Proceedings of the Measurement Science for Sustainable Construction and Manufacturing Workshop
Volume II. Presentations

Bilal M. Ayyub
Gerald E. Galloway
Richard N. Wright
University of Maryland

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Recommended Citations


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Ayyub, Bilal M., Galloway, Gerald E., and Wright, Richard N., University of Maryland

About the Workshop on Measurement Science for Sustainable Construction and Manufacturing

1. Background
Achieving long-term suitability poses a linked-systems challenge for policy makers to assess the consequences, trade-offs and synergies in economic, environmental and social domains. A sustainable society can be defined as the one that can thrive over generations; one that is far-seeing enough, flexible enough, and wise enough not to undermine its economic, environmental and social systems of support. A major need for achieving sustainable construction and manufacturing is to establish meaningful measurements for the complex attributes of sustainability suitable for lifecycle considerations. What one can measure, one can manage. NIST, ASCE, ASME and the University of Maryland are hold this workshop to address this challenge.

2. Objectives
The objective of the workshop was to examine the measurement science needed to guide decisions for sustainability throughout the life cycle of design, construction/manufacturing, operations, and maintenance of facilities and systems of the built environment and manufactured products, and to guide NIST and other key stakeholders in developing a portfolio of related programs. The workshop engaged key international and domestic thought leaders and experts from stake-holding disciplines including construction, manufacturing, codes and standards development, economics, government, industry, and academia, and addressed trends and needs relating to sustainable construction and manufacturing. The results from this effort are documented herein in coordination with NIST, ASCE and ASME.

3. Discussion Topics
Discussion topics included:
- Measurement science (definition, standards, metrics, indicators and ratings)
- Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)
- Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency), or
- Economic, environmental and social aspects (valuation, impacts and behavior).

4. Participants
The workshop was attended by about 77 people. A complete list is provided in Appendix A.
### 5. Agenda

**Day 1: June 12, 2014**

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<th>Topic</th>
<th>Duration</th>
<th>Room</th>
<th>Speakers</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00-8:30</td>
<td>Breakfast</td>
<td></td>
<td></td>
<td>Darryll Pines, Dean, School of Engineering, Un. Maryland (UMD)</td>
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<td></td>
<td></td>
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<td></td>
<td>Howard Harary, Acting Director, Engineering Laboratory, NIST</td>
</tr>
<tr>
<td>8:30-9:00</td>
<td>Welcome and Introduction</td>
<td></td>
<td></td>
<td>Bilal Ayyub, Director, Center for Technology &amp; Systems Management, CEE Professor, UMD</td>
</tr>
<tr>
<td></td>
<td>Opening remarks</td>
<td></td>
<td></td>
<td>Nabil Naar, Associate Provost for Academic Affairs &amp; Director of Golisano Institute for Sustainability, Rochester Institute of Tech., NY</td>
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<tr>
<td></td>
<td>Symposium program</td>
<td></td>
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<tr>
<td></td>
<td>Perspectives on sustainability for the Nation</td>
<td></td>
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<tr>
<td>9:00-9:25</td>
<td>Sustainable manufacturing</td>
<td></td>
<td></td>
<td>William Flanagan, Director, Ecoassessment Center of Excellence, GE Global Research, General Electric Company</td>
</tr>
<tr>
<td>9:25-9:50</td>
<td>Sustainable construction</td>
<td></td>
<td></td>
<td>Nancy Kralik, Fluor and Construction Industry Institute</td>
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<tr>
<td>9:50-10:00</td>
<td>Break</td>
<td>10</td>
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<tr>
<td>10:00-10:20</td>
<td>Sustainability metrics-measurement science</td>
<td>17+3</td>
<td>ASCE</td>
<td>Subhas Sikdar, Associate Director for Science, National Risk Management Research Lab, EPA, and AIChE</td>
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<tr>
<td>10:20-10:40</td>
<td>System sustainability: aggregation &amp; linkages</td>
<td>17+3</td>
<td>ASCE</td>
<td>Joseph Fiksel, Director, Center for Resilience at The Ohio State Un.</td>
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<tr>
<td>10:40-11:00</td>
<td>Planning, design and supply chain</td>
<td>17+3</td>
<td>ASCE</td>
<td>Gül Kremer, Professor, Industrial &amp; Manufacturing Eng., Penn State</td>
</tr>
<tr>
<td>11:00-11:20</td>
<td>Economic, environmental and social aspects</td>
<td>17+3</td>
<td>ASCE</td>
<td>Cliff Davidson, Director, Center for Sustainable Engineering, Thomas and Colleen Wilmot CEE Professor, Syracuse University</td>
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<tr>
<td>11:20-12:40</td>
<td>Quantified Urban Community at Hudson Yards</td>
<td>17+3</td>
<td>ASCE</td>
<td>Constantine E. Kontokosta, NYU Polytechnic School of Engineering</td>
</tr>
<tr>
<td>11:40-12:00</td>
<td>Population and Carrying Capacity: Metrics for Sustainability</td>
<td>17+3</td>
<td>ASCE</td>
<td>Eugenia Kalnay, NAE, Distinguished University of Maryland Professor of Atmospheric and Oceanic Science</td>
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<tr>
<td>12:00-1:00</td>
<td>Hosted Lunch (sandwiches)</td>
<td>60</td>
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<tr>
<td>1:00-2:48</td>
<td>Perspectives on sustainable construction and manufacturing</td>
<td>108</td>
<td>ASCE</td>
<td>Gerald Galloway (Moderator), NAE, Glenn L. Martin Institute Professor of Engineering, UMD</td>
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<tr>
<td></td>
<td>Implementation and challenges for metrics</td>
<td>15+3</td>
<td>ASCE</td>
<td>David Dise, Director of General Services, MD Montgomery County</td>
</tr>
<tr>
<td></td>
<td>A Case study on the role of metrics</td>
<td>15+3</td>
<td>ASCE</td>
<td>Fulya Kocak, Clark Construction Group, Bethesda, MD</td>
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<tr>
<td></td>
<td>Perspectives of a federal agency on metrics</td>
<td>15+3</td>
<td>ASCE</td>
<td>Joe Cresko, Lead internal analysis and strategic planning, Advanced Manufacturing Office, DOE</td>
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<tr>
<td></td>
<td>Metrics for sustainable products and process</td>
<td>15+3</td>
<td>ASCE</td>
<td>I. S. Jawahir, Director, Institute for Sustainable Manufacturing</td>
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<tr>
<td></td>
<td>Perspectives of owner and builder on metrics</td>
<td>15+3</td>
<td>ASCE</td>
<td>James Dalton, Chief, Engineering and Construction, Directorate of Civil Works, USACE</td>
</tr>
<tr>
<td></td>
<td>International perspectives on metrics</td>
<td>15+3</td>
<td>ASCE</td>
<td>Bohumil Kasal, Director of Fraunhofer Institute at Braunschweig, Germany and Professor at the Technical University of Braunschweig</td>
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<tr>
<td>2:48-3:00</td>
<td>Break</td>
<td>12</td>
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<tr>
<td>3:00-4:00</td>
<td>Panel 1 - Perspectives from users</td>
<td>60</td>
<td>ASCE</td>
<td>Richard Wright (Moderator, Research Professor, UMD), Michele Russo (McGraw Hill/ENR), Chris Pyke (US Green Building Council), William Bertero (Instit. for Sustain. Infrastructure), William Flanagan (General Electric Company)</td>
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<tr>
<td>4:00-5:00</td>
<td>Panel 2 - Perspectives from researchers</td>
<td>60</td>
<td>ASCE</td>
<td>Jelena Srebric (Moderator, Professor, UMD), Nabil Naar (Rochester Institute of Tech), Damon Fordham (TRB), Andrew Persily (NIST), Subhas Sikdar (AIChE/ EPA)</td>
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<tr>
<td>5:00-5:15</td>
<td>Second day breakout sessions</td>
<td>10</td>
<td>ASCE</td>
<td>Richard Wright, NAE, Research Professor, UMD (NIST retired)</td>
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<tr>
<td>6:00-8:30</td>
<td>Hosted Dinner (participants seated per breakouts)</td>
<td>150</td>
<td>Ballroom A</td>
<td>Joannie Chin, Acting Deputy Director, Engineering Laboratory, NIST</td>
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**Day 2: June 13, 2014**

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<tbody>
<tr>
<td>8:00-8:30</td>
<td>Breakfast</td>
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<td></td>
<td>Gerald Galloway, UMD</td>
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<tr>
<td>8:30-8:45</td>
<td>Getting oriented and allocated to breakout sessions</td>
<td>15</td>
<td>ASCE</td>
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<tr>
<td>8:45-9:45</td>
<td>Breakout 1: Measurement science</td>
<td></td>
<td>CH2M Hill</td>
<td>Co-moderators: I. S. Jawahir and Subhas Sikdar</td>
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<tr>
<td>8:45-9:45</td>
<td>Breakout 2: Systems</td>
<td></td>
<td>60</td>
<td>Harris</td>
</tr>
<tr>
<td>8:45-9:45</td>
<td>Breakout 3: Planning, design and supply chain</td>
<td></td>
<td>60</td>
<td>President</td>
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<tr>
<td>8:45-9:45</td>
<td>Breakout 4: Economic, environmental and social aspects</td>
<td></td>
<td>60</td>
<td>ASCE</td>
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<tr>
<td>9:45-10:00</td>
<td>Break</td>
<td>15</td>
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<tr>
<td>10:00-11:00</td>
<td>Breakout 1: Measurement science</td>
<td></td>
<td>60</td>
<td>CH2M Hill</td>
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<tr>
<td>10:00-11:00</td>
<td>Breakout 2: Systems</td>
<td></td>
<td>60</td>
<td>Harris</td>
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<tr>
<td>10:00-11:00</td>
<td>Breakout 3: Planning, design and supply chain</td>
<td></td>
<td>60</td>
<td>President</td>
</tr>
<tr>
<td>10:00-11:00</td>
<td>Breakout 4: Economic, environmental and social aspects</td>
<td></td>
<td>60</td>
<td>ASCE</td>
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<tr>
<td>11:00-11:15</td>
<td>Break to regroup</td>
<td>15</td>
<td></td>
<td></td>
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<tr>
<td>11:15-12:15</td>
<td>Summaries of breakouts 1, 2, 3 and 4</td>
<td>60</td>
<td>ASCE</td>
<td>By Co-moderators, report requirements (facilitor Richard Wright, UMD)</td>
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<tr>
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<td>Expected products and adjournment</td>
<td>15</td>
<td>ASCE</td>
<td>Bilal Ayyub, UMD</td>
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</table>
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This report was prepared for the National Institute of Standards and Technology (hereafter referred to as NIST) as the primary sponsor, and the American Society of Civil Engineers (hereafter referred to as ASCE), the American Society of Mechanical Engineers (hereafter referred to as ASME), the American Institute of Chemical Engineers (hereafter referred to as AIChE) and the American Society of Heating, Refrigerating and Air Conditioning Engineers (hereafter referred to as ASHRAE) by the Center for Technology and Systems Management of the University of Maryland and its associates and subcontractors (hereafter referred to as the UMD). Although this product was prepared using the best available resources, NIST, ASCE, ASME, AIChE and UMD do not make any warranty, expressed or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represent that its uses would not infringe on privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by NIST, ASCE, ASME, AIChE, ASHRAE and UMD. Opinions expressed in this report are personal opinions of the participants and do not reflect the opinions of the respective employers of the participants.
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Measurement Science for Sustainable Construction and Manufacturing: Opening Remarks
   Howard Harary

Workshop on Measurement Science for Sustainable Construction and Manufacturing:
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   Nabil Nasr

Sustainable Manufacturing from a Life Cycle Perspective
   William P. Flanagan

Sustainable Construction: An EPC Perspective
   Nancy K. Kralik

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   Subhas Sikdar

A Systems Approach to Sustainability and Resilience
   Joseph Fiksel

Sustainability Improvement at the Supply Chain Level Through Product Architecture Optimization
   Gül E. Okudan Kremer

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Fulya Kocak

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Metrics for Sustainable Products and Processes
I. S. Jawahir

Perspectives of an Owner & Builder on Metrics
James Dalton

Perspectives of an Owner & Builder on Metrics
Bohumil Kasal

High Performance Green Buildings
Chris Pyke

Introduction to Breakout Sessions
Richard Wright

Charge to the Breakout Groups
Joannie Chin

Concluding Remarks and Adjournment
Bilal M. Ayyub
Workshop on Measurement Science for Sustainable Construction and Manufacturing 8:30-9:00 am

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<tr>
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<td>Bilal Ayyub, CEE Professor, UMD*</td>
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<td>Howard Harary, Acting Director, Engineering Laboratory, NIST</td>
</tr>
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</tr>
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<td>Perspectives on sustainability for the Nation</td>
<td>Nabil Nasr, Associate Provost for Academic Affairs &amp; Director of</td>
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<td></td>
<td>Golisano Institute for Sustainability, Rochester Institute of Tech., NY</td>
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</table>

* CEE Chair Professor Charles Schwartz, and ME Chair Professor Balakumar Balachandran
Symposium Objectives

• Examine measurement science for sustainability throughout the lifecycle of the built environment and manufactured products
• Guide NIST and other key stakeholders in developing a portfolio of related research and development programs
• Engage key international and domestic thought leaders and experts from stakeholding disciplines
• Document in coordination with NIST, ASCE and ASME

Discussion Topics

• Measurement science (definition, standards, metrics, indicators and ratings)
• Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)
• Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)
• Economic, environmental and social aspects (valuation, impacts and behavior)
**Workshop on Measurement Science for Sustainable Construction and Manufacturing**

**Program – June 12, 2014**

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<tr>
<td>Opening</td>
<td>Welcome, introduction &amp; national needs</td>
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<td>Keynotes</td>
<td>Two on manufacturing &amp; construction</td>
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<td>Breakout presentations</td>
<td>Four sessions</td>
</tr>
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<td>Case studies</td>
<td>Two cases</td>
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<tr>
<td>Lunch</td>
<td>Cutoff time for breakout assignments</td>
</tr>
<tr>
<td>Six Ted-like lectures</td>
<td>Perspectives on manufacturing &amp; construction</td>
</tr>
<tr>
<td>Discussion panels</td>
<td>Two from users and researchers</td>
</tr>
<tr>
<td>Orientation for day 2</td>
<td>Presentation &amp; banquet</td>
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**Program – June 13, 2014**

<table>
<thead>
<tr>
<th>Activity</th>
<th>Details</th>
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<tbody>
<tr>
<td>Orientation</td>
<td><strong>All participants</strong></td>
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<tr>
<td>Four concurrent sessions</td>
<td>Problem lists</td>
</tr>
<tr>
<td></td>
<td>Problem descriptions</td>
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<tr>
<td>Summary</td>
<td><strong>All participants</strong> by the co-moderators</td>
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<tr>
<td>Expected products and adjournment</td>
<td>Proceedings</td>
</tr>
<tr>
<td></td>
<td>Recommendations</td>
</tr>
<tr>
<td>Time</td>
<td>Session</td>
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<tr>
<td>9:00-10:00 am</td>
<td><strong>Sustainable manufacturing</strong>&lt;br&gt;<strong>William Flanagan</strong>, Director,&lt;br&gt;Ecoassessment Center of Excellence,&lt;br&gt;GE Global Research, General Electric Company</td>
</tr>
<tr>
<td></td>
<td><strong>Sustainable construction</strong>&lt;br&gt;<strong>Nancy Kralik</strong>, Fluor and the&lt;br&gt;Construction Industry Institute</td>
</tr>
<tr>
<td></td>
<td><strong>Break</strong></td>
</tr>
<tr>
<td>10:00-11:20 am</td>
<td><strong>Sustainability metrics- measurement science</strong>&lt;br&gt;<strong>Subhas Sikdar</strong>, Associate Director for Science, National Risk Management Research Lab, EPA, and AIChE</td>
</tr>
<tr>
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<td><strong>System sustainability: aggregation &amp; linkages</strong>&lt;br&gt;<strong>Joseph Fiksel</strong>, Director, Center for Resilience at The Ohio State University</td>
</tr>
<tr>
<td></td>
<td><strong>Planning, design and supply chain</strong>&lt;br&gt;<strong>Gülf Kremer</strong>, Professor, Industrial &amp; Manufacturing Eng., Penn State</td>
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<tr>
<td></td>
<td><strong>Economic, environmental and social aspects</strong>&lt;br&gt;<strong>Cliff Davidson</strong>, Director, Center for Sustainable Engineering, Thomas and Colleen Wilmot CEE Professor, Syracuse University</td>
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</table>
### Workshop on Measurement Science for Sustainable Construction and Manufacturing

**11:20-12:00 am**

<table>
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<tr>
<th>Topic</th>
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<tbody>
<tr>
<td>Quantified Urban Community at Hudson Yards</td>
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<td><strong>Eugenia Kalnay</strong>, NAE, Distinguished University of Maryland Professor of Atmospheric and Oceanic Science, and <strong>Sofa Motesharrei</strong>, Systems Scientist at SESYNC, PhD candidate in Econophysics at UMD</td>
</tr>
<tr>
<td>Hosted Lunch (sandwiches)</td>
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### Workshop on Measurement Science for Sustainable Construction and Manufacturing

**1:00-2:48 pm**

<table>
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<th>Topic</th>
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<tr>
<td>Perspectives on sustainable construction and manufacturing</td>
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<td>International perspectives on metrics</td>
<td><strong>Bohumil Kasal</strong>, Director of Fraunhofer Institute at Braunschweig, Germany and Professor at the Technical University of Braunschweig</td>
</tr>
</tbody>
</table>
## Workshop on Measurement Science for Sustainable Construction and Manufacturing

**3:00-5:15 pm**

### Panel 1 - Perspectives from users
- **Richard Wright** (Moderator, Research Professor, UMD), **Michele Russo** (McGraw Hill/ENR), **Chris Pyke** (US Green Building Council), **William Bertera** (Instit. for Sustain. Infrastructure), **William Flanagan** (General Electric Company)

### Panel 2 - Perspectives from researchers
- **Jelena Srebric** (Moderator, Professor, UMD), **Nabil Nasr** (Rochester Institute of Tech), **Damon Fordham** (TRB), Andrew Persily (NIST), **Subhas Sikdar** (AIChE/EPA)

### Second day breakout sessions
- **Richard Wright**, NAE, Research Professor, UMD (NIST retired)

### Hosted Dinner (participants seated per breakouts)
- **Joannie Chin**, Acting Deputy Director, Engineering Laboratory, NIST
Measurement Science for Sustainable Construction and Manufacturing

Dr. Howard Harary
Acting Director
Engineering Laboratory
National Institute of Standards and Technology
U.S. Department of Commerce
Sustainability Science

• Defined by problems it addresses rather than by disciplines it employs

• Seeks understanding of fundamental interactions between nature and society

• Has a goal of creating and applying knowledge in support of decision making for sustainable development

• Energy systems, ecosystem resilience, industrial ecology, earth system complexity

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1Term established by National Research Council, 1999, Our Common Journey.
The Japanese Model – Inverse Manufacturing

R·I Fig. 1 The concept of Inverse Manufacturing

© 2014 Rochester Institute of Technology
Conceptual Relationship between Sustainable Manufacturing and Eco-Innovation

In a world with growing pressures on resources and the environment, the EU has no choice but to go for the transition to a resource-efficient and ultimately regenerative circular economy.”

Manifesto for a Resource Efficient Europe, December 2012

Transforming waste into high value resources is a high priority in today’s global economy. ResCoM is an European Commission co-funded project working on the development of closed-loop product systems. The project will focus on some of the key ways to do this including remanufacturing, reuse and multiple lifecycles.
Global Material Extraction & GDP

Material extraction
[Billion tons]

GDP
[trillion (10^12) international dollars]

- Ores and industrial minerals
- Fossil energy carriers
- Construction minerals
- Biomass
- GDP

OECD Project on Sustainable Manufacturing & Eco-Innovation

Process overview

• Formed an Advisory Expert Group (AEG)
• 50 members from 17 countries + EC
• Web-forum for ongoing discussions
• Supported questionnaire surveys & focus group meetings
• Review of report drafts prepared by the Secretariat … DSTI/IND(2009)5/PART1-5
Existing Metrics Approaches

Product | process | facility | corporation | sector | country | global

Measurement unit

Indicator Categories

- Environment
  - Resource Productivity
    - Climate Change
    - By-products
- Economy
  - Financial performance
  - Employees
- Society
  - Social responsibility

Sustainability components
Issue Areas
Indicators category

Social responsibility
Material use
Water use
Energy use
GHGs
Residuals
Costs
Labor
Social costs/benefit

scope of the current indicator set
internal data elements and future work
• Recycling rates of metals
  – According to the United Nations, recycling rates of metals are often far lower
    than their potential for reuse. Less than one-third of some 60 metals studied
    have an end-of-life recycling rate above 50% and 34 elements are below 1%
    recycling, yet many are crucial to promising clean technologies ranging from
    hybrid car batteries to the high-efficiency magnets in wind turbines.

• Decoupling natural resource use and
  environmental impacts from economic growth
  – By 2050, humanity could devour 140 billion tons of minerals, ores, fossil fuels
    and biomass per year – 3X its current appetite – unless the economic growth
    rate is “decoupled” from the rate of natural resource consumption. We need
    to rethink the links between resource use and economic prosperity and invest
    in technological, financial and social innovation to at least freeze per capita
    consumption in wealthy countries and help developing nations follow a more
    sustainable path.
Sustainable Manufacturing from a Life Cycle Perspective

William P. Flanagan, PhD
Director, Ecoassessment Center of Excellence
General Electric Company
GE Global Research
Niskayuna, NY

Measurement Science for Sustainable Construction & Manufacturing
NIST – ASCE – ASME – University of Maryland
ASCE Bechtel Center, Reston, VA

June 12-13, 2014

GE today

Power & Water  Energy Management  Oil & Gas  GE Capital
Healthcare  Aviation  Transportation  Home & Business Solutions

Aligned for growth
The Hush Hush Boys

In 1941, a group of GE engineers called the Hush Hush Boys (pictured left) worked in secret on a jet engine design developed by Britain’s Sir Frank Whittle (pictured right) and built America’s first jet engine.

http://www.gereports.com/post/86230911910/the-most-important-10-pages-in-the-history-of-aviation
WWII

The U.S. War Department picked GE to build the country’s first jet engine because of its research and innovation in turbine technology.

GE Aviation

That engine, called I-A (pictured on left), launched GE’s aviation business and started an engine dynasty culminating today in the largest and most powerful jet engines ever built: the GE90, GE9X, and GEnx (pictured on right).
Star Wars Episode VII
Coming May 2015

CFM LEAP Engine
Coming 2016

• CFM International is a 50/50 joint venture between GE and France's Snecma
• The LEAP engine is CFM's next-generation high-bypass turbofan jet engine
• 3D-printed fuel nozzles offer:
  o >20% weight reduction
  o 5x longer part life

LCA and systems level thinking

GE Ecoassessment
Center of Excellence

Technical credibility & product support
• Product LCA + LCM toolkits
• Strategic & selective application

Drive eco further into product development
• Customize to business context
• Identify opportunities for real improvement

Deliver customer value
• Strategic engagement
• Environmental and operational savings

Thought leadership
• Drive business perspective on sustainability
• Create & maintain momentum toward real change

Key Roles:
• Expertise and guidance
  ✓ Life cycle assessment (LCA)
  ✓ Life cycle management (LCM)
  ✓ Carbon, energy, water footprint
  ✓ ecoDesign / Design for Environment
• Tools and resources
• Education and awareness
• External networks

Support:
• Policy and advocacy
• Business strategies / integration
• Stakeholder engagement
Life Cycle Assessment (LCA)
Assess overall environmental impact throughout a product or service’s life cycle

Understanding the net environmental impact of a product/service across its value chain, how and where to make improvements

- Differentiate products
- Evaluate alternatives
- Prioritize opportunities for improvement
- Mitigate environmental issues

More than just carbon footprint

Areas of Protection (damage categories)

LCA is not a panacea

Holistic, but not comprehensive
- In practice, limited to existing impact categories and characterization factors
- Difficult to address specific effects and emerging issues (e.g., endocrine disruptors, nano materials)

Global vs. local perspective
- Difficult to address region-specific or application-specific impacts (e.g., regional species impacts, actual vs. potential exposures, other localized issues)

Water impacts under-represented

Social / economic / behavioral aspects often missing

Difficult to apply to emerging technologies (R&D)

LCA is an excellent tool, but is not comprehensive
A tiered life cycle management strategy

1. Environmental Product LCM Tool (qualitative)
   - Tool rapidly identifies follow-up needs
   - Address identified issues
     - Substances of concern
     - Material scarcity
     - Toxicology assessments
     - Environmental risk assessment
     - Nanomaterial EH&S
     - Product regulatory compliance
     - Etc.

2. Screening LCA
   - Apply level 1 tool early in product development across broad product portfolio

3. Streamlined LCA
   - Detailed LCA per ISO 14044

4. Detailed LCA per ISO 14044

Strategic | Comprehensive | Efficient | Effective

Anticipatory LCA

Wender et al.

Research factors:
- Technology developers
- Prospective tools
- Environmental researchers
- Social scientists

Research priorities:
- Environmental & social integration
- Environmental & social integration

Process development
- Extraction & beneficiation
- Manufacturing
- Product use
- End of life processing

Scale up modeling
- Life cycle inventory
- Characterization factor development
- Exposure modeling
- Fate & transport modeling

Structured scenarios
- Characterized inventory
- Stochastic multi attribute analysis
- Probability ranking

Multi-criteria Decision Analysis
- Social support
- Material flows
- Knowledge flows
- Knowledge feedback
Additive manufacturing

Billet vs. additive manufacturing

**Conventional**
- Start with a pre-formed billet, which gets formed and machined
- Material properties unchanged and cannot be location specific
- Limited to known set of geometries
- Design constrained by manufacturing
- Requires extensive tooling

**Additive**
- Starts with a powder or wire and produces part layer upon layer upon layer
- Build material properties as you build the part ... location specific
- More complex geometries possible
- Allows for faster iterations between design, materials and manufacturing
- Minimal tooling required

Ability to design new materials & implement them during the manufacturing process will create paradigm change
EADS Additive Case Study
Hinge Redesign

**Raw Material**
Uses less raw material: optimised design, net shaping, DMLS and not casting, titanium and not steel

**Transportation**
Leads to important energy consumption/CO₂ emissions reduction during the transport phase (a hundred times better): less material to be transported, based on a European supply chain

**Manufacturing**
Energy consumption is higher compared to Steel Casting, but less waste produced.

**Use Phase**
Allows 10 kg weight reduction per a/c, equivalent to €35K savings in fuel consumption and carbon tax

**End of Life**
No significant differences.

In this case, additive manufacturing has higher energy consumption during manufacturing, but lower overall life cycle impact.

GE Aviation Additive Case Study
Fan Blade Metal Leading Edge (MLE)

**PROBLEM**
- Composite fan blades enable significant engine performance vs. titanium forged blades
- Composites require metal leading edge for erosion protection
- Cost of machining Ti and other superalloys

**OBJECTIVE OR SOLUTION**
- Form inner face of MLE from sheet stock and laser clad (or other additive) bulk material

**APPROACH**
- Establish bulk and hybrid laser clad material properties
- Perform static impact testing of scaled hybrid
- Perform rotational impact on FAA cert program engines

- Cost reduction over extensive machining cycles of near net shape forging
- Laser cladding, cold spray, wire technologies and hybrids (e.g., forging/additive) emerging
- Establish new Supply Chain and footprint
US Department of Defense

- Defense industry consortium: Mission Ready Sustainability Initiative
  - GE Aviation, Lockheed Martin, BASF, 3M, General Dynamics, others
- Aimed at DoD sustainability initiatives:
  - DoD Strategic Sustainability Performance Plan, Air Force Energy Plan, Presidential Executive Orders 13514 / 13423
  - Sustainability tools and metrics may be imposed on DoD acquisitions
- Strong, active engagement from DoD:
  - Office of Secretary of Defense, Deputy Director of Chemical & Material Risk Management
- DoD Streamlined LCA / LCC methodology developed for use in defense acquisitions
  - Pilots underway: GE, 3M, BASF, Lockheed Martin
  - Method integrates environmental and cost aspects
  - Total Cost of Ownership

Additive Manufacturing of Fuel Nozzles
Pilot of US DoD streamlined LCA/LCC methodology

Traditional fuel nozzles are manufactured via forging and machining processes

Fuel nozzles manufactured by additive manufacturing processes offer:
  - >20% weight reduction
  - 5x longer part life

Potential for significantly reduced life cycle environmental impact and total cost of ownership due to:
  - Reduced part weight:
    - Reduced fuel consumption over the life of the aircraft system
    - Increased mission capability (load capacity)
  - Net lower raw material consumption
  - Enhanced performance

Direct metal laser sintering
Courtesy EADS Innovation Works
Pilot project benefits

Clear need for trade-off assessment
- Environmental impact
- Total cost of ownership
- Trade-offs relevant to supplier: design, supply chain, manufacturing, performance
- Trade-offs relevant to US DoD: total cost, mission, sustainment & operations

Opportunity to pilot methodology early in product development
- Ability to leverage insights gained

Focus on additive manufacturing
- Understand trade-offs before paradigm shift

Sustainable manufacturing

Sustainable manufacturing should consider all life cycle stages

Different manufacturing processes may:
- enable novel material choices
- have different material and energy efficiencies
- enable unique part geometries or other features affecting performance
- offer enhanced repair-ability, re-usability, recyclability at end of life

Different materials may have different:
- supply chain impacts
- manufacturability
- performance properties (e.g., thermal, mechanical)
- end of life options (e.g., recyclability, re-usability)

Additive manufacturing offers the potential for unique part geometries or performance that can yield environmental benefit across the full life cycle
Thanks!
Bill Flanagan
flanagan@ge.com

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Todd Rockstroh
GE Aviation
Sustainable Construction: An EPC Perspective

Nancy Kralik
Senior Director, Health, Safety, Environment & Sustainability
Fluor Corporation
June 12, 2014

Influence Curve

Adapted from CII Constructability Primer
Construction Phase

- Design
- Construction
- Operation

- Site Planning
- Final Commissioning Report

Safety Metrics (Social)

◆ Lagging
  - Lost time incidence rate
  - Recordable incident rate
  - Etc.

◆ Leading
  - Audits
  - Inspections
  - Training
  - Etc.
Economic Metrics

- Budget
- Schedule
- Cost of energy
- Cost of raw materials
- Water consumed

Environmental Metrics

- Brownfield
- Greenfield
Social Metrics

- Human Rights
- Labor Practices
- Community Impact and Involvement
- Worker Safety

Construction Industry Institute

- Guidance on sustainability during construction
  - RT304
- Compendium of sustainability practices
  - RT250
Sustainability Action Catalog

- Sustainability Impacts
- Project Conditions
- Output Metrics

Sustainability Action Screening Tool

◆ 2 types of Input:
  - Relative priorities/weightings of desired Sustainability impacts
  - Applicability of project conditions
Screening Tool Output

◆ Also available for Tablet or Smart Phone

Implementation Index
Predominant Output Metrics

- Percent of projects with Sustainability Performance section in project reports;
- Cost savings;
- Portion or volume of total waste recycled or diverted from a landfill;
- Street value of recycled material;
- Equipment environmental performance;
- Size of carbon footprint from project; and
- Number of complaints from community, agency, or camp residents.

7-Step Implementation Process

1. Establish Objectives
2. Rank Top Actions
3. Select Actions
4. Plan Action Implementation
5. Implement Actions
6. Measure Outcomes
7. Improve Process
Gaps & Research Needs

- Quantitative social metrics
- Easy-to-generate life-cycle assessments
- Industrial Sustainability Index Metrics
- Case studies for identified sustainability actions
  - New metrics?
  - Benchmarking
- Field use

Questions and Comments Welcome
How to Quantify Sustainability in Construction and Manufacturing, and the Need for Standards

Subhas Sikdar, US EPA, and
Humberto S. Brandi, INMETRO, Brazil

NIST-ASCE-ASME Sustainability Workshop, Rockville, MD, June 12-13, 2014

Sustainability is like the proverbial elephant. We, much like blind people, describe it in terms that depend on our field of expertise. Thus - - - -
Many Men, Many Minds
Sustainability through disciplinary lenses

• For an **economist**, sustainability is at first related to new economic models of growth and regulation, taking into account not only the traditional quantifiable components of welfare, but also a lot of environmental “externalities” and qualitative assets.

• For an **ecologist**, sustainability means the use of natural resources to the extent that the carrying and regenerative capacities of the ecosystems are not jeopardized.

• For a **physicist**, sustainability means the ability of biological systems to fight against degradation of energy and resources (entropy) by creating new forms of order (negentropy) using the various inputs of solar energy.

• For a **chemist** or an **engineer**, the challenge of sustainability is to complete material and energy life cycles created by human activities, through new techniques for material design, re-use, recycling and waste management.

• For a **social scientist**, sustainability implies the social and cultural compatibility of human intervention in the environment with its images constructed by different groups within society.

J. Pop-Jordanov, in Technological Choices for Sustainability, Ed. Sikdar, Glavic and Jain; Springer 2004, p. 305

---

**Bruntlund Sustainability**

Economic development (i.e. by technology application) with decreasing environmental impact and improving societal benefit

An Engineering Definition:

For a man-made **system**, sustainable development is continual improvement in one or more of the three domains of sustainability, i.e., economic, environmental, and societal without causing degradation in any of the rest, either now or in the future, when compared with quantifiable metrics, to a similar system it is intended to replace.
Scale and Nesting of Sustainable Systems

Five levels of scales for sustainable systems:

Level I: Global Scale (e.g. global CO2 budgeting)
Level II: National Scale (e.g. energy)
Level III: Regional Scale (e.g. watersheds)
Level IV: Business or Institutional Scale (e.g. eco-industrial park)
Level V: Sustainable Technologies Scale (e.g. sustainable products)

System-Surrounding Paradigm

Sustainability analysis is essentially an accounting of what impacts (environmental, economic, and societal) the system is causing to itself and to the surrounding, and how these impacts can be minimized.
Measurement and Standards

Quality, Uniformity, Confidence: Three Pillars of Sustainable Development

Clear understanding of what is wanted:
*Standardization* – Documentary standards

Proceeding to implement “what is wanted”:
*Conformity Assessment* - Certification, labelling, suppliers declaration, auditing. Accreditation

Guaranty that “what one has is what is wanted”:
Trust in measurements:
*Metrology* – Measurement standards

Example: GHG emission standards require:
- Harmonize knowledge
- Harmonize measurements
- Harmonize methodologies
- Harmonize inventories

Metrics and Indicators
**Methods of Sustainability Analysis:**

BASF Eco-efficiency Analysis

BASF Eco-efficiency analysis: combines Environmental and Economic Dimensions Of Sustainability

BASF Sustainability Analysis: combines All three dimensions of sustainability (called socio-eco-efficiency)

**Metrics Aggregation for a Sustainability View**

Eco services indicator is a qualitative composite of 8 indicators: crop production, forest production, preserving habitats and biodiversity, water flow regulation, water quality regulation, carbon sequestration, regional climate and air quality regulation, infectious disease mediation.
Construction of aggregate index:

Hypothesis: sustainability footprint $D_s$ or $D = f(x_i, i=1\text{ to } n)$ represents the overall state of the system as revealed by the set of chosen indicators.

**Sustainability footprint**

$$D_s = \sqrt{\sum_{j=1}^{n} \left( \frac{y_j - x_j(0)}{y_j - x_j(0)} \right)^2}$$

- Euclidean Distance Method
- Canberra Index Method
- Others

$$D = \left( \prod_{i=1}^{n} \left[ c_i \left( y_i^i / x_i^i \right) \right] \right)^{1/n}$$

or perfect sustainability, the value of sustainability footprint is zero

<table>
<thead>
<tr>
<th>Indicators, $X_i$</th>
<th>Process options</th>
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<td>$X_9$</td>
<td>$X_{1,9}$</td>
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</table>

Typical Data Matrix for $m$ options and $n$ indicators
PCA-PLS-VIP (Finding Redundant Indicators, and Rank Order)

Starting point: mxn data matrix $X$, m options, n indicators

PCA designs n-dimensional unit vectors (q's) and a correlation matrix $R$ (nxn), such that the following eigen value problem represents the data set.

$$RQ = \Delta Q$$

Mapping $\sqrt{\lambda}$ onto $Q$, we get the loading matrix $L$. The product of $L$ and $X$ is called score matrix $T$ $(XL = T)$

PCA-PLS-VIP, contd.

PLS-VIP is based on projecting the information from data with more variables to that with fewer.

Using the score of $X$, PLS develops a regression model between $X$ and $D_e$. In a reduced subspace of dimension $a$ ($a \leq n$)

$$X = TL + E = \sum_{j=1}^{a} t_j w_j + E$$

$T$ is score matrix, $L$ is load matrix, $E$, the residual. Score matrix $T$ can be related to response vector $D_e$ through a regression matrix $B$.

Each option vector $x$ from $X$ can be related to the score vector $t_j$ through weight vectors $w_j$ as $t_j = w_j^T x_i$

VIP for $k$ is

$$VIP_k = \sqrt{\frac{\sum_{j=1}^{n} b_j^2 w_j^2}{\sum_{j=1}^{n} b_j^2 t_j^2}}$$
## Case: Automotive Shredder Residue Treatment (Catholique U, Leuven)
(where improvement is described as negative)

<table>
<thead>
<tr>
<th>Treatment strategy</th>
<th>ST</th>
<th>LT</th>
<th>WC</th>
<th>LU</th>
<th>SN</th>
<th>WC</th>
<th>ST</th>
<th>LT</th>
<th>TC</th>
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<td>Recycle+Landfill Minimum</td>
<td>12.9</td>
<td>30</td>
<td>3.5</td>
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<td>1699</td>
<td>137</td>
<td>383</td>
<td>55</td>
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<tr>
<td>Energy recovery Minimum</td>
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<td>189.6</td>
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### Normalized Root Square D' Values

<table>
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<tr>
<th>Treatment strategy</th>
<th>Least Square D'</th>
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<tbody>
<tr>
<td>Landfill</td>
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<tr>
<td>Recycle+Landfill</td>
<td>0.066627 0.087053 0.36842 0.472121 0 0 0.4801 0.1097 0.100694 0.776648 1.19</td>
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<tr>
<td>Recycle-Energy Recovery</td>
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</table>

Best→Worst

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<th>D, Value</th>
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<td>Energy recovery</td>
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<tr>
<td>Recycle-Energy Recovery</td>
<td>1.82</td>
</tr>
</tbody>
</table>
The PLS-VIP score shows that Total Cost (TC) has the maximum contribution to overall sustainability.

Case: Comparison of Sustainability Footprint ($D_n$) for OECD Countries over 20 Years

Environmental sustainability of OECD countries using UN MDG data and indicators

Only 6 indicators could be used because of data availability:

- CO2/GDP, CO2/capita, CO2 giga tons, ODP Metric tons,
- Population NOT using safe drinking water, and wetlands protection.
Future Research Needs

- Needed a Methodology to confirm if all necessary indicators have been chosen for analysis (e.g., cost frequently not included as an indicator but should be)
- A method to determine the sensitivity of Sustainability Footprints ($D_s$ or $D$) to individual indicators
- Method for identifying which indicators and their underlying variables can be manipulated to make further sustainability advances of systems
- System optimization of Sustainability Footprint with respect to the indicators by process integration techniques
How to Quantify Sustainability in Construction and Manufacturing, and the Need for Standards

Subhas Sikdar, US EPA, and Humberto S. Brandi, INMETRO, Brazil

NIST-ASCE-ASME Sustainability Workshop, Rockville, MD, June 12-13, 2014
The content of this presentation reflects the views of the author and does not represent the policies or position of the U.S. EPA.

Joseph Fiksel

Executive Director, Center for Resilience
The Ohio State University

Special Assistant for Sustainability
Office of Research & Development
U.S. Environmental Protection Agency

Resilience is the capacity for complex, adaptive systems (e.g., cities, business enterprises) to survive, adapt, and flourish in the face of turbulent change...

much like living systems
## Indicators of System Resilience

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Urban community</th>
<th>Enterprise supply chain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diversity</strong></td>
<td>Economic sectors, resource channels, workforce skills</td>
<td>Markets, suppliers, facilities, and employee capabilities</td>
</tr>
<tr>
<td><strong>Cohesion</strong></td>
<td>Community identity, social networks, local coordination</td>
<td>Corporate identity, stakeholder relations, collaboration</td>
</tr>
<tr>
<td><strong>Adaptive capacity</strong></td>
<td>Ability to rapidly modify urban services, management practices</td>
<td>Ability to modify products, technologies, or processes</td>
</tr>
<tr>
<td><strong>Resource productivity</strong></td>
<td>Quality of life (security, peace) relative to ecological footprint</td>
<td>Shareholder value (profits, assets) vs. ecological footprint</td>
</tr>
<tr>
<td><strong>Vulnerability to Change</strong></td>
<td>Disruptive forces that threaten safety and well being</td>
<td>Disruptive forces that threaten business continuity</td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>Ability to continue normal activities if disruptions occur</td>
<td>Ability to continue normal activities if disruptions occur</td>
</tr>
<tr>
<td><strong>Recoverability</strong></td>
<td>Ability to overcome disruptions, restore critical public services</td>
<td>Ability to overcome disruptions, restore key business operations</td>
</tr>
</tbody>
</table>


---

**Sustainability** is the capacity for:
- human health and well being
- economic vitality and prosperity
- environmental resource abundance

**Resilience** is the capacity to:
- overcome unexpected problems
- adapt to change (e.g., sea level rise)
- prepare for and survive catastrophes
Examples of initiatives aimed at resilience and sustainability

- **Energy systems**—smart grid, distributed, renewable, PHEV
- **Eco-efficiency**—green buildings, local sourcing, waste reuse
- **Water systems**—rainwater harvesting, green infrastructure
- **Mobility**—alternative transport, vehicle sharing
- **Urban renewal**—brownfields, affordable housing
- **Smart growth**—land use, resource stewardship
- **Education**—STEM careers, workforce retraining
- **Economic development**—incubators, business clusters
- **Emergency preparedness**—early detection, evacuation plans

Examples of Synergies and Trade-offs

More sustainable (ecological footprint)
- Nuclear energy
- Rain harvesting
- Lean production
- Smart grid
- Grey water use
- Local sourcing

Less resilient
- Corn ethanol
- Bottled water
- Business as usual
- Diesel backup
- Desalination
- Redundancy

More resilient (adaptive capacity)

Less sustainable

What is a Systems Approach?

• A comprehensive methodology for understanding the interactions and feedback loops among
  • Economic systems—companies, supply chains....
  • Ecological systems—forests, watersheds....
  • Societal systems—cities, networks....

• Reveals consequences (sometimes unintended) of human interventions, such as new policies, technologies, and business practices

• **Case in point:** Degraded ecosystems threaten the sustainability and resilience of human communities

(Millennium Ecosystem Assessment, 2005)

---

**Triple Value (3V) Framework**

Economy (economic capital)

- **economic value** is created for society
- ecological goods and services are utilized in industry
- natural resources may be depleted

Environment (natural capital)

- some waste is recovered and recycled
- toxic or hazardous releases may harm humans
- waste and emissions may degrade the environment

Community (human & social capital)

- talent is utilized in industry
- ecosystem services provide sustenance for communities


**Example from U.S. EPA Narragansett Bay 3VS Project**

Apply “systems thinking” to the problems of nutrient pollution and coastal resilience in New England, working closely with Region 1 stakeholders.
Modeling Coupled Human-Natural Systems at a Watershed Scale Requires Aggregation

Environmental Resources
- Surface water
- Ground water
- Coastal areas
- Fish & shellfish
- Regional ecosystems
- Atmosphere & climate

Economic Activities
- Agriculture
- Commercial Fisheries
- Energy & Transportation
- Land Development
- Recreation & Tourism
- Water Treatment

Community Stakeholders
- Consumers & residents
- State & local agencies
- Water & energy utilities
- Regional businesses
- Septic tank users
- Private well users
Causal Relationships in 3VS Model

Legend
- Sustainability Indicator
- Causal Link
- Potential Intervention

Graphical User Interface

Define interventions
Foresee consequences

Narragansett Bay Sustainability Management

Scenario Setup

Assumptions
- Interventions
  1. Watershed
  2. Farm
  3. Wastewater
  4. Low Impact Development
  5. Atmospheric Deposition

Wastewater Treatment Unit Capital Cost
- $520

Nitrogen Removal Unit Cost
- $377

Average Precipitation
- Set Value

Effect of Algal Bloom on Turbidity Decrease
- Set Effect

Industry

Tourism Value Added
- Nitrogen Removal Cost
- Agriculture Production
- Fisheries Production

Algal Change in GDP

Environment

Development Land
- Concentration in Water
- Total Water Quality

Relative Risk of Toxic

Society

Employment
- Beach Closing
- Total Population

Municipal Tax Revenue
- Algal Change in Per Capita Disposable Income

products & services

watersupply

runoff & wastewater

Recreational & cultural uses

Industrial & commercial uses
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Andrea Bassi, Millennium Institute
Chien-Chen Huang, The Ohio State University
Gül E. Okudan Kremer  
Professor of Industrial Engineering & Engineering Design  
Summaries of collaborative work with Profs. Karl Haapala, Kyoung-yun Kim, Ratna Chinnam, Leslie Monplaisir, Alper Murat and current and former ADAPS Group Members: Saraj Gupta, Ming-Chuan Chiu, Wu Hsun Chung, Nirup Philip, Ting Lei and Junfeng Ma

Outline

- ADAPS Group
- Sustainable Product Collaboratory Project
- Lessons Learned
- Research Directions
Sustainable Product Collaboratory

Design for Life Cycle

- Low life cycle cost
- Low life cycle environmental impact

Product Family Design & Optimization

Design Complexity
Systematic Design Ideation (TRIZ, SmartPens)

Smart Health (Triage improvement through MAUT, GT)
What is Sustainability?

For the business enterprise, sustainable development means adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today, while protecting, sustaining and enhancing the human and natural resources that will be needed in the future.

International Institute for Sustainable Development (2011)

Sustainability in the Design Stage

The design stage determines 70% of life cycle costs.

It is important that design concurrently considers manufacturing of the product and its supply chain so that a company may gain:

- The ability to reduce waste or increase recyclability of materials
- Supplier selection insight
- Integrated modularity options
- End of life product recovery plans
- Flexibility
- Reduced costs
- Sustainability for profitability
Sustainable Supply Chain Management

The strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its supply chains.

Carter and Rogers (2008)

Broader Methods for Sustainable Design

- General goals for sustainability are to eliminate waste, improve energy efficiency, design products for reuse or recycling, conserve natural habitats and move toward zero consumption of non-renewable resources.

- Stakeholders should be considered including the customers, energy and material suppliers, community, waste contractors, trade associations, environmental agency, professional institutions, employers, local council, manufacturers, and end users.
Optimization Challenge


Collaborative R&D Framework

Jointly developed R&D Framework for Sustainable Product Collaboratory with colleagues from Wayne State & Oregon State
based concept generation to integrate modularity and hybrid design architectures, which enables customization (at the architecture level) to better serve life cycle concerns.
assembly, distribution, sustainment, collection, and disposal.
Tasks

4. Optimization of the product architecture variants while balancing the impact on procurement, manufacturing, distribution, sales/demand, sustainment, collection, and disposal. The algorithms will facilitate joint optimization of the best subset of design variants and configurations with mathematical models of life cycle processes. The research will develop hierarchical optimization models to jointly address the life cycle processes and product architecture.
Functions

Product architecture should be decided for its broader implications on product functions, its manufacturing and supply chain.

Manufacturability and Sustainability

Processes Suppliers

Architecture

Supply Chain Network

Lessons Learned

1. Product architecture & supply chain should be optimized simultaneously

2. Realistic case studies show that cost, lead time and carbon footprint minimization goals favor different type of product architectures

3. Existing modularity methods favor different performance measures

4. Robust modularity methods need to be developed to optimize life cycle costs & a proposed approach
Lesson 1. Product architecture & supply chain should be optimized simultaneously

Bicycle case study developed in collaboration with input/data from industry

- Content expertise pertaining to the components & assembly relations
- Supplier data and locations
- Part data (material, dimensions, cost, etc.)

Software architecture used to minimize bias in generating conceptual designs

- Uses functional decomposition of a product to build the product from bottom-up
- Energy-Material-Signal Diagram defines flows
- Generated designs are modularized based on Decomposition Approach, Design for Assembly filtering is used.

Unbiased experimentation requires automated generation of all design variants. This is accomplished through conceptualizing the product through Energy-Signal-Material modeling and Design for Assembly (DfA) filtering.
Case Study

DfA filtering involves the following criteria:
1) weight, 2) number of unique components, 3) stiffness, 4) length, 5) presence of the base component, 6) vulnerability hardness, 7) shape, 8) size, 9) composing method, 10) composition direction, 11) symmetry, 12) alignment, and 13) joining method.

### Road Bicycle Design
- Sample case, medium complexity
- 6 components with two alternatives
- Yields 64 design combinations with various DfA scores

[Image of a road bicycle with a diagram showing the components: Fork, Frame, Saddle, Structure System, Braking System, Transmission System, Wheel system, Motor, Accessory.]

Sample Design Combinations

**Sample 2-module architecture**

**Bike #13**

- **Structure Module**
  - (A) Saddle
  - (B) Frame
  - (C) Fork
- **Transport Module**
  - (D) Brake
  - (E) Wheel
  - (F) Trans.

**Sample 3-module architecture**

**Bike #13**

- **Structure Module**
  - (A) Saddle
- **Orientation Module**
  - (B) Frame
  - (C) Fork
- **Transport Module**
  - (D) Brake
  - (E) Wheel
  - (F) Trans.
Supplier Optimization for Specific Designs
3) For each component, select one component supplier
4) For each module, select one module supplier
5) For final product, select one final supplier
6) Time constraint from decision maker
7) Cost constraints from decision maker


<table>
<thead>
<tr>
<th>Measures</th>
<th>Only Design is Considered</th>
<th>Both Design &amp; Supply Chain are considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component Cost ($USD)</td>
<td>500.60</td>
<td>500.60</td>
</tr>
<tr>
<td>Assemble Cost ($USD)</td>
<td>39.00</td>
<td>31.00</td>
</tr>
<tr>
<td>Transportation Cost ($USD)</td>
<td>53.23</td>
<td>34.13</td>
</tr>
<tr>
<td>Inventory Cost ($USD)</td>
<td>15.42</td>
<td>15.19</td>
</tr>
<tr>
<td>Total Cost ($USD)</td>
<td>608.25</td>
<td>580.92</td>
</tr>
<tr>
<td>Diff</td>
<td>4.70%</td>
<td></td>
</tr>
<tr>
<td>Total Lead Time (days)</td>
<td>159.5</td>
<td>128.2</td>
</tr>
<tr>
<td>Diff</td>
<td>24%</td>
<td></td>
</tr>
<tr>
<td>Number of suppliers</td>
<td>9</td>
<td>8</td>
</tr>
</tbody>
</table>

**Case Study**

**Part Type Supplier (Process #)**

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Supplier (Process #)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABCDEF</td>
<td>X-bike(1)</td>
</tr>
<tr>
<td>ABC</td>
<td>Topkey(3)</td>
</tr>
<tr>
<td>DEF</td>
<td>Sram(4)</td>
</tr>
<tr>
<td>AB</td>
<td></td>
</tr>
<tr>
<td>BC</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td></td>
</tr>
<tr>
<td>EF</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Selle Royal(12)</td>
</tr>
<tr>
<td>B</td>
<td>Topkey(13)</td>
</tr>
<tr>
<td>C</td>
<td>Advanced(14)</td>
</tr>
<tr>
<td>D</td>
<td>HB(15)</td>
</tr>
<tr>
<td>E</td>
<td>Shimano(16)</td>
</tr>
<tr>
<td>F</td>
<td>Tien Hsin(17)</td>
</tr>
</tbody>
</table>

---

The table above lists the part types and their corresponding suppliers and processes. The diagram illustrates the relationship between different components and the suppliers involved in the process.

**Optimum Solution for the case where only design is considered**

**Optimum Solution for the case where both design & supply chain are considered**
Does modularity level impact the design performance?

2-Module Versus 3-Module Product Architecture in MIP

<table>
<thead>
<tr>
<th></th>
<th>Cost ($USD)</th>
<th>Time (Day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 module Cost</td>
<td>3 module Cost</td>
</tr>
<tr>
<td>Avg.</td>
<td>627.02</td>
<td>631.55</td>
</tr>
<tr>
<td>Diff</td>
<td>-</td>
<td>1%</td>
</tr>
<tr>
<td>STD</td>
<td>84.630</td>
<td>86.351</td>
</tr>
</tbody>
</table>

Lesson 1. Product architecture & supply chain should be optimized simultaneously

- The difference of supply chain consideration:
  - 5% in cost and 24% in lead time.

- The influence of modularity:
  - 2-module architecture dominates in MIN Cost condition,
  - 3-module is superior in time in MIN Lead time condition.


Lesson 2. Cost, lead time and carbon footprint minimization goals favor different type of product architectures

- Previous work
  - Included cost and lead time
  - Design for Assembly (DfA) rankings
  - Product architecture and modularity

- Previous work is expanded to include kg CO₂ equivalent as a sustainability metric accounting for:
  - Material extraction
  - Material processing
  - Transportation
Components and Supplier Options

<table>
<thead>
<tr>
<th>Component</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saddle</td>
<td>Comfortable saddle</td>
<td>Light weight saddle</td>
</tr>
<tr>
<td>Frame</td>
<td>Steel frame w/ suspension</td>
<td>Steel frame w/ suspension</td>
</tr>
<tr>
<td>Fork</td>
<td>Steel fork w/o suspension</td>
<td>Steel fork w/ suspension</td>
</tr>
<tr>
<td>Transmission</td>
<td>Single speed transmission</td>
<td>Transmission w/ six fly wheels</td>
</tr>
<tr>
<td>Brake</td>
<td>Reverse brake rotor</td>
<td>Braking system with brake shoes</td>
</tr>
<tr>
<td>Wheels</td>
<td>Wheels w/ steel spokes</td>
<td>Wheels w/ plastic spokes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBB</td>
<td>Holland</td>
</tr>
<tr>
<td>Bombshell</td>
<td>CA, USA</td>
</tr>
<tr>
<td>ATOM</td>
<td>CA, USA</td>
</tr>
<tr>
<td>Axxis</td>
<td>CA, USA</td>
</tr>
<tr>
<td>SRAM</td>
<td>IL, USA</td>
</tr>
<tr>
<td>Velo</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Tektro</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Shimano</td>
<td>Japan</td>
</tr>
<tr>
<td>ALEX</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Spinner</td>
<td>Taiwan</td>
</tr>
<tr>
<td>Falcon</td>
<td>Taiwan</td>
</tr>
</tbody>
</table>

Analysis Tools

- **SimaPro LCA software** used to calculate kg CO₂ equiv. for materials, processing, and transportation
  - **Life cycle inventory:** ecoinvent database
  - **Impact assessment:** IPCC 2007 GWP 20a V1.02

- **LINGO software** used to find the combination of components, suppliers, and product architecture using non-linear programming to optimize:
  - Cost
  - Lead time
  - Sustainability
### Example: Actual Processes to Produce Steel Fork

### Fork Materials and Processes for Life Cycle Inventory

<table>
<thead>
<tr>
<th>Part</th>
<th>Material</th>
<th>Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fork</td>
<td>Steel, low-alloyed, at plant/RER U</td>
<td>1.105</td>
</tr>
<tr>
<td></td>
<td>Alkyd paint, white, 60% in H2O, at plant/RER U</td>
<td>0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part</th>
<th>SimaPro</th>
<th>Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fork</td>
<td>Drawing of pipes, steel/RER U</td>
<td>1.095</td>
</tr>
<tr>
<td></td>
<td>Steel product manufacturing, average metal working/RER U</td>
<td>1.105</td>
</tr>
<tr>
<td></td>
<td>Sheet rolling, steel/RER U</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Sustainability: Material Compositions

<table>
<thead>
<tr>
<th>Material mass (kg)</th>
<th>B13</th>
<th>B54</th>
<th>SimaPro Process (ecoinvent database)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium carbon steel components (e.g., frame, fork)</td>
<td>7.5294</td>
<td>5.3464</td>
<td>Steel, low-alloyed, at plant/RER U</td>
</tr>
<tr>
<td>Alloy and stainless steel components (e.g., bearings)</td>
<td>2.47</td>
<td>2.784</td>
<td>Steel, electric, chromium steel 18/8, at plant/RER U</td>
</tr>
<tr>
<td>Composite nylon wheels</td>
<td>1.88</td>
<td></td>
<td>Nylon 66, glass-filled, at plant/RER U</td>
</tr>
<tr>
<td>Rubber components (e.g., tires and brake pads)</td>
<td>1.52</td>
<td>1.554</td>
<td>Synthetic rubber, at plant/RER U</td>
</tr>
<tr>
<td>Saddle support structure (shell)</td>
<td>0.41</td>
<td>0.4</td>
<td>Polypropylene, granulate, at plant/RER U</td>
</tr>
<tr>
<td>Saddle cover</td>
<td>0.08</td>
<td>0.07</td>
<td>Polyvinylchloride, suspension polymerised, at plant/RER U</td>
</tr>
<tr>
<td>Saddle padding</td>
<td>0.033</td>
<td>0.024</td>
<td>Polyurethane, flexible foam, at plant/RER U</td>
</tr>
<tr>
<td>Saddle thread</td>
<td>0.006</td>
<td>0.006</td>
<td>Viscose fibres, at plant/GLO U</td>
</tr>
<tr>
<td>Paint</td>
<td>0.06</td>
<td></td>
<td>Alkyd paint, white, 60% in H2O, at plant/RER U</td>
</tr>
<tr>
<td>Saddle glue</td>
<td>0.02</td>
<td></td>
<td>Acrylic binder, 34% in H2O, at plant/RER U</td>
</tr>
</tbody>
</table>
Sustainability: Manufacturing Process

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Mass (kg)</th>
<th>Length (m)</th>
<th>Process Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel component manufacturing (e.g., sprocket cutting/assembly)</td>
<td>9.9994</td>
<td></td>
<td>Steel product manufacturing, average metal working/RER U</td>
</tr>
<tr>
<td>Tube drawing (e.g., frame tubes)</td>
<td>4.9114</td>
<td>4.0254</td>
<td>Drawing of pipes, steel/RER U</td>
</tr>
<tr>
<td>Injection molding (e.g., saddle shell and tires)</td>
<td>1.93</td>
<td>3.834</td>
<td>Injection moulding/RER U</td>
</tr>
<tr>
<td>Wire drawing (e.g., springs and spokes)</td>
<td>0.54</td>
<td>0.775</td>
<td>Wire drawing, steel/RER U</td>
</tr>
<tr>
<td>Forming of medium carbon steel flat stock (e.g., for brackets)</td>
<td>1.044</td>
<td>0.546</td>
<td>Sheet rolling, steel/RER U</td>
</tr>
<tr>
<td>Forming of alloy/stainless steel flat stock (e.g., for sprockets)</td>
<td>1.38</td>
<td>0.035</td>
<td>Sheet rolling, chromium steel/RER U</td>
</tr>
<tr>
<td>Welding of frame (estimated overall weld length)</td>
<td>1 (m)</td>
<td>1 (m)</td>
<td>Welding, gas, steel/RER U</td>
</tr>
</tbody>
</table>

Sustainability - Comparison of carbon footprint

Graph shows the carbon footprint difference of two design variants
**Decision Variables**

MPCF – Carbon footprint for manufacturing and processing the chosen components  
TCF – The total carbon footprint for transporting the chosen components, modules and assembly parameters  
MPXpi – The carbon footprint value for process p and supplier i  
TLDpi – The distance travelled on land for process p and supplier i  
TSDpi – The distance travelled by sea for process p and supplier i  
TLDI – The carbon footprint per ton-mile travelled on land  
TSDI – The carbon footprint per ton-mile travelled by sea  
CWpi – The fraction of a ton for each component or module from process p and supplier i

**Optimization Results**

**NUMERICAL RESULTS**

<table>
<thead>
<tr>
<th>Optimizing (Minimizing)</th>
<th>Cost (US Dollars)</th>
<th>Lead Time (Days)</th>
<th>Carbon Footprint (kg CO2 eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>83.74</td>
<td>54.20</td>
<td>60.48</td>
</tr>
<tr>
<td>Lead Time</td>
<td>109.3</td>
<td><strong>38.80</strong></td>
<td>65.85</td>
</tr>
<tr>
<td>Carbon Footprint</td>
<td>99.94</td>
<td>172.80</td>
<td><strong>44.18</strong></td>
</tr>
</tbody>
</table>

**COST: Product Architecture**

<table>
<thead>
<tr>
<th>Part or Module</th>
<th>Supplier</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABCDEF</td>
<td>X-Bike</td>
<td>PA, USA</td>
</tr>
<tr>
<td>AB</td>
<td>2 Hip</td>
<td>CA, USA</td>
</tr>
<tr>
<td>CD</td>
<td>SRAM</td>
<td>IL, USA</td>
</tr>
<tr>
<td>EF</td>
<td>BBB</td>
<td>Holland</td>
</tr>
<tr>
<td>(A) Saddle</td>
<td>ATOM LAB</td>
<td>CA, USA</td>
</tr>
<tr>
<td>(B) Frame</td>
<td>2 Hip</td>
<td>CA, USA</td>
</tr>
<tr>
<td>(C) Fork</td>
<td>X-Bike</td>
<td>PA, USA</td>
</tr>
<tr>
<td>(D) Brake</td>
<td>SRAM</td>
<td>IL, USA</td>
</tr>
<tr>
<td>(E) Wheel</td>
<td>BBB</td>
<td>Holland</td>
</tr>
<tr>
<td>(F) Trans.</td>
<td>BBB</td>
<td>Holland</td>
</tr>
</tbody>
</table>
Lesson 2. Cost, lead time and carbon footprint minimization goals favor different type of product architectures

- Optimization results point to different product architectures for cost, lead time and CF
- Development of computational artificial intelligence is needed to:
  - Analyze more complex products
  - Exploit objective tradeoffs
  - Improve customization for products


Lesson 3. Existing modularity methods (logic) favor different performance measures

Modularity has implications on:

<table>
<thead>
<tr>
<th>Disassembly</th>
<th>Recycle/reuse/Disposal</th>
<th>Material selection</th>
<th>Serviceability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard time</td>
<td>Component classification</td>
<td>Material properties</td>
<td>Reliability factors</td>
</tr>
<tr>
<td>Energy</td>
<td>Life Cycle spanning</td>
<td>Material compatibility</td>
<td>Repair factors</td>
</tr>
<tr>
<td>Geometrical</td>
<td>Recycling methods</td>
<td>Hazardous material</td>
<td>Human factors</td>
</tr>
<tr>
<td>constraint</td>
<td>Material compatibility</td>
<td>Federal/local regulations</td>
<td>Facility factors</td>
</tr>
<tr>
<td>Accessibility &amp;</td>
<td>Special handling</td>
<td>Material classification</td>
<td></td>
</tr>
<tr>
<td>Positioning</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
We applied Stone et al.'s approach (FHM), Zhang et al.'s approach (B-FES), and Huang and Kusiak's (DA) for modularity on the same product. The final values for the three concepts are: 12.32 for DA, 14.40 for B-FES, and 23.41 for FHM.

Based on these results, we observe that the DA is better in comparison to B-FES and FHM approaches with regards to DFA and DfV index values.

## Comparison of DA & Multivariate Clustering

<table>
<thead>
<tr>
<th>Module</th>
<th>DA (component numbers within module)</th>
<th>Carbon Footprint (465.66 kg CO2 eq.)</th>
<th>MC(I) Interaction weight 0.35; End of life weight 0.65</th>
<th>Carbon Footprint (461.53 kg CO2 eq.)</th>
<th>MC(II) Interaction weight 0.65; End of life weight 0.35</th>
<th>Carbon Footprint (466.16 kg CO2 eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1, 2, 3, 4, 5, 6</td>
<td>25.2</td>
<td>1, 2, 3, 4, 6</td>
<td>21.2</td>
<td>1, 2, 3, 4, 5, 6</td>
<td>25.2</td>
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<tr>
<td>2</td>
<td>7, 8, 9, 10, 11</td>
<td>30.8</td>
<td>5, 10</td>
<td>0.01</td>
<td>7, 8, 9, 10, 11</td>
<td>30.8</td>
</tr>
<tr>
<td>3</td>
<td>12, 13, 26</td>
<td>323</td>
<td>7, 8, 9, 11</td>
<td>30.5</td>
<td>12, 13</td>
<td>321</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>13.6</td>
<td>12, 13, 14, 20, 21, 22, 26</td>
<td>352.6</td>
<td>14, 21, 22</td>
<td>24.3</td>
</tr>
<tr>
<td>5</td>
<td>15, 16, 17, 18</td>
<td>40.3</td>
<td>15, 16, 17, 23</td>
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<td>15, 16, 17</td>
<td>37.7</td>
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<tr>
<td>6</td>
<td>20</td>
<td>6.07</td>
<td>18</td>
<td>1.72</td>
<td>18</td>
<td>1.72</td>
</tr>
<tr>
<td>7</td>
<td>21, 22</td>
<td>9.03</td>
<td>19, 24, 25</td>
<td>15.2</td>
<td>19, 23, 24, 25</td>
<td>17.7</td>
</tr>
<tr>
<td>8</td>
<td>23, 24</td>
<td>3.26</td>
<td></td>
<td>20, 26</td>
<td></td>
<td>7.74</td>
</tr>
<tr>
<td>9</td>
<td>19, 25</td>
<td>14.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Results show reduction in carbon footprint.
Results show easy to separate subassemblies for disposal and recycle.

Implemented within the dedicated software environment.
Lesson 4. Robust modularity methods need to be developed to optimize life cycle costs & a proposed approach.
**Methodology Flow**

Step 1: Construct a connectivity graph for the product based on component interactions and component attributes.

Step 2: Use the SC model to evaluate the initial modular structure.

Step 3: Form an initial modular structure on the connectivity graph.

Step 4: Use the heuristic based on the output of SC model to generate promising modular structures for evaluation.

Step 5: Use the SC model to evaluate the promising modular structures generated.

Step 6: Can the objective value be improved?

- Yes: Update the modular structure with the one having the min. value.
- No: A near-optimal modular structure.

**Connectivity Graph**

Component Attributes (Vertices)

- Component 1
  - Mfg. cost ($): 19.10
  - Mfg. energy (kWh): 8.3
  - Weight (g): 2693
  - MTBF (month): 336
  - Reuse value ($): 19.2
  - Recyclng value ($): 0.78
  - End-of-life option: RU/RC/D
  - Service intent: Y/N

Component Interactions (Edges)

- Component 1 - Component 2: Assembly time (sec): 20, Assembly cost ($): 0.184, Assembly energy (kWh): 0.084
- Component 2 - Component 3: Disassembly time (sec): 20, Disassembly cost ($): 0.084, Disassembly energy (kWh): 0.084
- Component 3 - Component 4: Disassembly time (sec): 20, Disassembly cost ($): 0.084, Disassembly energy (kWh): 0.084
- Component 4 - Component 5: Disassembly time (sec): 20, Disassembly cost ($): 0.084, Disassembly energy (kWh): 0.084

**Design Structure Matrix**

- RU: Reuse
- RC: Recycling
- D: Disposal
Formulation of the Supply Chain Optimization Model

**Objective**

\[ \text{Min} \quad Z_{LCC} \]

\[ \text{Min} \quad Z_{LCEC} \]

where

\[ Z_{LCC} \text{ the life cycle cost in the supply chain (\$)} \]

\[ Z_{LCEC} \text{ the life cycle energy consumption in the supply chain (kWh)} \]

**Constraints**

**Forward Logistics Balance (Pull)**

\[ \sum \text{outbound product/module flow from the facilities in the forward flows} = \sum \text{inbound component/module/product flow to the facilities in the forward flows} \]

**Reverse Logistics Balance (Push)**

\[ \sum \text{outbound module flow from the facilities in the reverse flows} = \sum \text{inbound component/module/product flow to the facilities in the reverse flows} \]
The Criteria for Evaluating Potential Modular Structures in Costs

When the capacity is insufficient, the reuse/recycling value is divided by the resource required.
Numerical Examples:

Refrigerator & Coffee Maker

The product data set for the refrigerator is based on data from Umeda et al.’s work (2000) and is supplemented by data from websites.

The data set for the coffee maker (Product Model: Mr. Coffee PR15) is based on product dissection and supplemented by the literature.

Connectivity Graph of the Refrigerator
Component Interactions in DSM

- Disassembly times
- Disassembly costs
- Assembly times
- Assembly costs

Processing Facilities

<table>
<thead>
<tr>
<th>Process</th>
<th>Process description</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Product and module assembly</td>
<td>F1, F2, F3</td>
</tr>
<tr>
<td>P2</td>
<td>Service (maintenance)</td>
<td>F4, F5</td>
</tr>
<tr>
<td>P3</td>
<td>Product collection and disassembly</td>
<td>F6, F7</td>
</tr>
<tr>
<td>P4</td>
<td>Module inspection and rebuild</td>
<td>F8, F9</td>
</tr>
<tr>
<td>P5</td>
<td>Material recycling</td>
<td>F10, F11</td>
</tr>
<tr>
<td>P6</td>
<td>Disposal</td>
<td>D1, D2</td>
</tr>
</tbody>
</table>
Effectiveness refers to how good the quality of the modular structure found by ASCEM is. It indicates how far the life cycle performance (LCC or LCEC) of the modular structure is from the true optimal modular structure, and is measured by LCC or LCEC difference in percentage.

Efficiency refers to how quickly a near-optimal modular structure can be found and is measured by the number of iterations taken by the supply chain optimization model to reach the near-optimal modular structure, and is measured by LCC or LCEC difference in percentage.

Performance of ASCEM - Refrigerator

Effectiveness

LCC Comparison

Difference: 0.03%

Max LCC
LCC-SCEM
Min LCC

Efficiency

Iteration Comparison

Max LCEC
LCEC-SCEM

LCEC Comparison

Difference: 0.44%

Iteration Comparison

Iterations taken by SCEM
Total number of feasible structures
Lesson 4. Robust modularity methods should be developed to optimize life cycle costs

<table>
<thead>
<tr>
<th>Category</th>
<th>Small products</th>
<th>Large product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested product</td>
<td>Coffee maker</td>
<td>Refrigerator</td>
</tr>
<tr>
<td>Number of vertices (components)</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>Number of edges (interactions)</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td>LCC-ASCEM</td>
<td>16.37</td>
<td>751.72</td>
</tr>
<tr>
<td>Min LCC</td>
<td>16.37</td>
<td>751.48</td>
</tr>
<tr>
<td>Effectiveness: Difference%</td>
<td>0%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Max LCC</td>
<td>17.99</td>
<td>896.28</td>
</tr>
<tr>
<td>Efficiency: Iterations used</td>
<td>26</td>
<td>55</td>
</tr>
<tr>
<td>Total number of feasible structures</td>
<td>2,583</td>
<td>4,173,557</td>
</tr>
<tr>
<td>LCEC-ASCEM</td>
<td>8.1544</td>
<td>351.66</td>
</tr>
<tr>
<td>Min LCEC</td>
<td>8.1533</td>
<td>350.12</td>
</tr>
<tr>
<td>Effectiveness: Difference%</td>
<td>0.014%</td>
<td>0.44%</td>
</tr>
<tr>
<td>Max LCEC</td>
<td>8.67</td>
<td>425.2</td>
</tr>
<tr>
<td>Efficiency: Iterations used</td>
<td>31</td>
<td>86</td>
</tr>
<tr>
<td>Total number of feasible structures</td>
<td>2,583</td>
<td>4,173,557</td>
</tr>
</tbody>
</table>
Goal is to seamlessly infuse data sources into decision making (e.g., World Bank data on countries’ capabilities in manufacturing, logistics, and business operations.)
For more information on these works, contact information is provided below.

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Tel: 814 8631530
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Measurement Science for Sustainable Construction and Manufacturing

Breakout 4
Economic, Environmental, and Social Aspects

Cliff I. Davidson
Thomas & Colleen Wilmot Professor of Engineering
Director, Center for Sustainable Engineering
Syracuse University

ASCE, Reston, Virginia
June 12, 2014

Outline

Economic, Environmental, and Social Issues summarized from papers by participants of Breakout 4:

- Individual buildings
- Infrastructure projects
- Entire urban areas
- Overarching issue: Changing Human Behavior
Individual Buildings

Design → Construction → Operation & Use → Demolition

• Ability to incorporate sustainability decreases as we move forward

• Previously: cost dominated design considerations. New software includes sustainability, but not used much (Athena Sust. Materials Inst.)

• Could apply current knowledge of sustainable product manufacturing to buildings (RFID tags to track logistics)

• Data collection during construction
  -- Energy, materials, water, social issues
  -- Embedded energy and water in materials

• Data collection during use phase
  -- Sensors for microclimate, HVAC, lighting, electricity, appliance use, flow of people
  -- Personal monitors - air quality, noise, vibrations
  -- Monitors for interaction with natural environment - wind, temp, humidity, rain runoff, vegetation growth
Individual Buildings

• Data collection during demolition
  -- Degradation of building envelope over time
  -- Differences in degradation for different parts of the building
  -- Re-use, recycle building components

Infrastructure Projects

Design → Construction → Operation & Use → Demolition

• As with individual buildings, ability to incorporate sustainability decreases as we move forward
• Indicators of safety are well-established - need the equivalent for sustainability
• Need for quantifiable social sustainability metrics
Infrastructure Projects

Design → Construction → Operation & Use → Demolition

• Need to make infrastructure more resilient
  -- Performance of infrastructure during disasters such as severe storms, terrorist attacks, evacuation
  -- Avoiding increase in vulnerability due to human development close by - buildings adjacent to a major roadway
  -- Avoiding increase in vulnerability by not accounting for natural processes - beach erosion

Urban areas

• Establish ability to obtain large data sets for metabolism of a city
  -- Flows of energy, materials, water, people, information

• Can we use such data to improve Quality of Life and resilience?
  -- Energy balance, material balance, water balance
  -- How people are spending their time in cities: Performing services, engaged in recreation, engaged with family, etc.
  -- Health monitoring of people in cities
Urban areas

Reduce social inequity

• Low income and minority residents in cities are generally under-represented in decision making
  -- distrust of government
  -- language problems
  -- previously marginalized

• Necessary for engineers to make special effort to bring these people into discussion

Changing Human Behavior

Habits are difficult to break

• Change requires several steps: first step is the desire to change

• Do most people understand the impact of their day-to-day activities?

• To explore the answer for one example situation, survey was conducted

• Questions involved estimating the energy consumption for normal household activities.
Question 1:

“A 100-watt incandescent light bulb uses 100 units of energy in one hour. How many units of energy do you think each of the following devices typically uses in one hour?”

- A compact fluorescent light bulb that is as bright as a 100-watt incandescent light bulb
- An electric clothes dryer
- A portable heater
- A room air conditioner
- A central air conditioner
- A dishwasher

Question 2:

“Turning off a 100-watt incandescent light bulb for one hour saves 100 units of energy. How many units of energy do you think each of the following changes will save?”

- Replacing one 100-watt incandescent bulb with equally bright compact fluorescent bulb that is used for one hour
- Replacing one 100-watt kitchen bulb with a 75-watt bulb that is used for one hour
- Drying clothes on a clothes line for one load
- Turning up the thermostat on your air conditioner by 5°F in summer
Human perceptions of home energy use
Attari, Dekay, Davidson, Bruine de Bruin (PNAS, 2010)

- Perception curve is relatively flat
  - Slight overestimate for low energy appliances
  - Large underestimate for high energy appliances where perceptions are most important
- Overall perceptions show an underestimate of a factor of 2.8
Conclusions

• We have the capability to collect large quantities of technical data, but we need to determine which technical data are most important for understanding sustainability in manufacturing and infrastructure development.

• It is much more difficult to collect data to quantify social sustainability and assess our progress.

• Achieving change in human behavior in the correct direction will require educational efforts for people to understand the impacts of their activities and how to reduce them.
The Quantified Community: Measuring, Modeling, and Understanding the Urban Environment

Dr. Constantine E. Kontokosta, PE, AICP, LEED AP, FRICS
Deputy Director, NYU-CUSP
Director, NYU Center for the Sustainable Built Environment
Associate Research Professor, NYU-Polytechnic School of Engineering
Head, Quantified Community Research Initiative

The CUSP vision includes New York City as its laboratory

The Center for Urban Science and Progress (CUSP) is a unique public-private research center that uses New York City as its laboratory and classroom to help cities around the world become more productive, livable, equitable, and resilient. CUSP observes, analyzes, and models cities to optimize outcomes, prototype new solutions, formalize new tools and processes, and develop new expertise/experts. These activities will make CUSP the world’s leading authority in the emerging field of “Urban Informatics.”
## The CUSP Partnership

### University Partners
- NYU/ NYU-Poly
- The City University of New York
- Carnegie Mellon University
- University of Toronto
- University of Warwick
- IIT-Bombay

### National Laboratories
- Brookhaven
- Lawrence Livermore
- Los Alamos
- Sandia

### Industrial Partners
- IBM
- Microsoft
- Xerox
- Cisco, Con Edison, Lutron, National Grid, Siemens
- AECOM, Arup, IDEO

### City & State Agency Partners
- The City of New York
- Buildings
- City Planning
- Citywide Administrative Services
- Design and Construction
- Economic Development
- Environmental Protection
- Finance
- Metropolitan Transportation Authority
- Fire Department
- Health and Mental Hygiene
- Information Technology and Telecommunications
- Parks and Recreation
- Police Department
- Sanitation
- Transportation

A diverse set of other organizations have expressed interest in joining the partnership.

---

### Urban Data Sources

- **Organic data flows**
  - Administrative records (census, permits, ...)
  - Transactions (sales, communications, ...)
  - Operational (traffic, transit, utilities, health system, ...)
  - Twitter feeds, blog posts, Facebook, ...

- **Sensors**
  - Personal (location, activity, physiological)
  - Fixed *in situ* sensors
  - Crowd sourcing (mobile phones, ...)
  - Choke points (people, vehicles)

- **Opportunities for “novel” sensor technologies**
  - Visible, infrared and spectral imagery
  - RADAR, LIDAR
  - Gravity and magnetic
  - Seismic, acoustic
  - Ionizing radiation, biological, chemical
  - ...

---
What can cities do with the data?

- **Optimize operations**
  - traffic flow, utility loads, services delivery, ...
- **Monitor infrastructure conditions**
  - bridges, potholes, leaks, ...
- **Infrastructure planning**
  - zoning, public transit, utilities
- **Model the dynamics of land use and neighborhood change**
- **Public health**
  - Nutrition, epidemiology, environmental impacts
- **Identify and respond to abnormal conditions and shocks**
  - Hazard detection, emergency management
- **Data-driven formulation of performance-based policies**
  - Energy use, road pricing and congestion charging, etc.
- **Improve regulatory compliance** (“nudges”, efficient enforcement)
- **Inform, empower, and engage residents**

The Quantified Community (QC)

*Understanding the Patterns of Urban Life*

The CUSP “Quantified Community” (QC) will be a fully instrumented urban neighborhood that uses an **integrated, expandable sensor network and citizen engagement** to support the measurement, integration, and analysis of neighborhood conditions. Through an **informatics overlay**, data on physical and environmental conditions and use patterns will be processed in real-time to **maximize operational efficiencies, improve quality of life for residents and visitors, and drive evidence-based planning.**
Huge New York Development Project Becomes a Data Science Lab

By STEVE LOHR

April 14, 2014, 7:00 am

NYU’s CUSP to Turn Hudson Yards into New York City’s First Smart Development

By David Sokol

May 02, 2014

Buildings
Resource consumption; indoor air quality; productivity, health measures

Infrastructure
Solid waste, storm-water management, power generation/distribution

Safety and Security
Network Security, Situational Awareness, Emergency Management Integration, Event Forecasting

Environment
carbon emissions; air pollution and particulates; noise; climate

People
Behavior; mobility; health; activity; social networks, metagenomics
Next Steps

- Pilot project underway
  - Initial data by Fall 2014; simulation and modeling by early Spring 2015
- Planning of “informatics overlay” at Hudson Yards underway
  - Focus on district infrastructure and first building to be completed
  - Data-driven construction safety, mobility, and logistics optimization project in development
- Hiring postdocs/research scientists
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Population and Carrying Capacity: Metrics for Sustainability

Eugenia Kalnay\textsuperscript{1}, Jorge Rivas\textsuperscript{2}, and Safa Motesharre\textsuperscript{1,3}

\textsuperscript{1}University of Maryland; \textsuperscript{2}University of Minnesota; \textsuperscript{3}National Socio-Environmental Synthesis Center (SEYSNC)

Presentation at the NIST-UMD Workshop on Measurement Science for Sustainable Construction and Manufacturing June 12, 2014

Growth of Population and GDP/Capita: Consumption of Resources is their Product!

\begin{tabular}{|c|c|}
\hline
Year & Population (b) \\
\hline
1AD & 0.3b \\
1650 & 0.5b \\
1804 & 1.0b \\
1927 & 2.0b \\
1960 & 3.0b \\
1975 & 4.0b \\
1987 & 5.0b \\
1998 & 6.0b \\
2011 & 7.0b \\
\hline
\end{tabular}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{population_gdp.png}
\caption{World Population and GDP per Capita, 0 to 2000 A.D.}
\label{fig:population_gdp}
\end{figure}

Maddison, (2001)
Why was the population able to grow so fast since the 1950’s?

Two reasons:
1) Sanitation and Antibiotics (Public Health → living longer)
2) **Use of fossil fuels in agriculture** starting in the 1950’s:
   - fertilizers, pesticides, irrigation, mechanization (Green Revolution).

1950 to 1984: production of grains increased by 250% and the population doubled

Without fossil fuels population would be much smaller!

- Growth in grain production is now flattening out
- Industrial farming is destroying forests, soil
- Urban and suburban sprawl is overrunning best farmland

This is not sustainable: “We are drawing down the stock of natural capital as if it was infinite” (Herman Daly)

---

**Standard Neoclassical Economic Model**

As Herman Daly, Robert Costanza, and other scholars in the field of Ecological Economics describe,

![Diagram of Standard Neoclassical Economic Model]

The standard Neoclassical Economic Model does not account for:

- Inputs (resources)
- Outputs (pollution)
- Stocks of Natural Capital
- Dissipation of Energy (i.e., a Perpetual Motion Machine)
- Depletion, Destruction or Transformation of Matter

Therefore, no *effects on the Earth System*, and *No Limits to Growth*. 
Realistic **Ecological** Economic Model (Herman Daly)

- Incorporates INPUTS, including **DEPLETION** of **SOURCES**
- Incorporates OUTPUTS, including **POLLUTION** of **SINKS**

```
Inputs:
1. Energy
   Oil, Coal, Gas, Nuclear, Biomass, Renewables, etc

2. Matter
   Soil, Minerals, Lumber, and Other Material Resources

Outputs:
1. Emissions
   CO2, Methane, etc

2. Waste Products
   Garbage, Toxics, etc

3. Surface Changes
   Urbanization, Deforestation, Desertification, etc
```

Sources:
- Stock of Natural Capital
- Flows of Energy

"Empty World" Model

- Throughout most of human history, the **Human Economy** was so **small** relative to the **Earth System**, that it had little impact on the **Sources** and **Sinks**.
- In this scenario, the standard isolated economic model might have made sense.
“Full World” Ecological Economic Model

- Today, the Human Economy has grown so large, it has very large Effects on the Earth System, Depleting the Sources and Filling the Sinks. It is clear that growth cannot continue forever.
Could an advanced society like ours **collapse**?

- **Collapses of many advanced societies** have taken place in the last 5000 years!
- A recent study of the many collapses that took place in Europe has excluded climate forcing, war, and disease as the root cause of such collapses, so that it concluded:
  - The collapses were due to **overrunning the Carrying Capacity**
- We developed a “Human and Nature Dynamical model” (**HANDY**) to start understanding the nonlinear feedbacks between the Earth and the Human System.

**HANDY**: **Human and Nature Dynamical model** with Rich and Poor: **for Thought Experiments**

**Commoner Population**

\[ \dot{x}_C = \beta_C x_C - \alpha_C x_C \]

**Elite Population**

\[ \dot{x}_E = \beta_E x_E - \alpha_E x_E \]

**Nature**

\[ \dot{y} = \gamma y (\lambda - y) - \delta x_C y \]

**Wealth**

\[ \dot{w} = \delta x_C y - C_C - C_E \]
State Variables (Stocks) and Flows in HANDY1

- **Population (Elite & Commoner)**
  - Births
  - Deaths
- **Nature**
  - Regeneration
  - Depletion
- **Wealth**
  - Production (= Depletion)
  - Consumption

**Carrying Capacity**

- **Carrying Capacity**: The population level that the resources of a particular environment can sustain over the long term

Carrying Capacity in HANDY: \[ \chi = \frac{\gamma}{\delta} \left( \lambda - \eta \frac{s}{\delta} \right) \]

Maximum Carrying Capacity: \[ \chi_M = \frac{\gamma}{\eta s} \left( \frac{\lambda}{2} \right)^2 \]
Experiments for an Egalitarian Society

High depletion rate can lead to collapse.

What if we introduce Inequality?

Up until $t = 500$, both scenarios show the exact same dynamics.
An otherwise *sustainable* society could collapse if there is high inequality ($\kappa = 100$).

What happens if we have *both* high inequality and high depletion rate?

Typical Collapse: High Depletion Rates and High Inequality at the same time

*Is there any hope for an unequal society to survive?*
If we reduce the *depletion per capita* and *inequality*, and slow down the *population growth*, it is possible to reach a steady state and survive well.

Reaching this equilibrium requires **changes in policies**:

- Reduce depletion per capita
- Reduce inequality ($\kappa = 10$)
- Reduce population growth

Could a collapse be prevented if we have large stocks of Nonrenewable Energy?

What happens when we add fossil fuels?

This is the classic HANDY1 full collapse scenario, with only regenerating Nature. We then add to the regenerating Nature a nonrenewable Nature.
Impact of adding fossil fuels (nonrenewable energy resources)

The collapse is postponed by ~250 years and the peak population increases by a factor of ~25!

State Variables (Stocks) and Flows in HANDY1

- Births
- Population (Elite & Commoner)
- Deaths

- Regeneration
- Nature
- Depletion

- Production (= Depletion)
- Wealth
- Consumption
Metrics for Sustainability

The conditions for sustainability of **resources** depend on their **type**:

1. **Regenerating resources** (e.g., forests, fisheries, herds):
   
   \[ \text{Total Depletion Rate} \leq \text{Regeneration Rate} \]

2. **Renewable resources** (e.g., Flows of solar and wind):
   
   *Sustainable by definition*, since the total extraction rate is always smaller than the flow rate.

Also, consumption of Accumulated Wealth must be sustainable to ensure societal sustainability, therefore:

\[ \text{Total Consumption} \leq \text{Total Production} \]

But what about **Nonrenewables**? Could their extraction be **sustainable**?

A Metric for Sustainability of Nonrenewables

We define a new metric **Time to Depletion**, \( T_N(t) \), for Nonrenewable resources (e.g., fossil fuels, aquifers, minerals):

\[ T_N(t) = \text{Time to Depletion} = \frac{\text{Total Nonrenewable Stock}}{\text{Depletion rate of Nonrenewables}} = \frac{y_N(t)}{D_N(t)} \]

For extraction of nonrenewables to be **sustainable**, **Time to Depletion** has to increase with time:

\[ T_N(t + dt) \geq T_N(t) \]

It can be shown that this is equivalent to:

\[ \frac{d^2}{dt^2} \left( \log y_N(t) \right) \geq 0 \]

This also means that the **net depletion** rate of nonrenewables must **decrease** with time if their extraction is to be sustainable.
CONCLUSIONS

• The Human System has dominated the Earth System.
• In order to assess Societal Sustainability and issues like Climate Change, we need to couple the Earth System with Population, include bidirectional (two-way) feedbacks, and take into account the impact of policies on longer time scales (>50 years, >2 generations).
• Carrying Capacity is a widely applicable measure for societal sustainability.
• Additional sustainability metrics are also derived for all three types of resources.
• For Regenerating resources, net depletion must be within net regrowth rate of the resource.
• Extraction of Renewables is inherently sustainable.
• For Nonrenewables, Time to Depletion must increase with time.
• Therefore, net depletion of Nonrenewables has to decrease.
• This means if population is relatively steady, depletion per capita of nonrenewables must decrease with time.
National Institute of Standards and Technology

Measurement Science for Sustainable Construction and Manufacturing

Challenges and Metrics in Public Buildings and Infrastructure

David Dise, Director
Department of General Services
david.dise@montgomerycountymd.gov

DEPARTMENT OF GENERAL SERVICES

• Completed over 50 capital projects since 2007
• $1.2 billion in planning, design and construction costs
• Project range from $1M to $100M+
• More than 50 active projects in design or construction
• Custodian of 412 buildings, 9.5 million square feet
DEPARTMENT OF GENERAL SERVICES

Priorities for facility performance:
• Low environmental impact
• Durability
• Low, long-term O&M
• Long operating hours
• Flexibility for varying uses
• Resiliency

DEPARTMENT OF GENERAL SERVICES

Sustainability priorities in new capital projects:
• Passive solar design
• Daylight harvesting
• Geothermal
• Designed for future active solar
• Water capture/reuse
• Reduced impervious surface
• Use of rapidly renewable/recycled materials
Example Projects:

CHALLENGES

- Competing priorities
  - Budget vs. ROI
  - Environmental Impact
  - Durability
  - Community concerns and interests
- Regulatory requirements
- Internal client expectations
Equipment Maintenance and Transit Operations Center

Case Study: Equipment Maintenance and Transit Operations Center

- Multiple buildings
- 200+ transit buses, highway trucks and equipment, and some light duty fleet
- Fueling facility
- LEED Gold
- Tight site conditions
- Plan for future capacity
- Energy efficiency
- Light harvesting
- 400 kW of Onsite Solar – potential for expansion.
- 4 acres of vegetative roof
- Continuing measurement and verification
- On-site compressed natural gas
Future Efforts

- More aggressive solar photovoltaic/thermal
- Combined Heat and Power/Microgrids
- Expanded occupant education/engagement
- Innovative P3 opportunities
Needed Metrics to Facilitate Sustainable Construction

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Measuring Sustainable Construction

By Fulya Kocak, LEED AP, BD+C, GGP
Clark Construction Group, LLC

How do we measure Sustainability in Construction Industry?
But first...
What is Sustainable Construction?

Constructing Green Buildings?
Capabilities in LEED Certification?

CERTIFIED 40-49 points
SILVER 50-59 points
GOLD 60-79 points
PLATINUM 80+ points

Health & Well Being?
Environmental Compliance?

Environmental Management Systems?

ISO 14001
Education and Awareness?

Reducing disruption to land & habitats?
Minimized transportation?

Progress in new green technologies & products?
Minimizing pollution during construction operations?

Reduce, Reuse, Recycle Construction Waste?
Making green buildings cost effective?

Assisting the clients build green?
Supporting local communities & businesses?

Tracking carbon emissions from construction operations?
Marketing?

Profitability?
Challenges?

Various meanings and priorities for sustainability
Lack of client demand
High cost, low tangible benefits
Lack of awareness
Limited resources
Long-term commitment
Slow progress

Opportunities

Profitability,
Competitive Advantage,
Reduced liability and risk,
Employee satisfaction.
United States Manufacturing Industry

Manufacturing industry
• Constitutes 11% of GDP
• Employs 12 million people
• Employs 60% of engineers and scientists
• Accounts for ~30% of primary energy consumption in the United States\(^1\)

AMO programs target:
• Research, Development and Demonstration of new, advanced processes and materials technologies that reduce energy consumption for manufactured products and enable life-cycle energy savings
• Efficiency opportunities through deployment of known technologies to existing manufacturing practices, especially for energy-intensive steam, process heating, and machine drive end-uses

\(^1\)historically program has communicated in terms of site energy use; little precedent for materials flows, cross-sector impacts, economics & competitiveness.
Manufacturing and Advanced Manufacturing

“The economic evidence is increasingly clear that a strong manufacturing sector creates spillover benefits to the broader economy, making manufacturing an essential component of a competitive and innovative economy.”

Gene Sperling, Director of the National Economic Council
Remarks at the Conference on the Renaissance of American Manufacturing, March 27, 2012

“There is a close connection between R&D and manufacturing in many of the emerging sectors ....... R&D engineers may have to stay close to manufacturing to develop new strategies for making processes more efficient. The tighter integration of innovation and production may also present opportunities to bring design closer to end users, as advanced manufacturing technologies make it possible to produce higher-value goods at lower volume.”

Professor Suzanne Berger, co-chair of MIT’s Production in the Innovation Economy (PIE)

“Advanced Manufacturing involves both: new ways to manufacture existing products, and especially the manufacture of new products emerging from new advanced technologies.”

President’s Council of Advisors on Science and Technology,
“Report to the President on Ensuring America’s Leadership in Advanced Manufacturing,” June 2011

Advanced Manufacturing and Clean Energy at DOE

**Advanced Manufacturing**
Making things in a manner such that technology provides a competitive advantage over the practices widely in use.

**Clean Energy Manufacturing**
Making things such that environmental impact is reduced in the making, use, or disposal of the product made.
The “Missing Middle”

Target: Reduce life-cycle energy consumption of select manufactured products by 50% within 10 years of the start of each development effort

Target: Reduce manufacturing energy intensity by 25% over ten years

• Leverage Federal support of basic research
• Partner with the private sector to accelerate commercialization

Advanced Manufacturing Office – focus on Technologies

Technologies

Processes, Materials, Enabling

Existing
• Technologies and materials that already exist and no further improvements are required

Emerging
• Technologies and materials that are incrementally improving their performance and are under continuing improvement

Advanced
• New generation technologies and materials that offer “breakthrough” performance advancements
Advanced manufacturing and supply chains

Future supply chains dependent upon advanced manufacturing technologies

What is Advanced Manufacturing?

Advanced Manufacturing is the creation of integrated solutions that require the production of physical artifacts coupled with value-added services and software, while exploiting custom-designed and recycled materials using ultra-efficient processes.

Supply chains and U.S. manufacturing competitiveness

EERE’s Clean Energy Manufacturing Initiative (CEMI):

1. Increase U.S. competitiveness in the production of clean energy products

   Products that generate clean energy
   Products that save energy and increase efficiency

2. Increase U.S. manufacturing competitiveness across the board by increasing energy productivity and use of clean and low-cost fuels and feedstocks

   Advanced Manufacturing Technologies
   Industrial Energy Efficiency
   Combined Heat & Power
   Low-Cost Natural Gas
Drivers affecting US Manufacturing

“......natural gas is likely to remain 50 to 70 percent cheaper in the U.S. than in Europe and Japan ...”

Boston Consulting Group analysis

Shale gas production has more than doubled since January 2010.

Dry shale gas production
In billions of cubic feet per day each month

This has helped increase overall U.S. natural gas production, despite flat to declining production in traditional gas fields. In the future, shale gas is expected to play an even bigger role.

U.S. natural gas production
In trillions of cubic feet per year by type of gas

Natural gas wellhead prices crashed in April. They have recovered somewhat but remain near the lowest level in the past decade.

U.S. natural gas wellhead prices
In dollars per thousand cubic feet

Sources: Lippman Consulting, U.S. Energy Information Administration. The Washington Post. Published on November 14, 2012, 8:00 p.m.

Evaluating US Manufacturing competitiveness

Solar, wind batteries, carbon fiber, WBG semiconductors

1. Characterize the current industry structure (develop a benchmark)
2. Map the value stream
3. Develop a high-level understanding of manufacturing cost drivers
4. Identify areas where the United States has (or may have) viable manufacturing opportunities
5. Select technologies for analytical “deep dive”
   - Refine market analysis
   - Develop cost models
   - Assess qualitative factors driving factory location decisions

Regional carbon fiber reinforced plastics market values (billion $/# mfg. sites)

Evaluating competitiveness starts with technologies

AMO targets investments in high impact technologies

- **Transformative:** Results in significant change in the life-cycle impact (energetic or economic) of manufactured products

- **Pervasive:** Creates value in multiple supply chains, diversifies the end use/markets, applies to many industrial/use domains in both existing and new products and markets

- **Globally Competitive:** Represents a competitive/strategic capability for the United States

- **Significant in Clean Energy Industry:** Has a quantifiable energetic or economic value (increase in value-added, increase in export value, increase in jobs created)

---

**Wide range of metrics**

<table>
<thead>
<tr>
<th>Relevant Technology Characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High level drivers:</strong></td>
<td><strong>More detailed metrics:</strong></td>
</tr>
<tr>
<td>Enabling?</td>
<td>Production volume (units per year)</td>
</tr>
<tr>
<td>Add-value?</td>
<td>Process cycle time (time per unit)</td>
</tr>
<tr>
<td>Add quality?</td>
<td>Percent cost reduction (relative to current)</td>
</tr>
<tr>
<td>Reduce energy use?</td>
<td>Percent weight reduction (relative to current)</td>
</tr>
<tr>
<td>Reduce materials waste?</td>
<td>Energy cost savings target?</td>
</tr>
<tr>
<td>Improve production speed?</td>
<td>Others?</td>
</tr>
<tr>
<td>Others?</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barriers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology risks/uncertainties</td>
<td>Technical limitations</td>
</tr>
<tr>
<td>Availability of verifiable testing capabilities</td>
<td>Lack of knowledge</td>
</tr>
<tr>
<td>High capital cost</td>
<td>Insufficient tools</td>
</tr>
<tr>
<td>High material cost</td>
<td>Workforce availability</td>
</tr>
<tr>
<td>Material supply chain insecurity</td>
<td>Other?</td>
</tr>
<tr>
<td>Lack of customer demand</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Existing Approaches</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal assets (R&amp;D; technology experts, etc.)</td>
<td>Universities</td>
</tr>
<tr>
<td>Consultants</td>
<td>Shared R&amp;D facility (capable of precompetitive and protected work)</td>
</tr>
<tr>
<td>Commercial labs</td>
<td>Other?</td>
</tr>
<tr>
<td>Technology vendors</td>
<td></td>
</tr>
</tbody>
</table>
Life cycle approach to better understand system-wide impacts

Energy Use in Manufacturing Process
New products or processes may lead to change in energy use in manufacturing sector.

Energy Use in Environment
Change occurs in energy use across sectors as a result of deployment of new product.

Flow of Energy through the U.S. Economy

Estimated U.S. Energy Use in 2012: ~95.1 Quads

Source: LLNL 2012. Data is based on EIA's '9000 Data Sets of US Energy 2013-13'. Note: If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, unless otherwise specified. Data was performed Distributed electricity represents only retail electricity sales and does not include self-generation. All reports use the energy content of renewable resources (i.e., hydro, wind, geothermal, solar for electricity, or ethanol for gasoline) in 2010-12. The efficiency of electricity production is calculated as the percentage of the energy content of renewable resources. The efficiency of the fossil fuel generation in 2010-12 was 15%. The efficiency of the commercial sector is 80% for the residential sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-LL-0415027
The opportunity space: economy-wide energy impacts resulting from clean energy manufacturing.

Products for clean & efficient energy generation & delivery

Energy Production
- Electricity production
  - 40 Q Input
  - 14.3 Q generated
  - 25.7 Q rejected

Non-electricity production

Energy Use

Buildings Energy Use
- 18.9 Q input
- 12.3 Q used
- 6.6 Q rejected

Transportation Energy Use
- 26.7 Q input
- 5.6 Q used
- 21.1 Q rejected

Industrial Energy Use
- 23.9 Q input
- 19.1 Q used
- 4.8 Q rejected

Manufacturing

Opportunity space impacted by manufacturing:
- More effective utilization of 37 Q used
- Reduction of the 58 Quads wasted

* >30% is feedstock

Primary Energy Consumption by sectors, 2012 (Total 95 Quads)

Systems Approach – What affects the system?

Carbon Intensity, e.g.:
- Feedstock substitution
- Green chemistry
- Biomass-based fuels
- Process changes

Energy Intensity e.g.:
- Process Efficiency
- Electrotechnologies
- Process integration
- Waste heat recovery
- Supply chain integration

Use Intensity e.g.:
- Recycling
- Reuse and remanufacturing
- Material efficiency and substitution
- By-products
- Behavioral change
- Product-Service-Systems

Drivers to reduce energy & emissions through the product lifecycle
Where do we start? Energy data...

- National sample survey that collects information on the stock of U.S. manufacturing establishment, their energy-related building characteristics, and their energy consumption and expenditures.
  - 250,000 U.S. manufacturing plants
  - Statistical sample of approximately 15,500 establishments are surveyed representing 97% - 98% of U.S. manufacturing payroll and energy consumption
- MECS data released every four years
  - Current footprint (2010)

Fuel End Use by Sector
Economy-wide lifecycle energy impacts – starts with technology

- Identify opportunities for manufacturing impacts in clean energy production and use.
- Target timely, high-impact, foundational clean energy technologies with the potential to transform energy use and accelerate their introduction into the US economy.

Clean energy technologies
- Wind
- Solar
- Hydro
- Geothermal
- CHP

Expand clean energy production

Reduce energy use across the lifecycle
Economy-wide lifecycle energy impacts – starts with technology

- Identify opportunities for manufacturing impacts in clean energy production and use.
- Target timely, high-impact, foundational clean energy technologies with the potential to transform energy use and accelerate their introduction into the US economy.

**Bandwidth Studies**

**Clean energy technologies**
- Wind
- Solar
- Hydro
- Geothermal
- CHP

Expand clean energy production

- Manufacturing energy/emissions reductions
- Increased manufacturing efficiency (lower energy, faster throughput, etc.)
- New and improved processes/product

**Use and re-use energy/emissions reductions** (e.g., light-weighting)
- Increased value-added
- Improved quality
- Improved service

Reduce energy use across the lifecycle

**Target Technologies**

**Chemical Bandwidths - CA, SOA, PM and TM**

\[
SOA\ Savings\ % = \frac{CA-\ SOA}{CA-TM}
\]

\[
PM\ Savings\ % = \frac{CA-\ PM}{CA-TM}
\]
Julie,

I would like to create a new slide before this one that helps viewers understand this figure. I would like to show the single pie chart first, maybe start with one generic colored pie labeled Current Savings by Process Area with Process Area 1, Process Area 2...thru 6. Then show the bar showing generic current opp, future opp, impr opp, no numbers in generic version. Finally link the two pies with the bar, maybe animation showing connecting expansion lines. All generic, no sector, no numbers. You can just use one of existing to mock up numbers.

Sabine Brueske, 5/18/2014
Expanding the perspective... Materials Flows through Industry (MFI)

**Aluminum Materials Flows – U.S. and Canada, 2009 Billions of Pounds**

<table>
<thead>
<tr>
<th>btu/lb</th>
<th>primary</th>
<th>secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current average</td>
<td>26,000</td>
<td>2,200</td>
</tr>
<tr>
<td>Practically achievable</td>
<td>20,000</td>
<td>925</td>
</tr>
<tr>
<td>Current savings potential</td>
<td>5,000 btu/lb Process improvement</td>
<td>1,275</td>
</tr>
<tr>
<td>Theoretical minimum</td>
<td>10,200</td>
<td>510</td>
</tr>
</tbody>
</table>

**Key Opportunities:**

A. Materials shift - Technologies to enable increase in secondary aluminum use by manufacturing sector.

B. End-of-life shift - Technologies to enable greater capture and use of 7.6 billion pounds aluminum (landfill + scrap export).

C. Process improvements - Technologies to improve primary aluminum processing.

New opportunities throughout the system – in materials design, product design, manufacturing, use and re-use.

---

**Economy-wide lifecycle energy impacts – starts with technology**

**Industry Energy Use**

- Dramatically increased buy/fly for complex components
- Less process heating

**Non-Industry Energy Use**

- Lighter components
- Novel, energy-efficient designs

Reduces material use and costs by up to 90%

“...in our lifetime at least 50% of the engine will be made by additive manufacturing”

~ Robert McEwan GE

Source: The Economist.

www.economist.com/node/18114221
Economy-wide lifecycle energy impacts – continues with technology

- Identify opportunities for manufacturing impacts in clean energy production and use.
- Target timely, high-impact, foundational clean energy technologies with the potential to transform energy use and accelerate their introduction into the US economy.

Expand clean energy production

Clean energy technologies
- Wind
- Solar
- Hydro
- Geothermal
- CHP

Lifecyle Industry, Greenhouse gas, Technology, & Energy through the Use-Phase (LIGHTEn-UP)

Expand clean energy production

Reduce energy use across the lifecycle

Target Technologies

- Manufacturing energy/emissions reductions
- Increased manufacturing efficiency (lower energy, faster throughput, etc.)
- New and improved processes/product

- Use and re-use energy/emissions reductions (e.g. light-weighting)
- Increased value-added
- Improved quality
- Improved service

Advanced Manufacturing

Materials \(\rightarrow\) Manufacture \(\rightarrow\) Transport \(\rightarrow\) Use \(\rightarrow\) Disposal/Re-use

Use and re-use energy/emissions reductions (e.g. light-weighting)
Increased value-added
Improved quality
Improved service

Illustrative
LIGHTEn-UP Tool – Publically Available U.S. Energy Consumption Data

![Graph showing energy consumption data](image)

- **20 AEO† Tables covering 17 Modes x 13 Energy Sources**
- **2 AEO† Tables covering 3 Building Types, 6 Energy Sources x 14 End-Use Types**
- **2 AEO† Tables covering 11 Building Types, 5 Energy Sources x 10 End-Use Types**
- **12 AEO† Tables 83 MECS†† Manufacturing Classifications, 6 Energy Sources x 22 End-Use Types**

† Annual Energy Outlook (AEO) Tables
†† Manufacturing Energy Consumption Survey

Protocol – Distilling scenarios to Three Key Variables

**Analyst’s Homework**

- Technology Performance
- Deployment
- Additional affects?

**Documentation**

**Three Key Variables For LIGHTEn-UP Tool**

- **Where?** (Sector & end-use)
- **What?** (Energy Impact)
- **When?** (Start & End years)
Where will the impact be?

AEO Sectors

- Industrial
- Commercial
- Residential
- Transportation

Reported in AEO

AEO Industrial Sub-Sectors

- Food
- Paper
- Chemicals
- Steel
- Misc.

Disaggregated By MECS Share-weights

MECS Sub-Sub-Sectors

- Grains
- Corn
- Sugar
- Dairy
- Tobac.

Disaggregated By MECS Share-weights

AEO Energy Sources by MECS Share-weights

- Electricity
- NG
- Pet
- Coal
- Steam
- Other

Disaggregated By MECS Share-weights

MECS End-Use Of AEO Energy

- Boilers
- Process
- Machines
- Other

What will the impact be?

Technical Adoption Potential % & Relative Energy Savings %

Measure 1 (M1)

Total Energy Consumption $\sum_{n,F,E-U}^{M1,n,F,E-U}$

Technical Adoption Potential $\sum_{n,F,E-U}^{M1,n,F,E-U}$

Relative Energy Savings $\sum_{n,F,E-U}^{M1,n,F,E-U}$

Sector (List)

Sub-Sector 1 (List)

Sub-Sector n (List)

Fuels (List)

End-Use $T = \text{End Year}$ (Energy)

Technical Adoption Potential % = \frac{\text{Technical Adoption Potential}_{M1,n,F,E-U}}{\text{Total Energy Consumption}_{n,F,E-U}}

Relative Energy Savings % = \frac{\text{Relative Energy Savings}_{M1,n,F,E-U}}{\text{Technical Adoption Potential}_{M1,n,F,E-U}}
**Time – and when will the impact occur...?**

*Where? What? When?*

<table>
<thead>
<tr>
<th>Where: Which Sector &amp; End-Use?</th>
<th>What Impact at End Year</th>
<th>When?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>Sub-Sector</td>
<td>End-Use</td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Energy**

Technical Adoption Potential at End Year
Relative Energy Savings at End Year

Equations:
1) \( E_{t2} = E_{t1} \times GR \)
2) \( E (TP)_{t2} = E (TP)_{t1} \times (TP) \)
3) \( E (RS)_{t2} = E (TP)_{t1} \times (RS) \)

Energy Impact = green area

**Output:** Scale-Up of Novel Low-Cost carbon Fibers Leading to High-Volume Commercial Launch

- **LIGHTEn_UP** shows fleet annual net energy impact (black line) increasing in initial years as CFRP production ramps up
- Beyond year 2030, net energy savings are realized as use phase benefits accrue (i.e. black line falls below x-axis)
- Within industrial sector:
  - Energy increases in carbon fiber and resin sectors due to increased CFRP production
  - Energy decrease in steel sector due to avoided steel production
Energy Consumption Savings from Lightweighting Carbon Fiber Reinforced Plastics (CFRP) vs. Steel; Improved CF (polyolefin) vs. current CF (polyacrylonitrile)

- Per vehicle savings of 2600 MJ per PAN vehicle and 11,500 MJ per PO vehicle
- Net energy impact of PO (dashed line) in US LDV fleet also compared with PAN (dotted line)
- Significantly greater materials and manufacturing energy investment with PAN – net energy savings temporally delayed and lesser magnitude


The importance of improving materials and manufacturing energy use

The importance of use phase energy savings

Thank You!

Joe Cresko
Joe.cresko@ee.doe.gov

Team:
Alberta Carpenter – NREL
Sujit Das – ORNL
Diane Graziano -ANL
Maggie Mann – NREL
William Morrow – LBNL
Eric Masanet - Northwestern
Sachin Nimbalkar - ORNL
Arman Shehabi - LBNL
Introduction:

Sustainability as the Basis for Sustainable Growth and Value Creation

- Sustainability is a **global phenomenon**
- Sustainability **IS NOT** Sustainment, but is the basis for **sustainable growth and value creation**

- Designing **sustainable products** and developing **sustainable manufacturing processes** have been a major research focus in **sustainable manufacturing**
Sustainability is the driver for innovation

Innovation promotes accelerated growth in manufacturing

Manufacturing is the engine for wealth generation and societal well-being

Societal well-being and economic growth heavily depend on the level and quality of education and training
Sustainable Manufacturing: Definitions

- Numerous definitions and descriptions exist for sustainable manufacturing:
  - US Department of Commerce, 2009
  - NACFAM, 2009
  - NIST, 2010
  - ASME, 2011, 2013
  - NSF 2013

- Almost all definitions fall short of showing the connectivity among the integral elements – No connectivity shown between sustainability and innovation or value creation

- Sustainable manufacturing offers a new way of producing functionally superior products innovative sustainable technologies and manufacturing methods through the coordination of capabilities across the entire supply chain, not just the process chain

- Sustainable manufacturing must enable sustainable value creation for all stakeholders.

Sustainable Manufacturing: Revised Definition

Sustainable manufacturing must:
- demonstrate reduced negative environmental impact,
- offer improved energy and resource efficiency,
- generate minimum quantity of wastes,
- provide operational safety, and
- offer improved personal health while maintaining and/or improving the product and process quality

Source: Jayal et al. (2010) and Jawahir (2012) – Adapted from US Department of Commerce (2009)
**Sustainable Manufacturing: Basic Elements**

**Expectations:**
- Reducing *energy consumption*
- Reducing *waste*
- Reducing *material utilization*
- Enhancing *product durability*
- Increasing *operational safety*
- Reducing *toxic dispersion*
- Reducing *health hazards/Improving health conditions*
- Consistently improving *manufacturing quality*
- Improving *recycling, reuse and remanufacturing*
- Maximizing *sustainable sources of renewable energy*

---

**ISM Focus**

Diagram showing the relationships between Systems, Sustainable Manufacturing, Products, and Processes.
**Holistic and Total Life-cycle Approach**

Emphasis on all four product life-cycle stages

- Manufacturing
- Use
- Pre-manufacturing
- Post-use

**Closed-loop Material Flow – The 6R Approach**

3R Concept

- Manufacturing
- Use

6R Concept

- Remanufacture
- Reuse
- Recover
- Retire
- Treatment & Disposal

Source: Jawahir et al. (2006)
**Evolution of Sustainable Manufacturing**

![Diagram of Evolution of Sustainable Manufacturing]

**Total Life-cycle 6R Applications for Sustainable Products**

![Diagram of 6R Applications for Sustainable Products]
Overview of Existing Sustainability Measurement Systems

A list of existing measurement systems

<table>
<thead>
<tr>
<th>Indicator Set / Database</th>
<th>components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Reporting Initiative (GRI)</td>
<td>70 indicators</td>
</tr>
<tr>
<td>Dow Jones Sustainability Index (DJSI)</td>
<td>12 criteria based single indicator</td>
</tr>
<tr>
<td>2005 Environmental Sustainability Indicators</td>
<td>76 building blocks</td>
</tr>
<tr>
<td>2006 Environment Performance Indicators</td>
<td>19 Indicators</td>
</tr>
<tr>
<td>United Nations Committee on Sustainable Development Indicators</td>
<td>50 indicators</td>
</tr>
<tr>
<td>OECD Core indicators</td>
<td>46 indicators</td>
</tr>
<tr>
<td>Indicator database</td>
<td>409 indicators</td>
</tr>
<tr>
<td>Ford Product Sustainability Index</td>
<td>8 indicators</td>
</tr>
<tr>
<td>GM Metrics for Sustainable Manufacturing</td>
<td>46 Metrics</td>
</tr>
<tr>
<td>ISO 14031 environmental performance evaluation</td>
<td>155 example indicators</td>
</tr>
<tr>
<td>Wal-Mart Sustainability Product Index</td>
<td>15 questions</td>
</tr>
<tr>
<td>Environmental Indicators for European Union</td>
<td>60 indicators</td>
</tr>
<tr>
<td>Eco-Indicators 1999</td>
<td>3 main factors based single indicator</td>
</tr>
</tbody>
</table>

Comparison of the existing measurement systems

(Feng et al. 2010)
**Product and Process Metrics for Sustainable Manufacturing: NIST-sponsored Project**

**Project Title:** Development of Metrics, Metrology and a Framework for Product-Process Ontology for Interoperability in Model-Based Sustainable Manufacturing

**Project Team:**
- **Faculty:** Dr. I.S. Jawahir, Dr. F. Badurdeen, Dr. O.W. Dillon, Jr., Dr. K. Rouch
- **Graduate Students:** T. Lu, M. Shuaib, X. Zhang, A. Huang, C. Stovall

**Sponsor:** NIST  
**Industry partners:** TOYOTA, LEXMARK

**Project Objective:** To develop and implement tools and principles for quantitative evaluation of manufactured products and their manufacturing processes from the aspect of sustainable manufacturing

**Metrics for Sustainable Manufacturing**
- **Manufacturing is an engine for wealth generation,** and achieving sustainability in manufacturing is crucial to economy
- There is a **critical need for developing improved metrics** to evaluate the sustainability performance of a product and its manufacturing processes
- Metrics can help to **improve decision-making with optimized product and process design** for sustainable manufacturing

**Project Summary**
- The major sustainability elements and metrics of **products and processes for sustainable manufacturing** identified
- A framework for developing comprehensive product and process metrics for sustainable manufacturing developed

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**Product Design for Sustainability**

- **Design for Sustainability (DFS)**
  - Environmental Impact
  - Social Impact
  - Economic Impact

  - Regional and Global Impact
  - Energy Efficiency/Power Consumption
  - Material Utilization
  - Use of Renewable Source of Energy
  - Product Lifecycle
  - Life Cycle Cost
  - Manufacturing Methods

  - Packaging
  - Assembly
  - Storage
  - Transportation

- **Jawahir et al., 2006**
Hierarchical Structure of Product Sustainability Evaluation Method

Product Clusters

Product Sustainability Index (ProdSI)

- Economic
  - Initial Investment
  - Overhead Expense
  - Benefits and Losses

- Environmental
  - Material Use and Efficiency
  - Energy Use and Efficiency
  - Natural Resource Use and Efficiency
  - Waste and Emissions
  - Product End of Life

- Societal
  - Product Quality and Durability
  - Functionality
  - Product EOL management
  - Product Safety and Health
  - Regulations and Certification
### Example Metrics for Product Clusters and Life-cycle Stages

<table>
<thead>
<tr>
<th>Metrics Clusters</th>
<th>Example Metrics</th>
<th>Unit (D/L dimensionless)</th>
<th>PM (pre-mfg.)</th>
<th>M (mfg.)</th>
<th>U (use)</th>
<th>PU (post-use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residues</td>
<td>Emissions Rate (carbon-dioxide, sulphur-oxides, nitrous-oxides etc.)</td>
<td>mass/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Energy Use and Efficiency</td>
<td>Remanufactured Product Energy</td>
<td>kWh/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Product End-of-Life Management</td>
<td>Design-for-Environment Expenditure</td>
<td>$/$/D/L</td>
<td>✓</td>
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<td></td>
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<tr>
<td>Material Use and Efficiency</td>
<td>Restricted Material Usage Rate</td>
<td>mass/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Water Use and Efficiency</td>
<td>Recycled Water Usage Rate</td>
<td>gallons/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>Product Operational Cost</td>
<td>$/unit</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profitability</td>
<td>Average Disassembly Cost</td>
<td>$/unit</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Product Quality</td>
<td>Defective Products Loss</td>
<td>$/unit</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warranty Cost Ratio</td>
<td>$/unit</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Education</td>
<td>Employee Training</td>
<td>Hours/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Customer Satisfaction</td>
<td>Repeat Customer Ratio</td>
<td>(D/L)</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Post-Sale Service Effectiveness</td>
<td>(D/L)</td>
<td></td>
<td>✓</td>
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<td></td>
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<tr>
<td>Product End-of-Life Management</td>
<td>Ease of Sustainable Product Disposal</td>
<td>$/unit</td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Product Safety and Societal Well-being</td>
<td>Product Processing Injury Rate</td>
<td>incidents/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<tr>
<td></td>
<td>Landfill Reduction</td>
<td>mass/unit</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

(Weigharathne et al., 2004)
## Process Sustainability Metrics

<table>
<thead>
<tr>
<th>Environmental Impact</th>
<th>Energy Consumption</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emission from energy consumption of the line (ton CO₂ eq./unit)</td>
<td>In-line energy consumption (kWh/unit)</td>
<td>Labor cost ($/unit)</td>
</tr>
<tr>
<td>Ratio of renewable energy used (%)</td>
<td>Energy consumption on maintaining facility environment (kWh/unit)</td>
<td>Cost for use of energy ($/unit)</td>
</tr>
<tr>
<td>Total water consumption (ton/unit)</td>
<td>Energy consumption on transportation into/out of the line (kWh/unit)</td>
<td>Cost of consumables ($/unit)</td>
</tr>
<tr>
<td>Mass of restricted disposals (kg/unit)</td>
<td>Ratio of use of renewable energy (%)</td>
<td>Maintenance cost ($/unit)</td>
</tr>
<tr>
<td>Noise level outside the factory (dB)</td>
<td></td>
<td>Cost of by-product treatment ($/unit)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operator Safety</th>
<th>Personnel Health</th>
<th>Waste Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure to Corrosive/toxic chemicals (points/person)</td>
<td>Chemical contamination of working environment (mg/m³)</td>
<td>Mass of disposed consumables (kg/unit)</td>
</tr>
<tr>
<td>Exposure to high energy components (points/person)</td>
<td>Mist/dust level (mg/m³)</td>
<td>Consumables reuse ratio (%)</td>
</tr>
<tr>
<td>Injury rate (injuries/unit)</td>
<td>Noise level (dB)</td>
<td>Mass of mist generation (kg/unit)</td>
</tr>
<tr>
<td></td>
<td>Physical load index (dimensionless)</td>
<td>Mass of disposed chips and scraps (kg/unit)</td>
</tr>
<tr>
<td></td>
<td>Health related absenteeism rate (%)</td>
<td>Ratio of recycled chips and scraps (%)</td>
</tr>
</tbody>
</table>

### Three-level Process Sustainability Metrics for Energy Consumption

**Line Level**
- In-line energy consumption
- Energy consumption of machine operations
- Energy consumption of communication / controlling system
- Energy consumption of illumination
- Energy consumption of in-line transportation

**Workstation Level**
- Energy consumption of centrifuge
- Energy consumption of main spindle motor
- Energy consumption of coolant supply pump
- Energy consumption of oil pressure pump
- Energy consumption of mist collector, cooler and control unit
- Energy consumption of the servos
**Process Sustainability Clusters and Sub-clusters**

- Machining cost
  - Direct cost
  - Indirect cost
  - Capital cost
- Energy consumption
  - Production
  - Maintenance
  - Transportation
  - Facilities
  - Renewable energy
- Environmental impact
  - Energy
  - Water
  - Restricted Material
  - Disposed Waste
  - Noise Pollution
- Waste management
  - Consumables
  - Packaging
  - Used Raw Material
  - Scrap Parts
- Operator safety
  - Injuries
  - Working environment conditions (safety)
- Personal Health
  - Physical Load Index (PLI)
  - Absenteeism rate
  - Working environment conditions (health)

---

**ProdSI and ProcSI Evaluation**

\[
ProdSI = \frac{1}{3} \left( Ec + Ev + So \right) = \frac{1}{3} \left( \sum_{i=1}^{3} w_i^c C_i + \sum_{i=4}^{8} w_i^w C_i + \sum_{i=9}^{13} w_i^L C_i \right)
\]

\[
ProcSI = \frac{1}{6} \sum_{i=1}^{6} C_i = \frac{1}{6} \left( C_1 + C_2 + \sum_{n=10}^{12} w_i^w SC_n + \sum_{n=15}^{18} w_i^w SC_n + \sum_{n=19}^{21} w_i^w SC_n + \sum_{n=22}^{23} w_i^w SC_n \right)
\]

\[
SC_n = \sum w_i^w M_j \forall j
\]
Examples of ProdSI and ProcSI

(a) ProdSI

(b) ProcSI

Sustainability Improvement in Products and Processes

Case studies were conducted on three major manufactured products
**Implementing Product and Process Sustainability Metrics**

**Current State:**
- Considerable effort in the manufacturing industry, with corporate commitment to sustainability
- Promotion of dedicated educational and training programs and workforce development

**Limitations:**
- Slow progress and limited effectiveness in implementing sustainable practices --- No economic benefits shown, and no standards despite significant push for regulatory measures
- Difficulty in identifying relevant tools and techniques for evaluation
- Complexity in measuring and quantifying sustainability elements in manufactured products and manufacturing processes

**Outlook and Opportunity:**
- Metrics-based evaluation of sustainable products and processes offers a new opportunity for quantitative evaluation of sustainability in manufacturing
- Sustainability is the driver for innovation
- Significantly improved manufacturing productivity through product/process innovation

**Acknowledgements**

- Project Sponsor: NIST (Award No: 60NANB10D009) 2010-13
- Industry Participants:
  - GE-Aviation
  - Toyota Motor Manufacturing
  - Lexmark International
As we design and build…

- Data measured from prior project informs new design efforts
- Energy models are not predictive of energy use
- Holding designers, builders and users to a meter reading is difficult
- Smart Meters and digital control system architectures can be a challenge
- Maintaining new technologies is difficult
- Struggling with mechanical systems
An Owner-Builders Perspective (continued)

Some additional thoughts ......

- Measure only what we need to know
  - How are we informed what that is?
  - Are dashboards more effective than meters?
  - Is there a role for BIM?

- Require measures that hold a designer/builder accountable
  - We have had success with air tightness and infrared testing
  - Help us discern Designer/Building/User affects on building performance
  - Need something more....

Sample Army MDMS Display work in progress

Compare against reference building monthly consumption to detect seasonal trends

Compare across climate zones for same building type

Compare across building types in same climate zone

Compare annual EUI of ‘your’ building with reference building
The Fraunhofer-Gesellschaft

**Research and development**
- Application-oriented research of direct use to businesses and for the benefit to society
- Application-oriented basic research
- Departmental research for the German Federal Ministry of Defense

**Business community**
- Institutes work as profit centers
- One-third of the budget consists of income from industrial projects
- Spinoffs by Fraunhofer researchers are encouraged

**Contracting partners/clients**
- Industrial and service companies
- Public sector
of which 1.7 billion euros is generated through contract research.

- 2/3 of this research revenue derives from contracts with industry and from publicly financed research projects.
- 1/3 is contributed by the German federal government and the Länder governments in the form of institutional financing.

- International collaboration through representative offices in Europe, the US, Asia and the Middle East
SUSTAINABILITY AND RESEARCH

Hans Carl von Carlowitz -

discoverer of the principle of sustainable yield forestry

16th December 1643, Dornstetten
1715 Mainz, Hesse, Germany

Morgenstadt-City of the future Initiative

Vision of the Morgenstadt Visions

Shaping the cities future

Urban Development - Electric Mobility - Industry 4.0 - Demographic Change - Climate Crisis - Internet of Things - Shareconomy... the world is changing fast and entire industries are reinventing themselves in response to complex transformations in social, economic, and environmental arenas. Increasing urbanisation is a key trend and the...
Phases of construction

- land development phase
- material production phase
- construction phase
- building function/use phase
- maintenance and repair phase
- deconstruction and recycling phase
Material production phase

- production of building materials
- can be speculative if not defined for a specific project with known suppliers
Construction phase can be speculative if not defined for a specific project with known suppliers and manufacturers of goods.

Building function/use phase

- can be measured/quantified
- building can be instrumented and data collected
  - energy use
  - water use
  - building comfort parameters......
Deconstruction

- speculative
- no good data available
- hard to predict
Sources of uncertainty

- Random error and statistical variation (measurement error)
- Systematic error and subjective judgment
- Linguistic imprecision (Assigning quantitative parameter estimates based on qualitative descriptors)
- Variability (data variability)
- Inherent randomness and unpredictability
- Expert uncertainty and disagreement
- Approximation

<table>
<thead>
<tr>
<th>Component/Parameter</th>
<th>Temperature RWVP</th>
<th>Acceleration/Vibrations</th>
<th>Noise intensity</th>
<th>Formaldehyd concentration</th>
<th>VOC concentration</th>
<th>Light intensity</th>
<th>Air exchange</th>
</tr>
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<tbody>
<tr>
<td>Component/Parameter</td>
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<table>
<thead>
<tr>
<th>Parameters and frequency of measurements – building envelope</th>
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<tbody>
<tr>
<td>Walls</td>
</tr>
<tr>
<td>Openings</td>
</tr>
<tr>
<td>Roof</td>
</tr>
<tr>
<td>Interior partitions</td>
</tr>
<tr>
<td>Ceilings/Floors</td>
</tr>
<tr>
<td>x</td>
</tr>
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<td>x</td>
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<thead>
<tr>
<th>Energy consumption/mechanical systems (HVAC)</th>
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<tbody>
<tr>
<td>Rooms</td>
</tr>
<tr>
<td>Mech. systems</td>
</tr>
<tr>
<td>x</td>
</tr>
<tr>
<td>x</td>
</tr>
<tr>
<td>x</td>
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<td>x</td>
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<table>
<thead>
<tr>
<th>Ageing of materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
</tr>
<tr>
<td>x</td>
</tr>
<tr>
<td>x</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Water consumption Wastewater discharge</th>
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<tbody>
<tr>
<td>Building</td>
</tr>
<tr>
<td>continuously</td>
</tr>
<tr>
<td>x</td>
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<td>x</td>
</tr>
<tr>
<td>x</td>
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<td>x</td>
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<td>x</td>
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<table>
<thead>
<tr>
<th>Exterior environment (weather station)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
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<tr>
<td>x</td>
</tr>
<tr>
<td>x</td>
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</table>

© Fraunhofer WKI
<table>
<thead>
<tr>
<th></th>
<th>warm side room climate</th>
<th>cold side outside climate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>[°C]</td>
<td></td>
</tr>
<tr>
<td>0 ... 35</td>
<td>-40 ... 60</td>
<td></td>
</tr>
<tr>
<td><strong>Humidity</strong></td>
<td>[% r.H.]</td>
<td></td>
</tr>
<tr>
<td>30 ... 95</td>
<td>20 ... 95</td>
<td></td>
</tr>
<tr>
<td><strong>Volume</strong></td>
<td>[m³]</td>
<td></td>
</tr>
<tr>
<td>main chamber</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>auxiliary chamber</td>
<td>2 x 13</td>
<td>(2 x 7)*</td>
</tr>
<tr>
<td><strong>Heating power</strong></td>
<td>[kW]</td>
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</tr>
<tr>
<td>8 x 3</td>
<td>6 x 4,5</td>
<td></td>
</tr>
<tr>
<td><strong>Cooling power</strong></td>
<td>[kW]</td>
<td></td>
</tr>
<tr>
<td>6 x 5</td>
<td>8 x 8</td>
<td></td>
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<tr>
<td>condensation temperature</td>
<td>[°C]</td>
<td></td>
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<tr>
<td>45</td>
<td>45</td>
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<tr>
<td>vaporization temperature</td>
<td>[°C]</td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td>-35</td>
<td></td>
</tr>
</tbody>
</table>

* Standby chambers for sun- and rain simulators
Indoor air quality-example of inconsistencies (HCHO)

- California/USA
  - CARB
  - Phase 2
  - PB: 0.09 ppm
  - MDF: 0.11 ppm
  - Thin MDF: 0.13 ppm
  - PLY: 0.05 ppm

- Japan
  - F**...F****
  - F**** (JIS chamber): 0.05 µg/h·m²
  - F**** (JIS desiccator): 0.3 mg/L
  - F**** can be used indoor without any restriction coated PB: 0.1 ppm
  - probably new (July 1st, 2014): 0.11 ppm
  - PLY: 0.1 ppm
  - PB: 8 mg/100 g dry board

- Russia
  - E1
  - PB: 0.1 ppm
  - PLY: 0.1 ppm

- China
  - E1 E2
  - E1: ≤ 0.1 ppm
  - ≤ 9.0 mg/100 g dry board
  - E2*: ≤ 30 mg/100 g dry board
  - *use for indoor air only after surface treatment
Indoor air quality is an example of inconsistencies (HCHO).

**Assessment of building sustainability**

- Considered "soft science"
- Number of standards available
- Many parameters subjective or speculative ¹
- Using of materials from renewable resources makes the building not automatically sustainable
- Stochastic approaches desirable ¹, ²

---


people in rich countries use 10x more natural resources than those in poor countries

**Our ability to move towards sustainability may be limited.**
Perhaps, our solutions should be adjusted to the needs of the 80% of the population


CURRENT & FUTURE OPPORTUNITIES FOR MEASURES OF HIGH PERFORMANCE GREEN BUILDINGS

A DECADE OF GREEN BUILDING RESULTS ON THE GROUND
LEED AND ENERGY STAR: 74,265 BUILDINGS WITH >2,000 GREEN ATTRIBUTES AND PERFORMANCE MEASURES
### Implied Value of Metrics

<table>
<thead>
<tr>
<th>Rank</th>
<th>Rating Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operational Energy</td>
</tr>
<tr>
<td>2</td>
<td>Operational Water</td>
</tr>
<tr>
<td>3</td>
<td>Materials</td>
</tr>
<tr>
<td>4</td>
<td>Occupant Behavior &amp; Performance</td>
</tr>
</tbody>
</table>

**Categories:**
- **Energy**
  - ASHRAE 90.1
  - Title 24
  - Energy Star
  - Renewable Energy
  - Green Power
- **Site Design**
  - Accessibility
  - Stormwater
  - Heat Island
- **Occupants**
  - Satisfaction
  - Comfort
  - Control
- **Water**
  - Fixtures Efficiency
  - Landscaping
  - Process
- **Materials**
  - Source
  - Recycled Content
  - End-of-Life
## IMPLIED VALUE OF METRICS

<table>
<thead>
<tr>
<th>RANK</th>
<th>RATING SYSTEMS</th>
<th>ENV IMPACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OPERATIONAL ENERGY</td>
<td>OCCUPANT BEHAVIOR &amp; PERFORMANCE</td>
</tr>
<tr>
<td>2</td>
<td>OPERATIONAL WATER</td>
<td>OPERATIONAL ENERGY</td>
</tr>
<tr>
<td>3</td>
<td>MATERIALS</td>
<td>MATERIALS</td>
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<td>4</td>
<td>BEHAVIOR &amp; SATISFACTION</td>
<td>OPERATIONAL WATER</td>
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## IMPLIED VALUE OF METRICS

<table>
<thead>
<tr>
<th>RANK</th>
<th>RATING SYSTEMS</th>
<th>ENV IMPACT</th>
<th>FINANCIAL IMPACT</th>
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<tbody>
<tr>
<td>1</td>
<td>OPERATIONAL ENERGY</td>
<td>OCCUPANT BEHAVIOR &amp; PERFORMANCE</td>
<td>OCCUPANT BEHAVIOR &amp; PERFORMANCE</td>
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<td>BEHAVIOR &amp; SATISFACTION</td>
<td>OPERATIONAL WATER</td>
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</tr>
</tbody>
</table>
Introduction to Breakout Sessions

Richard N. Wright, Dist.M.ASCE, NAE
June 12, 2014

Sustainability in Construction and Manufacturing

• No separation between construction and manufacturing because constructed facilities are manufactured products.
• For both, we are interested in sustainability over their whole life cycles.
• Generally similar measurement issues are expected, but distinctions should be noted as they occur to a breakout session team.
Objectives of Breakout Sessions

• Identify knowledge gaps and research needs relating to measurement science for sustainable construction and manufacturing

• Provide suggestions in the form of problems, descriptions, analyses, recommendations and actions for the consideration of NIST

Breakout Sessions

1. Measurement science (definition, standards, metrics, indicators and ratings)

2. Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)

3. Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)

4. Economic, environmental and social aspects (valuation, impacts and behavior).
Breakouts Are Not Silos

We expect synergies to arise as similar or identical issues/problems are identified and dealt with in two or more breakouts.

Breakouts do provide different starting foci.

We hope this helps capture the most important measurement science needs.

Draw upon the workshop papers and presentations and your own experiences.

Breakout Forms

1. Problem Definition: Problem Name, Problem Description (Drafted in advance by the co-moderators)

2. Recommendation: Name, Root Cause, Recommendation, Action Plan, Roles

3. Breakout Team: Name, Affiliation, Email, Phone
### 1. Problem Description

<table>
<thead>
<tr>
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### 2. Problem Analysis

**Problem or Issue:**

**Root Cause:**

**Recommendation:**

**Action Plan:** *Possible steps towards the goal*

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<th>Roles</th>
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NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014
## 3. Breakout Team

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NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014

### Breakout Schedule

In advance, co-moderators select a person to provide a summary of outcomes at the closing session.

- **8:45:** Problem definitions - identify, describe and assign key problems/issues to working groups (one or more participants)
- **9:15:** Problems analysis - working groups analyze individual problems/issues
- **9:45:** Break
- **10:00:** Presentation/discussion of analyses
- **10:45:** Working groups complete analyses responding to discussions.
- **11:00:** Breakouts end.
NIST-UMD Workshop on Measurement Science for Sustainable Construction and Manufacturing

Charge to the Breakout Groups

Dr. Joannie Chin
Acting Deputy Director
Engineering Laboratory
NIST

NIST’s Mission

To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.
NIST Laboratories

Engineering Lab (EL) Mission

To promote U.S. innovation and industrial competitiveness in areas of critical national priority by anticipating and meeting the measurement science and standards needs for technology-intensive manufacturing, construction, and cyber-physical systems in ways that enhance economic prosperity and improve the quality of life.
EL Core Capabilities

- Fire protection, fire physics, materials flammability
- Structural analysis, disaster and failure studies
- Intelligent sensing, control, robotics and automation
- Sustainability, durability, and service life prediction of engineered materials
- Systems integration, information modeling, model-based engineering
- Building and renewable energy, indoor environment, and building systems performance measurement

Partnering Strategies with Industry, Academia and Other Federal Agencies

- Planning and Roadmapping Workshops
- Testbeds, Facilities, and Tools
- Codes and Standards Engagement
- Cooperation Mechanisms
- NIST Sponsored Events
Engineering Laboratory Strategic Goals

• Smart Manufacturing, Construction, and Cyber-Physical Systems

• Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure

• Disaster-Resilient Buildings, Infrastructure, and Communities

Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure

• Sustainable Manufacturing

• Sustainable Engineered Materials

• Net-Zero Energy, High-Performance Buildings

• Embedded Intelligence in Buildings
BEES and BIRDS

• Building for Environmental and Economic Sustainability (BEES)
  – Sustainability Performance of Similar Building Products

• Building Industry Reporting and Design for Sustainability (BIRDS)
  – Sustainability Performance of Whole Building Designs
Research Facilities and Testbeds

• Virtual Cement and Concrete Testing Laboratory
• Integrating Sphere for Service Life Prediction of Materials
• Virtual Cybernetic Building Testbed
• Smart Grid Testbed Facility
• Solar Photovoltaic Systems

Net-Zero Energy Residential Test Facility

• Demonstrate net-zero energy for residence similar in appearance to surrounding homes
• Provide a test bed for in-situ measurements of advanced components and systems
• Quantify energy use reductions using embedded intelligence
• Compare actual installed performance to controlled laboratory measurements
Breakout Groups

• Workshop Objective:
  Identify knowledge gaps and research needs in measurement science for sustainable construction and manufacturing.

• Measurement Science:
  – Scientific and technical basis for standards, codes, and practices
  – Includes: performance metrics; measurement and testing methods; predictive modeling and simulation tools; test and calibration protocols; reference materials, artifacts and data; evaluation of technologies, systems, and practices (including uncertainty analysis); devices and instruments

Breakout Groups

• Breakout Categories:
  – Measurement science (definition, standards, metrics, indicators and ratings)
  – Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)
  – Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)
  – Economic, environmental and social aspects (valuation, impacts and behavior).
Anticipated Outcomes

• Guidance document that will serve as a roadmap for NIST’s future programs in sustainability, and help facilitate our technology transfer and implementation mission.

• Document will include:
  – Definition of sustainability relevant to construction and manufacturing
  – Appropriate sustainability metrics
  – Systems level considerations
  – Economic valuation and impacts
  – Research gaps and needs
### Breakout Team 1

**Problem or Issue:** Sustainability science is unclear

**Root Cause:**
- Not all aspects of sustainability is measurable
- Multi-facets of sustainability exist
- Subjectivity and selectivity involved

**Recommendation:**
- Integration of multi-disciplinary aspects
- Develop quantitative methodologies for evaluating sustainability

**Action Plan:** *Possible steps towards the goal*

1. Identify experts in social, economic and behavioral sciences along with urban planners (e.g. dedicated workshops, meetings, etc.)
2. Integrate deterministic and non-deterministic methodologies
3. Promote educational and training programs (need for new knowledge and data)

**Roles**

- **Industry**
  - All stakeholders to collaborate. All segments of construction and manufacturing industries must be engaged.

- **Government**

- **Academia**

- **NGO**

- **Software/Hardware**

---

**NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014**
**Problem or Issue:** Value issues need further vetting

**Root Cause:** Sustainability & decisions are a combination of science and value judgments. It is critical to assure that these are distinguished.

**Recommendation:** Provide frameworks for prioritizing and valuing the relative importance of the components or elements of sustainability.

**Action Plan:** *Possible steps towards the goal*

- Assess the state of the science and application as well as identify research gaps needed by industries
- Fund research on value framework that is translational, multidisciplinary and includes elements of sustainability that are challenging to measure and prioritize
- Demonstrate and apply the framework in construction and manufacturing

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<tr>
<th>Roles</th>
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<td>Collaborate with researchers, fund, define challenges</td>
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<td>Fund, prioritize, conduct assessment</td>
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<td>Conduct research, assess, demonstrate, and disseminate</td>
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<tr>
<td>Fund, collaborate and demonstrate</td>
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<td>Develop algorithms, measurement/data collection</td>
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**Problem or Issue:** Measuring is challenging (2a) Not all things we care about are measurable (2b)

**Root Cause:** Dynamics of the multidimensional nature of issues Values are relative and not easily quantifiable

**Recommendation:** Create a framework for system identification
- Identify metrics and indicators
- Identify or create methodology for assigning relative weights to values that we care about
- Identify or create assessment methodology for decision making

**Action Plan:** *Possible steps towards the goal*

- Create a framework for system identification
- Identify metrics and indicators
- Identify or create methodology for assigning relative weights to values that we care about
- Identify or create assessment methodology for decision making

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### Breakout Team 1. Measurement science

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<tr>
<th>Problem or Issue:</th>
<th>Measurement science (definition, standards, metrics, indicators and ratings)</th>
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<tr>
<td>Root Cause:</td>
<td>Sources: Definition, time horizon, interactions (systems)</td>
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<td>Types: Variability, lack of information, approximations</td>
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<td>Quantification methods: Probabilistic &amp; non-probabilistic frameworks</td>
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**Uncertainty in measurement**

**Develop methodologies for assessing uncertainty**

**Recommendation:**

Identify sources, Identify types, Develop frameworks/methods to assess uncertainty

**Action Plan:** Possible steps towards the goal

1. Identify high-value problem areas as anchors for uncertainty-related tasks.
2. For each problem area, follow recommendation above.
3. Generalize Step 2 outcomes.
5. Disseminate and educate.
6. Obtain feedback and improve steps 1 to 5.

**Primary Roles**

- **Industry**
  - Establish relevance, feasibility

- **Government**
  - Provide leadership, policy, investment and incentives

- **Academia**
  - Fundamental research, training
  - Human resource development

- **NGO**
  - Provide liaison among society, researchers and practitioners

- **Software/Hardware**
  - Software needed to implement methods

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**Breakout Team 1**

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*NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014*
2. Systems Break-Out Session: Selected 3 Problems

<table>
<thead>
<tr>
<th>Problem Title</th>
<th>Problem Description</th>
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<tr>
<td>System boundary setting</td>
<td>Since all systems are connected from micro to macro scale, how can one establish boundaries for analysis?</td>
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<tr>
<td>Loss of fidelity in aggregation</td>
<td>How can one perform aggregated, high-level system-level analysis without losing important fine-grain details?</td>
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<td>Coupling of human and natural processes</td>
<td>What methods are useful for characterizing the linkages among mechanistic processes designed by humans and organic processes that have evolved in nature?</td>
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<tr>
<td>Predictive assessment for sustainability and resilience</td>
<td>How can decision makers assess the potential ecological, economic, and social impacts of new policies or technologies (a \ priori) without empirical knowledge?</td>
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<td>Understanding cross-scale interactions</td>
<td>Are there tractable methods available for practitioners to understand the complex interactions within a system of systems across multiple spatial and temporal scales?</td>
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<td>General vs. specified resilience</td>
<td>Can systems be designed for “inherent” resilience to disruptions in general, rather than to specified threats?</td>
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<tr>
<td>Justification of need for systems approach</td>
<td>How can issues that require systems thinking be identified and communicated, with an appropriate business case?</td>
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<td>Establishment of accepted practice</td>
<td>How can we establish commonly accepted, credible methods, practices, and data, with compelling examples?</td>
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NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014

Breakout Team 2: Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)

Problem or Issue: What methods are useful for characterizing the linkages among mechanistic processes designed by humans and organic processes that have evolved in nature?

Root Cause: Economic development has led to undesired ecological impacts, leading to greater awareness of interdependence between human and natural systems.

Recommendation: Improve quantification of resource flows, emissions, and other interactions between human and natural systems.

Action Plan: Possible steps towards the goal

1. Identify ecological constraints, such as scarce minerals, land availability, that influence construction and manufacturing decisions
2. Develop full understanding of resource depletion and other ecological impacts of human activities
3. Identify ecological conditions, such as biodiversity, soil quality, nutrient cycling, that are disrupted by human activities
4. Characterize beneficial ecosystem services that enhance sustainability of construction and manufacturing, e.g., stormwater management
5. Develop early warning indicators of change, such as indicator species.
6. Develop indicators of resilience to unexpected shocks, e.g., diversity, buffering

Roles

Industry

Government

Academia

NGO

Software/Hardware

NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014
## Breakout Team 2

**Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)**

### Problem or Issue:
How can decision makers assess the potential ecological, economic, and social impacts of new policies or technologies *a priori* without empirical knowledge?

### Root Cause:
In an age of rapid innovation and globalization, systems are becoming more complex, and their emergent properties are poorly understood.

### Recommendation:
Develop possible future scenarios, and utilize advanced measurement science tools and techniques to monitor and interpret observable outcomes.

### Action Plan: *Possible steps towards the goal*

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<th>Step</th>
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<tr>
<td>1.</td>
<td>Engage stakeholders in developing scenarios to understand envelope of possible futures</td>
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<td>2.</td>
<td>Characterize relevant baseline system conditions and historical changes</td>
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<td>3.</td>
<td>Enable extensive data collection, validation, and interpretation, using &quot;big data analytics&quot;</td>
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<td>4.</td>
<td>Inventory available system modeling tools and identify appropriate applications</td>
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<td>5.</td>
<td>Utilize multi-criteria decision-making tools to establish collective stakeholder priorities</td>
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<td>6.</td>
<td>Adopt an adaptive management approach to respond to changing conditions and unexpected outcomes</td>
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<td>7.</td>
<td>Encourage development of a common ontology for indicators to characterize sustainable and resilient systems</td>
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### Roles

- **Industry**
- **Government**
- **Academia**
- **NGO**
- **Software/Hardware**

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## Breakout Team 2

**Systems (aggregation, linkages, system of systems, sustainability-resilience synergy and interdependencies)**

### Problem or Issue:
Are there tractable methods for practitioners to understand the complex interactions within a system of systems across multiple spatial and temporal scales?

### Root Cause:
Complex, dynamic, non-linear systems are heavily influenced by cross-scale linkages, from micro to macro and vice versa (e.g., climate change drives local flooding, isolated incidents can cascade into large-scale supply disruptions).

### Recommendation:

### Action Plan: *Possible steps towards the goal*

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<tbody>
<tr>
<td>1.</td>
<td>Develop guidance for establishing system boundaries for analyzing broader implications of manufacturing or construction design decisions (beyond conventional &quot;life cycle&quot;)</td>
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<td>2.</td>
<td>Expand concepts of energy, water, and material balance beyond individual structures and processes to a regional or even global scale</td>
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<td>3.</td>
<td>Encourage research on how to perform aggregated, high-level system-level analysis without losing important fine-grain details</td>
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<td>4.</td>
<td>Utilize analytic methods to understand the sensitivity of system sustainability or resilience indicators to key variables at higher or lower scales of resolution</td>
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<td>5.</td>
<td>Develop meta-data standards to assure compatibility and interoperability</td>
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### Roles

- **Industry**
- **Government**
- **Academia**
- **NGO**
- **Software/Hardware**

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*NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014*
# Breakout Team 2. Systems

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<tr>
<td>Matthew Dahlhausen</td>
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<td>Ryan Colker</td>
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* co-moderators

NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014
### 3. Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)

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<tr>
<th>Problem Title</th>
<th>Problem Description</th>
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<tbody>
<tr>
<td>How to apply systems thinking during planning and design of systems that considers interdependencies &amp; trade-offs between economic, environmental and societal impacts?</td>
<td>Sustainability-oriented interventions often involve trade-offs between various activities along the value chain. Without a systems-oriented approach, the impact of these interdependencies are difficult to evaluate.</td>
</tr>
<tr>
<td>How to develop predictive models that can realistically estimate future cross-company and cross-supply chain economic, environmental or societal impacts?</td>
<td>Sustainability improvements often take a long-term to materialize and benefits are likely to accrue across the supply chain. However, existing frameworks do not lend themselves to accurately determine cross-company benefits, economic or otherwise. Can predictive models be developed to realistically predict the influence of such improvement efforts? Can models be developed to predict impacts of emergent and future conditions; to evaluate and design adaptive alternatives?</td>
</tr>
<tr>
<td>How to ensure designed systems have the resilience to withstand disruptive events and operational turbulence?</td>
<td>Global supply chains are increasingly exposed to uncertain events and disruptions. The sustainability performance of supply chains is catastrophically affected when such unpredictable events occur. Quantitatively models for evaluating interdependent risks between supply chain partners and methods to analyze their propagation through the supply chains are lacking.</td>
</tr>
<tr>
<td>How to develop a common nomenclature and terminology related to sustainability that can be across the supply chain?</td>
<td>Sustainability is a relatively new concept and common language for talking about it does not yet exist. The definition of sustainability itself varies from person to person, making it difficult to address the aspects of the issue and develop effective ways to measure it. Establishing consistent, standard terminology for talking about sustainability will help to align researchers and manufacturers communicating about common issues and designing products that address those needs.</td>
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### 3. Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)

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<tbody>
<tr>
<td>How to increase data sharing and interoperability between relevant stakeholders across the supply chain?</td>
<td>In this electronic age, companies amass considerable data related to their products, processes and systems. However, this data is not used effectively to produce actionable information; in situations where such information is available, it is not shared across the supply chain to increase benefits to all stakeholders.</td>
</tr>
<tr>
<td>How to design products, processes and systems to increase remanufacturing, recycling and end-of-life management?</td>
<td>To enable closed-loop material flow across multiple life-cycles of products, they must be designed and manufactured to enable better remanufacturing, recycling and end-of-life management.</td>
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<tr>
<td>How to routinely optimize reverse logistics operations given uncertainty in quality and quantity of end-of-life products?</td>
<td>The uncertainties in the quality and quantity of product flow in reverse supply chains makes it difficult for companies to engage in these activities profitably. What strategies can be implemented to encourage OEMs to engage in reverse logistics operations?</td>
</tr>
<tr>
<td>How to ensure material and energy efficiency become integral steps during the planning and design of products, processes and systems/supply chains?</td>
<td>Assessment categories currently being used in standard LCA analyses don’t allow for a comprehensive analysis of material and energy efficiency. What tools can be used and how can LCA be complemented?</td>
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### Breakout Team 3

**Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)**

#### Problem or Issue: Design for EOL – Remanufacturing, recycling

- **Root Cause:** Lack of design methodologies, incentives, tools
- **Recommendation:** Metrics, methods, measurements

**Action Plan:** *Possible steps towards the goal*

- Lead/support development of design tools and methodologies for design for EOL with metrics and targets
- Support development of sector based metrics for design for EOL
- Benchmark data (design and implementations) sharing
- Lessons learned from EOL products

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#### Roles

- **Industry:** Participate in development, provide data, validation
- **Government:** Lead development, provide incentives, fund research
- **Academia:** Development, research
- **NGO:** Support
- **Software/Hardware:** Integrative software, validation equipment

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### Breakout Team 3

**Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)**

#### Problem or Issue: Reverse logistics/ Reverse supply chains

- **Root Cause:** Lack of Integrated approaches, incentives, tools
- **Recommendation:** Metrics, methods, measurements

**Action Plan:** *Possible steps towards the goal*

- Developments of frameworks for reverse logistics and metrics for measuring effectiveness
- Support development of standard data exchange

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<th>Roles</th>
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<td>Industry</td>
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<td>Academia</td>
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<td>NGO</td>
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<tr>
<td>Software/Hardware</td>
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</table>

#### Roles

- **Industry:** Participate in development, provide data, validation
- **Government:** Lead development, provide incentives, fund research
- **Academia:** Development, research
- **NGO:** Support
- **Software/Hardware:** Integrative software, validation equipment
### Breakout Team 3
Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)

#### Problem or Issue:
Sustainability impacts improvements often occur at different points during the life of the product or structure and may take a long-term to materialize and its benefits are likely to accrue across the supply chain. However, existing frameworks do not lend themselves to accurately determine time dependent cross-company benefits (environmental, economic or societal). Can predictive models be developed to realistically predict the influence of such improvement efforts? Can models be developed to predict impacts of emergent and future conditions; to evaluate and design adaptive alternatives?

#### Root Cause:
Analysis approaches tend to take a unit process view and overall impacts are treated on an additive basis rather than a time series, integrated system view.

#### Recommendation:
1) Not only collect LCI/LCA data for materials and products in a national database but also typical use statistics such as recovery and reuse rates, typical product lifespans, and incremental impacts to assembly or building operational cycles. 
2) Research should be conducted on developing a system of prioritization matrices that quantify the trade offs of various impacts over time and “present-values” those impacts into a comparable form. Note: this may seem to be impossible but only if it is looked at in absolute terms rather than a tool that could be used to assess a variety of scenarios.  
3) Develop a tool to utilize these matrices in relation to product and building design decisions across the cradle-to-cradle lifecycle of the product or building as a contribution to the initial decision making process.

#### Action Plan: Possible steps towards the goal

<table>
<thead>
<tr>
<th>Roles</th>
<th>Action Plan: Possible steps towards the goal</th>
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</thead>
<tbody>
<tr>
<td>Industry</td>
<td>Industry should be prepared to collect and share necessary data (reuse and recovery rates, operational impacts and typical lifespans) just as EPD data is shared.</td>
</tr>
<tr>
<td>Government</td>
<td>Serve as a catalyst to this process through further definition of the issues involved, sponsoring research projects and promoting the concept. Government should maintain and manage the database. Perhaps the tool development should be driven through an organization such as NIST so that the base level of the tool is cross-disciplinary, cross-industry and extensible.</td>
</tr>
<tr>
<td>Academia</td>
<td>Engage in meaningful, creative research</td>
</tr>
<tr>
<td>NGO</td>
<td>Industry trade organizations need o take the lead in collection of industry wide data and support the effort.</td>
</tr>
<tr>
<td>Software/Hardware</td>
<td>Tool has to be credible but not overly complex in order to encourage its utilization.</td>
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### Breakout Team 3
Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)

#### Problem or Issue:
How to apply systems thinking during planning and design of systems that considers interdependencies & trade-offs between economic, environmental and societal impacts?

#### Root Cause:
Lack of information about the total life cycle issues of, materials, processes, and products, data ownership, lack of understanding of process capabilities in terms of energy, material, and water Percepcion that sustainability cost more

#### Recommendation:
Develop Design for sustainable supply chain for risk-based better multi-criteria decision making. Develop data standards, analytical tools that can readily consume data,

#### Action Plan: Possible steps towards the goal

<table>
<thead>
<tr>
<th>Roles</th>
<th>Action Plan: Possible steps towards the goal</th>
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<tbody>
<tr>
<td>Industry</td>
<td>Challenge problems, change perspective on sustainability as competitiveness</td>
</tr>
<tr>
<td>Government</td>
<td>Promote and enable standards, better informed policy instruments, consumer awareness, promote high risk research for long term benefits</td>
</tr>
<tr>
<td>Academia</td>
<td>Education and training, work with industry to develop science for sustainable construction and manufacturing, develop curriculum that reflects industry and society needs and requirements</td>
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<tr>
<td>NGO</td>
<td>Industry and technology roadmap, help develop better policy instruments, better balance of public and private good. And partnership</td>
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<tr>
<td>Software/Hardware</td>
<td>Open architecture platforms for s/w and h/w to enable life cycle information flow, Information models, implementation of data standards and development tools</td>
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<tr>
<td>Breakout Team 3</td>
<td>Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)</td>
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**Problem or Issue:** Resilience - How to ensure designed systems have the resilience to withstand disruptive events and operational turbulence?

**Root Cause:** Lack of: 1) Performance criteria at a component level 2) Performance data of components against the climate change spectrum 3) Sensitivity of matrices in life cycle cost analysis and risk assessment modeling

**Recommendation:** NIST should define performance criteria against the climate change spectrum at the component and building levels. This will allow decision makers to use the appropriate indicators for better decisions.

**Action Plan:** Possible steps towards the goal

1. Develop and publish component-level performance criteria.
2. Evaluate and compare US regional codes to develop climate change spectrum.
3. See “Roles” section for further actions.

**Roles**

<table>
<thead>
<tr>
<th>Industry</th>
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<tbody>
<tr>
<td>1) Provide all the basis of design at a molecular level to NIST so they can test and define criteria. 2) Provide system integration modeling so NIST can complete testing.</td>
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<td>Use and enforce criteria through acquisition regulation.</td>
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<td>Provide criteria to students, the future implementers and building owners.</td>
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<td>Use criteria to propose changes to policy and regulation.</td>
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<th>Software/Hardware</th>
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<tr>
<td>Tools utilizing NIST performance criteria to allow for users to predict for better decision making.</td>
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**Breakout Team 3, question 8, Joe Cresko and Kathi Futornick**

**Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)**

**Problem or Issue:** Restating: “Data sharing and interoperability between relevant stakeholders across the supply chain is insufficient to enable improvements in EE and ME”

**Root Cause:** Benefits through a supply chain are unknown and/or diffuse (principal agent type problem). Supply chains are highly variable, and estimating as well as allocating benefits is complicated.

**Recommendation:** Build off of existing, appropriate tools/models, and ultimately standardize underlying data and tool architectures.

**Action Plan:** Possible steps towards the goal

1. Define materials efficiency and energy efficiency in this context.
2. Identify existing, appropriate tools/models – possibly include embodied energy; materials flows through the economy; cross-sector energy impacts; energy use of (specific) products through their lifecycle;
3. Build upon those tools/models (one example framework could be embodied energy and cross-sectoral energy impacts tools being develop by DOE; another could be BEES tool at NIST).
4. Materials certification – currently, certifications are required for products marketed to EU; underlying data analysis should be standardized/verified and then could be utilized
5. Include in the existing tools/models, or develop additional model frameworks to include other materials-associated “externalities” that directly or indirectly impact costs such as environmental, labor, regulatory, risks.

**Roles**

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<tr>
<td>Examples: engage in standards development, and implementation</td>
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<tr>
<td>Examples: NIST work with standards groups (ISO, ANSI, etc.); DOE work with industry on voluntary programs; USG to collaborate on tools/models/databases</td>
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<td>Examples: engage in standards development, and work with local regulatory agencies. Take leadership role in defining sustainability, materials efficiency, etc., and develop training/tools/etc. useful to industry and society.</td>
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</table>
**Problem or Issue:** How to develop a common nomenclature and terminology related to sustainability that can be used across the supply chain?

**Root Cause:** No consistent definition for sustainability

**Recommendation:** Define common grounds for sustainability in both construction and manufacturing industries based on their needs to sustain business and operations while reducing impact on critical environmental areas. Quantify uncertainties in statements and criteria. Account for subjectivity such as social aspects.

**Action Plan: Possible steps towards the goal**

<table>
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<tr>
<th>Defined Needs to sustain business and impact on the env.:</th>
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<tr>
<td><strong>Resources</strong></td>
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<tr>
<td>1. energy, fossil fuels</td>
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<td>2. water</td>
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<td>3. raw materials</td>
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<td><strong>Tangible impacts</strong></td>
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<td>1. climate (carbon emissions and ozone)</td>
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<td>2. land</td>
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<td>3. water</td>
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<td>4. pollution</td>
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<td>4. pollution</td>
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| **Economic impact** |
| 1. profits |
| 2. Investment |
| 3. Risk |
| 4. Life cycle costs |

| **Intangible impacts** |
| 1. social justice |
| 2. health and well being |

| **Roles** |
| **Industry** |
| Provide sets of criteria relevant to their operations and ensure practicability. |
| **Government** |
| Define priorities and fund accordingly. |
| **Academia** |
| Develop scientific framework to minimize subjectivity and deal with uncertainty. |
| **NGO** |
| Supporting role. |
| **Software/Hardware** |
Breakout Team 3 | Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)
Problem or Issue: | How to develop predictive models that can realistically estimate future cross-company and cross-supply chain economic, environmental or societal impacts?
Root Cause: |
Recommendation: |

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Breakout Team 3 | Planning, design and supply chain (lifecycle analyses and treatments, and material and energy efficiency)
Problem or Issue: | How to ensure designed systems have the resilience to withstand disruptive events and operational turbulence?
Root Cause: |
Recommendation: |

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Breakout Team 3. Planning, design and supply chain

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NIST Workshop on Measurement Science for Sustainable Construction and Manufacturing, June 12-13, 2014
Measurement Science for Sustainable Construction and Manufacturing

Concluding Remarks and Adjournment

Summary

• Workshop: Measurement Science for Sustainable Construction and Manufacturing
  – Background, context, challenges, problems and needs
  – Knowledge gaps and research needs

• By the numbers
  – 80 participants
  – 38 papers
  – 25 speakers and panelists
Workshop Outcomes

• Problem lists
• Problem descriptions
• Breakout reports
• Proceedings

• Opportunity
  – Send comments
  – Send papers

Next Steps

• Publication of proceedings – public domain

Special Thanks to
NIST/Drs. Chin ad Chapman
This publication is available free of charge from: http://dx.doi.org/10.6028/NIST.GCR. 15-986-2