Extending Manufacturing Process Models for Sustainability Assessment," *ASME 2018 13th International Manufacturing Science and Engineering Conference*, ASME, College Station, Texas, p. V001T05A024.

[18] Brodsky, A., Krishnamoorthy, M., Nachawati, M. O., Bernstein, W. Z., and Menasce, D. A., 2017, "Manufacturing and Contract Service Networks: Composition, Optimization and Tradeoff Analysis Based on a Reusable Repository of Performance Models," *2017 IEEE International Conference on Big Data (Big Data)*, IEEE, Boston, MA, pp. 1716–1725.

[19] Bernstein, W. Z., Lechevalier, D., and Libes, D., 2018, "UMP Builder: Capturing and Exchanging Manufacturing Models for Sustainability," *Volume 1: Additive Manufacturing; Bio and Sustainable Manufacturing*, ASME, College Station, Texas, USA, p. V001T05A022.