NSF Workshop on Sustainable Manufacturing:
Urgent Research Needs and Multidisciplinary Collaboration

The National Science Foundation
4201 Wilson Boulevard, Arlington, Virginia 22230

August 20-21, 2015

Organized by the NSF RCN-SEES Sustainable Manufacturing Advances in Research and Technology (SMART) Coordination Network

1. Overview

U.S. manufacturing, a key component of national economic development and prosperity, has been greatly challenged by competitive trends over the past decade, as global manufacturing competition has begun to shift towards rapid technology innovation and fast implementation in manufacturing, frequent product transitions, and shifting of technical personnel to meet changing needs. Further burdens are being placed on all industries owing to uncertain energy and material prices, possible greenhouse gas constraints, etc. Revitalization of U.S. manufacturing is of utmost importance to the national economy.

In October 2014, the President's Council of Advisors on Science and Technology (PCAST) released a report entitled "Accelerating U.S. Advanced Manufacturing" (AMP 2.0). A renewed national effort has been made to secure U.S. leadership in emerging technologies that will create high-quality jobs and enhance America's global competitiveness. According to PCAST, "advanced manufacturing is manufacturing that entails rapid transfer of science and technology into manufacturing products and processes." The federally backed National Network for Manufacturing Innovation (NNMI) is creating a competitive, effective, and sustainable manufacturing research-to-manufacturing infrastructure for U.S. industry and academia to solve industry-relevant problems. Since 2012, five advanced manufacturing institutes have been created; these are AmericaMakes (focus area: additive manufacturing), PowerAmerica (focus area: wide bandgap semiconductors), LIFT (focus area: lightweight technology), DMDII (focus area: integrated digital design and manufacturing, and IACMI (focus area: Advanced fiber-reinforced polymer composites). Additional institutes will be created (link: http://manufacturing.gov/docs/Institutes-Summary.pdf). In addition to these institutes, U.S. Department of Commerce (DOC) has announced the designation of 24 manufacturing communities as part of the Investing in Manufacturing Communities Partnership (IMCP) initiative (link: http://www.eda.gov/challenges/imcp/). The DOC-led program is designed to accelerate the resurgence of manufacturing in communities nationwide by supporting the development of long-term economic development strategies.

In a PCAST report on "capturing domestic competitive advantage in advanced manufacturing" in July 2012, sustainable manufacturing is listed as a top cross-cutting technology area. According to the DOC, sustainable manufacturing is "the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers."

Over the past decade, as numerous innovative technologies have been developed for designing and manufacturing novel, high-performance products using energy-material efficient processes, a serious concern is how these and future technologies can ensure manufacturing sustainability. This creates a need to pursue fundamental studies on sustainable manufacturing. For instance, the first advanced manufacturing institute, AmericaMakes, created in 2012 has a focus area on additive manufacturing. The researchers and industrial practitioners have already identified a need to address some key environmental sustainability issues with additive manufacturing. An NSF workshop on Environmental Implications of Additive Manufacturing was held in Oct. 2014; the workshop report is accessible via http://www.wilsoncenter.org/sites/nsfamenv/index.html.

2. Workshop Background

In 2012, the National Science Foundation, though its RCN-SEES program, funded the CACHE Corporation a five year project, *Sustainable Manufacturing Advances in Research and Technology Coordination Network (SMART CN)*. At its launch, the Network included 14 domestic universities, 6 foreign universities, as well as 11 national organizations and university centers, and is currently being expanded. The purpose of SMART CN is to bridge the gap between academic knowledge discovery and industrial technology innovation to advance sustainable manufacturing. Figure 1 in Attachment A depicts some key areas for coordinated effort, which should be critical to the manufacturing technology innovations that are commonly stated in known technology roadmaps for various manufacturing industries.

In August 2013, SMART CN organized the Sustainable Manufacturing Roadmap Development Workshop. The participants, specifically selected for their expertise and representing a mix of academic, industry, and government interests, participated in a structured process of information gathering and knowledge extraction. Much of the workshop was conducted in small groups addressing three areas: Technology Development, Process and Systems Management, and Enterprise Management. Crosscutting topics of Workforce Education and Management; Water Management, Land, and Air Quality; and Life Cycle Assessment and Design for Sustainability were addressed by all three groups. Figure 2 in Attachment A shows a functional model used for roadmap development. The groups addressed a vision for future success, its barriers and challenges, and corresponding goals for a sustainable future. The brainstorming discussions led to the identification of 10 key themes that represent high-level needs that should be addressed by the sustainable manufacturing community. The themes include:

1) **Standards and Platforms for Information Exchange**. Standard structures for data and toolsets related to sustainable manufacturing are essential for addressing the key issues in an inclusive and systematic way. Platforms and frameworks that enable interoperability of diverse data sets and tools are prerequisite to addressing the scope of the challenge and supporting common communication.

2) **Clear Definition and Semantic Understanding**. A deep understanding of the terms and scope of sustainable manufacturing is foundational for integrated solutions. That definition should include the creation of a common taxonomy and an ontology that enable a common semantic understanding.

3) **Pervasive Adoption of Sustainability Practices**. The issues associated with sustainability include technical challenges, business process requirements, and a culture of value assessment and investment in sustainability. This key theme embraces all areas of need for pervasive adoption, but focuses mostly on the cultural challenges.

4) **Comprehensive Characterization and Quantification of Manufacturing Processes**. The complete understanding of materials and their interaction in manufacturing processes enables optimized design of products and processes. Quantification of processes is a major factor in product development, and characterization of processes facilitates rapid quantification.

5) **Comprehensive Life-Cycle Assessment**. Life-Cycle Assessment (LCA) has become common in product development. Unfortunately, in many cases, it has become more of an administrative and accounting requirement than a value-added design aid. The adoption of a systems engineering methodology and the inclusion of a rich enabling technology toolset can allow LCA to move forward as a keystone in sustainable design.

6) **Sustainable Manufacturing Education**. The pervasive adoption of sustainability practices requires education of all stakeholders in the global community. This key theme specifically addresses the necessity of sustainability education in all educational disciplines, with an emphasis on the engineering community.

7) **Model-Based Assessment and Control for Sustainability**. A model-rich environment is essential for efficiently developing material systems, products, and processes and for managing the manufacturing enterprise. Model development for LCA, materials evaluation, process development, and all other applications tends to be ad hoc. There is no existing structure to define modeling priorities and systematically fill the voids. The use of modeling systems for process control is, likewise, applied on a case-by-case basis. A coordinated systems approach is needed.

8) **Data and Model Access for Sustainability**. Characterization of materials and processes requires a rich underpinning of data and models. While there are excellent examples of data management, there is no comprehensive system by which data is developed, screened, and managed. The result is that most researchers and developers must invest their energies in data access at the expense of applications development. A shared repository for managed access to data and models to support sustainable manufacturing is needed.

9) **Optimized Design for Sustainability**. A systems approach to product and process design should begin with product requirements and extend, in a seamless digital thread, through the evaluation of alternatives and the selection of the best solutions, to mature designs. The system should be integrated to ensure that best total value takes clear priority over point optimization.

10) **Systematic Sustainability Achievement**. While the key themes are important individually, coordinated implementation of a fully integrated roadmap is required for success. This key theme acknowledges that a well-managed, collaborative effort is needed.

That workshop prioritized specific technical topics in each of the three pillars shown in Fig. 2 of Attachment A. These topics are summarized in Tables 1 through 3 in the same attachment. The workshop report is openly accessible from the SMART CN website (Link: http://www.research.che.utexas.edu/susman/documents/workshop/SMART%20CN_SM%20Roadmap%20Workshop_Final%20Report%20_041514.pdf).

3. Workshop Objective

Sustainability has become a general, critical issue in advanced manufacturing. However, sustainability science is far from exact, and there is a serious lack of theories, methodologies, and tools for pursuing sustainable manufacturing in industries. The communication and collaboration between the sustainability community and the manufacturing community are clearly insufficient. Sustainability problems are always very complex due to their triple-bottom-line-based nature and therefore effective collaboration is required among different disciplines. The Steering Committee of SMART CN believes that it is time for us to organize this workshop, which is designed for leading/active academic researchers, industrial leaders, and governmental officers to review the main challenges in advanced manufacturing. An important objective of this workshop is to identify and prioritize urgent research needs in the field of sustainable manufacturing and to suggest the best strategies for achieving the research goals in order to make a long-term impact on advanced manufacturing.

4. Workshop Format

To ensure the workshop's success, SMART CN formed a Workshop Organizing Committee (see the name list in Attachment B) and held a workshop planning meeting in Dallas, TX on April 24, 2015. The committee reviewed the 34 technical topics identified at the 2013 Sustainable Manufacturing Roadmap Workshop's findings (see Tables 1 through 3 in Attachment A), and suggested eight research topic areas that should be more specifically discussed in this workshop. These areas are listed in Table 4 of Attachment A. Additional important areas may be identified by the participants in this workshop.

The workshop agenda is shown in Attachment C. The two-day workshop will be initiated by a keynote session. The keynotes from the officers in the Advanced Manufacturing Offices of DOE and DOC should stimulate thinking within and across the areas of Sustainable Manufacturing. Two breakout sessions will follow, providing opportunities for the participants to discuss in depth sustainability implications in advanced manufacturing research and practice, and then to identify urgent, specific research and educational needs that are critical in sustainable manufacturing research. The Day 1 program will be summarized through a panel session, during which a number of academic and industrial leaders will provide their views on urgent research needs, and all participants will have opportunities to participate in discussions. The Day 2 program will start with NSF program officers' presentations on NSF funding focus and opportunities. A keynote presentation on a successful national research and educational platform on nanotechnology has been arranged for the participants to learn more about a successful national effort in an emerging area. Following this, a final breakout session will discuss approaches and strategies to achieve the identified research goals. The workshop will end with closing remarks.

5. Breakout Discussion Topics and Group Report

As shown in the workshop agenda, there will be three breakout sessions, each of which has two or three groups for intensive discussion:

Breakout Session 1 – Sustainability Implications in Manufacturing

- Group 1.1 - Tech. Management
- Group 1.2 - Product/process Development
- Group 1.3 - Enterprise Management

Breakout Session 2 – Research and Education Need Specifics

- Group 2.1 - System Design for Sustainability
- Group 2.2 - Sustainable Manufacturing
- Group 2.3 - Sustainable Industrial Networks

Breakout Session 3 – Major Collaboration Needs and Platforms

- Group 3.1 - Multidisciplinary Collaboration
- Group 3.2 - Academic and Industrial Collaboration

While the breakout groups have different technical foci, the Workshop Organizing Committee has designed four general questions for all groups in their discussion. These are:

- Question 1: What are the significant sustainability implications in advanced manufacturing and how can sustainability principles be fully applied in advanced manufacturing innovations?

- Question 2: What are the key fundamental research areas critical to the progress of sustainable advanced manufacturing technologies and how should they be prioritized?

- Question 3: What are the effective approaches for multidisciplinary collaboration among sustainability communities and advanced manufacturing communities, and between academic institutions and industries to achieve the priority research areas?

- Question 4: What kind of major platform could be created to promote national research and educational collaboration in the field of sustainable advanced manufacturing?

Group discussions will be facilitated by group chairs, and each group will have a scribe. After each breakout session, each group will report the findings to the full workshop group. Attachment D shows a complete list of the workshop participants, and Attachment E lists the names for each breakout group.

Attachment A - Summarized Technical Findings at the Sustainable Manufacturing Roadmap Development Workshop in Cincinnati, OH, Aug. 15-16, 2013

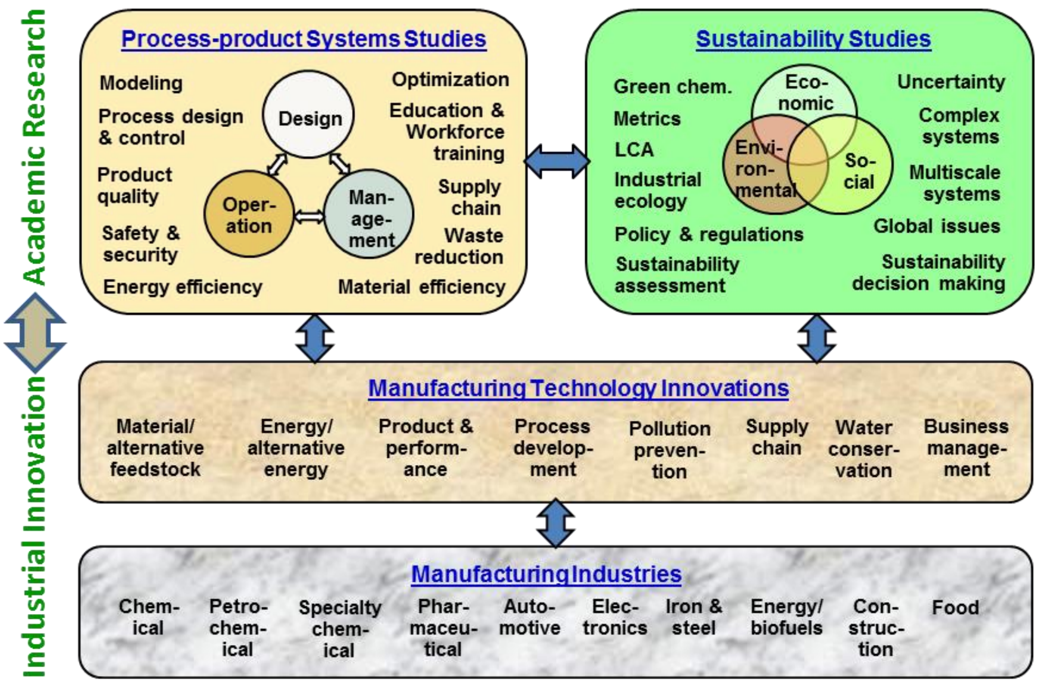

Figure 1. Areas for academic and industrial collaboration.

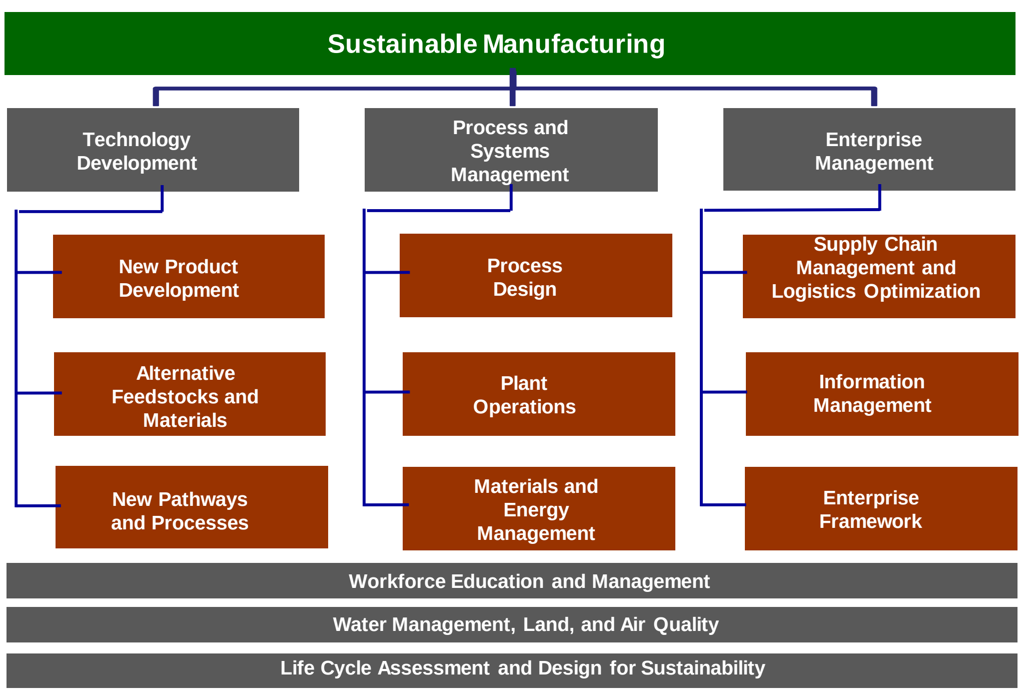

Figure 2. The functional model used for the development of a sustainable manufacturing roadmap at the workshop in Cincinnati, Aug. 15-16, 2013.

Table 1. Research topics identified in the Technology Development pillar at the Sustainable Manufacturing Roadmap Workshop in Cincinnati, Aug. 15-16, 2013.

Rank	Research Topic	Type*
1	Develop comprehensive interoperable LCA and sustainability assessment tools matching the LCA outputs with the inputs for decision-making. Provide a standard structure/framework for defining the needed inputs/outputs for necessary decisions.	A/I
2	Make sustainability thinking pervasive in all academic disciplines	A
3	Develop model-based systems that utilize a complete understanding to optimize the product development process including sustainability issues. Develop models that include LCA based metrics and indicator data for making decisions on sustainability for a product.	A
4	Gather data for a complete understanding of the structure/ property/activity/functionality/impact relationships enables informed design and development. Include product performance and performance against sustainability metrics.	A/I
5	Sustainable manufacturing and product design framework that supports collection of data, decision support and product definition, delivering optimized value added in product development	A/I
6	Develop tools to support MFA (material flow analysis) and SFA (substance flow analysis) to enable reduction, reuse, and remanufacturing of the materials and their substitutes including alternatives that do not recycle	A
7	Improve the sustainability calculation/analysis capabilities across the basic industrial workforce (and all workers) - combination of user friendly tools and education	A
8	Integrate LCA tools with existing and emerging design and manufacturing toolset (PLM plus)	A
9	Develop metrics, tools, data, standards (capabilities and competencies) that enable quantification and trades regarding how sustainable	A
10	Provide coordination of national R&D efforts to define present toolsets, voids and communication failures and focus on building to solution	A/I

*: A – Academic research; I – Industrial research

Table 2. Research topics identified in the Process and Systems Management pillar at the Sustainable Manufacturing Roadmap Workshop in Cincinnati, Aug. 15-16, 2013.

Rank	Research Topic	Type*
1	Develop consensus across disciplines as to a working definition of sustainable manufacturing in terms of tangible, well defined terms that has a common utility	I/A
2	Standardize and make LCA easier (and faster) so that the tools and results can be better incorporated into design	I/A
3	Develop an ability to characterize manufacturing processes that includes the quantification of system boundaries and externalities. Develop tools that include all relevant factors in supporting manufacturing process development.	A/I
4	Systematize the sustainability challenge: Develop a maturity model that quantifies the achievement of sustainable manufacturing. Develop a compendium of methodologies, practices, and tools to support achievement of the goals of the maturity model.	A/I
5	Bridge the scales of modeling from models based in first principles to continuum models	A
6	Better data collection and analysis and better definition of the data requirements for sustainability analysis	I/A
7	Develop sustainability performance standards, not just a design standards	I/A
8	Include social and political implication of sourcing material and energy supplies and consumption	I/A
9	Quantify the scope of sustainable manufacturing related to systems and sectors. Identify the key stakeholders for each system/sector, including societal representation.	I/A
10	Develop modeling tools that predict and model consumer behavior to support the innovation/ideation process, including the reaction to sustainability practices and the extent to which they will respond e.g. paying more for protecting the environment	A/I
11	Infuse sustainability factors into plant design and automation	A
12	Integrate ecosystem (industrial symbiosis) opportunities in materials and energy management	A
13	Develop design capability for control for sustainable design and operation – including stochastic control (uncertainty). This means that sustainability factors are captured in the monitor, analyze and control methodologies and toolsets.	A
14	Include end of life issues such as product reuse, remanufacture, and redesign into the product design process.	I/A
15	Extend present LCA toolsets to include uncertainties and explore the alternative results from various boundary selections	A
16	Find synergistic options and new services (such as product LCA monitoring) that give both economic, environmental and social benefits	I/A
17	Extend energy and material balances to the manufacturing realm for existing manufacturing processes and transformational new processes.	A/I

*: A – Academic research; I – Industrial research

Table 3. Research topics identified in the Enterprise Management pillar at the Sustainable Manufacturing Roadmap Workshop in Cincinnati, Aug. 15-16, 2013.

Rank	Research Topic	Type*
1	Create standards and information platforms (tools/data/information) for a sustainable enterprise	A/I
2	Enterprise Framework Sustainability: Create a sustainability culture that pervades the behavior and decisions of all levels of manufacturing enterprise and its supply chain	I
3	Conflicting priorities: New decision framework to incorporate multiple conflicting (non-financial) objectives in a unified framework, configurable and visible	A/I
4	Better Data: Ensure that collecting new information and current data is accurate, relevant, and cost-effective (cheap, good data?) require on-going maintenance in a cost-effective way	I/A
5	Supply Chain models that include sustainability considerations and externalities along with technical & business issues	A/I
6	Sharing data: Trust: Reporting Sustainability Data across the supply chain	I
7	LCA and Design for sustainability: Create mechanism to assess current manufacturing business decisions against available metrics and tools to select optimal for sustainability.	A/I

*: A – Academic research; I – Industrial research

Table 4. Re-ordered top research topic areas recommended by the Workshop Organizing Committee in April 2015.

Rank	Research Topic Ares in Technology Development
1	Sustainable manufacturing and product design framework that supports collection of data, decision support and product definition, delivering optimized value added in product development
2	Develop model-based systems that utilize a complete understanding to optimize the product development process including sustainability issues. Develop models that include LCA based metrics and indicator data for making decisions on sustainability for a product.
3	Develop metrics, tools, data, standards (capabilities and competencies) that enable quantification and trades regarding how sustainable is.
4	Develop comprehensive interoperable LCA and sustainability assessment tools matching the LCA outputs with the inputs for decision-making. Provide a standard structure/framework for defining the needed inputs/outputs for necessary decisions.
Rank	**Research Topic Area in Process and Systems Management**
1	Develop modeling tools that predict and model consumer behavior to support the innovation/ideation process, including the reaction to sustainability practices and the extent to which they will respond e.g. paying more for protecting the environment
2	Bridge the scales of modeling from models based in first principles to continuum models
Rank	**Research Topic Area in Enterprise Management**
1	Conflicting priorities: New decision framework to incorporate multiple conflicting (non-financial) objectives in a unified framework, configurable and visible
2	Resource and water use efficiency in manufacturing

Attachment B – Workshop Organizing Committee

Luke Achenie	Virginia Tech.
Bhavik Bakshi	Ohio State Univ.
Cliff Davidson	Syracuse Univ.
Mario Eden	Auburn Univ.
Thomas Edgar	Univ. of Texas - Austin
Mahmoud El-Halwagi	Texas A&M Univ.
David Fasenfest	Wayne State University
Yinlun Huang	Wayne State University
Christos Maravelias	Univ. of Wisconsin
Kimberly Ogden	Univ. of Arizona
Mary Rezac	Kansas State Univ.

Attachment C - Workshop Agenda

NSF WORKSHOP ON SUSTAINABLE MANUFACTURING:
URGENT RESEARCH NEEDS AND MULTIDISCIPLINARY COLLABORATION

National Science Foundation, Arlington, VA
August 20-21, 2015

Workshop Agenda

Day 1 - August 20, 2015	
8:00 – 8:30am	Registration/Breakfast
8:30 – 8:45am	Welcome Remarks • JoAnn Lighty, Division Director, CBET, NSF • George Hazelrigg, Deputy Division Director, CMMI, NSF
8:45 – 9:45am	Keynote Session on Advanced Manufacturing • Mark Johnson, Director, Adv. Mfg. Office, DOE • Michael Molnar, Director, Adv. Mfg. Prog. Office, NIST, DOC
9:45 – 10:00am	Break
10:00 – 10:20am	Workshop Objectives and Instruction for Breakout Yinlun Huang (Wayne State U.), Thomas Edgar (U. Texas Austin), Mahmoud El-Halwagi (Texas A&M U.), Cliff Davidson, Mario Eden (Auburn U.), and Bhavik Bakshi (Ohio State U.)
10:20 – 12:20pm	Breakout Session 1 – Sustainability Implications in Manufacturing Group 1.1 - Tech. Management Group 1.2 - Product/process Development Group 1.3 - Enterprise Management
12:20 – 01:00pm	Lunch
01:00 – 01:20pm	Breakout Session 1 Report on Findings and Prioritization
01:20 – 03:20pm	Breakout Session 2 – Research and Education Need Specifics Group 2.1 - System Design for Sustainability Group 2.2 - Sustainable Manufacturing Group 2.3 - Sustainable Industrial Networks
03:20 - 03:35pm	Break
03:35 – 03:55pm	Breakout Session 2 Report on Findings and Prioritization
03:55 – 05:00pm	Panel: Observations on Urgent Research Needs: Panelists: • Ignacio Grossmann (Carnegie Mellon U.) • Gintaras Reklaitis (Purdue U.) • Thomas Edgar (U. Texas Austin) • Timothy Gutowski (MIT) • Sudarsan Rachuri (NIST) • Richard Helling (Dow)

Day 2 - August 21, 2015	
08:00 – 08:30am	Registration/Breakfast
08:30 – 09:30am	NSF Officers' Speeches on Funding Focus and Opportunities: • Bruce Hamilton (Environ. Sustainability, CBET) • Khershed Cooper (NanoMfg, CMMI) • Zhijian Pei (MME, CMMI) • Chris Paredis (ESD & SYS, CMMI)
09:30 – 10:00am	Keynote on Multidisciplinary Collaboration and National Platform: NanoHUB • Michael Zenter, Purdue U.
10:00 – 11:30am	Breakout Session 3 – Major Collaboration Needs and Platforms Group 3.1 - Multidisciplinary Collaboration Group 3.2 - Academic and Industrial Collaboration
11:30 – 11:50am	Breakout Session 3 Report on Findings and Prioritization
11:50 – 12:00pm	Closing Comments
12:00pm	Adjourn

Attachment D – Workshop Participant List

NSF Workshop on Sustainable Manufacturing:
Urgent Research Needs and Multidisciplinary Collaboration

PARTICIPANT LIST

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Attachment E – Breakout Session Grouping

AUG. 20, 10:20AM – 12:20PM

Group 1.1 - Technology Management	Group 1.2 - Product and Process Development	Group 1.3 - Enterprise Management
M. Bagajewicz	L. Achenie **(Chair)**	B. Bakshi
J. Bravo	P. Daoutidis	J. Bradburn
C. Davidson	B. DuPont **(Scribe)**	M. Eckelman
M. Eden	M. El-Halwagi	T. Edgar
R. Helling **(Scribe)**	R. Elms	I. Grossmann
J. Isaacs	T. Gutowski	K. Haapala
M. Mehta	Y. Huang	N. Kralik
K. Ogden **(Chair)**	I.S. Jawahir	P. Mukherjee
C. Piluso	E. Olivetti	J. Rickli **(Scribe)**
J. Seay	S. Rachuri	A. Rossiter
D. Sengupta	G. Reklaitis	D. Sekulic
R. Smith	P. Witherell	G. Thorsteinson
T. Theis	C. Yuan	F. You **(Chair)**
M. Zenter	F. Zhao	

AUG. 20, 1:20 – 3:20PM

Group 2.1 - System Design for Sustainability	Group 2.2 – Sustainable Manufacturing	Group 2.3 – Sustainable Industrial Networks
L. Achenie	J. Bravo	B. Bakshi **(Chair)**
M. Bagajewicz	P. Daoutidis	J. Bradburn
B. DuPont	M. Eden **(Chair)**	C. Davidson
M. El-Halwagi **(Chair)**	T. F. Edgar	M. Eckelman **(Scribe)**
R. Elms	T. Gutowski	R. Helling
I. Grossmann	Y. Huang	N. Kralik
K. Haapala	J. Isaacs	P. Mukherjee
E. Olivetti	I.S. Jawahir	K. Ogden
C. Piluso	M. Mehta	J. Rickli
G. Reklaitis	S. Rachuri	R. Smith
A. Rossiter	J. Seay **(Scribe)**	T. Theis
D. Sekulic	G. Thorsteinson	F. You
D. Sengupta **(Scribe)**	C. Yuan	M. Zenter
P. Witherell	F. Zhao	

AUG. 21, 10:00 – 11:30AM

Group 3.1 – Multidisciplinary Collaboration	Group 3.2 – Academic/Industrial Collaboration
L. Achenie	M. Bagajewicz
B. Bakshi	J. Bradburn
J. Bravo	B. DuPont
P. Daoutidis	M. Eden
C. Davidson (**Chair**)	T. Edgar
M. El-Halwagi	R. Elms
I. Grossmann	K. Haapala **(Scribe)**
T. Gutowski	J. Isaacs
R. Helling	I.S. Jawahir
Y. Huang	P. Mukherjee
N. Kralik	K. Ogden
M. Mehta	C. Piluso (**Chair**)
E. Olivetti	G. Reklaitis
S. Rachuri	J. Rickli
D. Sekulic	A. Rossiter
T. Theis **(Scribe)**	D. Sengupta
P. Witherell	R. Smith
F. You	G. Thorsteinson
M. Zenter	C. Yuan
	F. Zhao