Implementing Sustainable Manufacturing:
Recent Progress, Challenges and Opportunities

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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
  - ISM, 2014

- Sustainable manufacturing offers a new way of producing functionally superior products using 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 at *product, process and systems* levels must:

- demonstrate reduced *negative environmental impact,*
- offer improved *energy and resource efficiency,*
- generate *minimum quantity of wastes,*
- provide *operational safety,* and
- offer improved *personnel health*

while maintaining and/or improving the *product and process quality* with the overall *life-cycle cost benefits.*

*Source:* Jawahir et al. (2014) and Jayal et al. (2010) – Adapted from US Department of Commerce (2009)
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*
Integral Elements of Sustainable Manufacturing

Systems

Sustainable Manufacturing

Products

Processes
Product Recovery as a Starting Point for Multi Life-cycle Products

Source: Jawahir and Bradley (2015)
From Circular Economy to Sustainable Value Creation

From Lean to Green to Sustainable Manufacturing

Source: Jawahir and Bradley (2015)
Comparison of the existing measurement systems

Source: Feng et al. (2010)
Product and Process Metrics for Sustainable Manufacturing: NIST-sponsored Project (2010-14)

Project Title: Development of Metrics and Framework for Products and Processes in Sustainable Manufacturing

Project Team:

Faculty: Dr. I.S. Jawahir, Dr. F. Badurdeen, Dr. O.W. Dillon, Dr. K. Rouch

Sponsor: NIST

Industry partners: TOYOTA, GE, 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
Product Sustainability Clusters

Source: Hapuwanatte et al. (2016)
### Example Metrics for Product Clusters and Life-cycle Stages

<table>
<thead>
<tr>
<th>Metrics Clusters</th>
<th>Example Metrics</th>
<th>Unit</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>
</tr>
<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>Energy Use and Efficiency</td>
<td>Maintenance/ Repair 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>
<td></td>
<td></td>
<td>√</td>
</tr>
<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>$/unit</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Innovation</td>
<td>Average Disassembly Cost</td>
<td>$/unit</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Profitability</td>
<td>Profit</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>$/unit</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Education</td>
<td>Employee Training</td>
<td>Hours/unit</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Customer Satisfaction</td>
<td>Repeat Customer Ratio</td>
<td>(D/L)</td>
<td></td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Customer Satisfaction</td>
<td>Post-Sale Service Effectiveness</td>
<td>(D/L)</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Product End-of-Life Management</td>
<td>Ease of Sustainable Product Disposal</td>
<td>$/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>
</tr>
<tr>
<td></td>
<td>Landfill Reduction</td>
<td>mass/unit</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
Process Sustainability Elements

Environmental Friendliness
Personnel Health
Operational Safety
Manufacturing Cost
Energy Consumption
Waste Management

Process Sustainability Clusters and Sub-clusters

Process Sustainability Index (ProcSI)

- Machining cost
  - Direct cost
  - Indirect cost
  - Capital cost

- Energy consumption
  - Production
  - Mainineance
  - 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)
  - Abseenteism rate
  - Working environment conditions (health)
## 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**

- **Operation Level**
  - Energy consumption of the centrifuge
  - Energy consumption of the main spindle motor
  - Energy consumption of the coolant supply pump
  - Energy consumption of the oil pressure pump
  - Energy consumption of the mist collector, cooler and control unit
  - Energy consumption of the servos
**ProdSI and ProcSI Evaluation**

\[
\text{ProdSI} = \frac{1}{3} (Ec + Ev + So) = \frac{1}{3} \sum_{i=1}^{3} w^c_i C_i + \frac{8}{3} \sum_{i=4}^{8} w^c_i C_i + \frac{13}{3} \sum_{i=9}^{13} w^c_i C_i \div C_m = SC_j w^sc_j
\]

\[
\text{ProcSI} = \frac{1}{6} \sum_{i=1}^{6} C_i = \frac{1}{6} C_1 + C_2 + \frac{1}{5} \sum_{i=10}^{14} w^sc_i SC_i + \frac{1}{4} \sum_{i=15}^{18} w^sc_i SC_i + \frac{1}{3} \sum_{i=19}^{21} w^sc_i SC_i + \frac{1}{2} \sum_{i=22}^{23} w^sc_i SC_i \div
\]

\[
SC_n = w^m_j M_j j
\]
Examples of ProdSI and ProcSI

(a) ProdSI

(b) ProcSI
Sustainability Improvement in Products and Processes

Case studies were conducted on three major manufactured products:

- **Automotive Product**
- **Aerospace Product**
- **Consumer Product**
Metrics Hierarchy – Products/Processes/Systems

System Metrics

- Line
- Plant
- Enterprise
- Supply chain

Process Metrics
- Manufacturing cost
- Operator safety
- Energy consumption
- Waste management
- Environmental impact
- Personnel health

Product Metrics
- Product safety and related impact
- Product quality and durability
- Resources use and efficiency
- Direct/Indirect cost

Stakeholders
- Customers
- Employees
- Governments
- Shareholders
- Communities
- Suppliers
- Others

Performance Measurement Framework

Triple Bottom Line Emphasis
- Economic impacts
- Environmental impacts
- Societal impacts

6R Methodology
- Reduce
- Reuse
- Recycle
- Remanufacture
- Redesign
- Recover

Total Life Cycle Focus
- Pre-manufacturing
- Manufacturing
- Use
- Post-use

Sustainable Manufacturing Philosophy
System Metrics – Production Line Level

Production line: **Example: Satellite Dish Production Line**

- **Steel Coils** → **Stamping** → **Wash** → **Paint** → **Cure Oven** → **Pad Printing** → **Kitting** → **Dish Kit**

- Other materials → **Energy** → **Labor**

- **Waste** → **Emissions** → **By-products**

**Line-level Sustainability Evaluation**

<table>
<thead>
<tr>
<th>Economic Sustainability Evaluation</th>
<th>Cycle time</th>
<th>Changeover time</th>
<th>Uptime</th>
<th>Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Sustainability Evaluation</td>
<td>Raw material usage</td>
<td>Process water consumption</td>
<td>Process energy consumption</td>
<td>Transportation energy consumption</td>
</tr>
<tr>
<td>Societal Sustainability Evaluation</td>
<td>Physical Load Index (PLI)</td>
<td>Noise</td>
<td>Risk Circle</td>
<td></td>
</tr>
</tbody>
</table>

DOE Workshop on Sustainable Manufacturing
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Portland, OR
# Systems Metrics – Enterprise Level

## Economy
- Internal business process
- Financial perspective
- Customer perspective
- Learning & growth

### Sample metrics
- Indirect cost ratio
- Cash flow margin
- Return on capital employed
- Financial robustness
- Order fill rate
- On-time delivery ratio
- Recovery cost
- Cost of recycling

## Environment
- Residues
- Energy
- Resource (other than energy)

### Sample metrics
- GHG emission rate
- Solid emission rate
- Energy efficiency rate
- Renewable energy ratio
- Restricted raw material usage
- Water usage rate

## Society
- Anti-corruption
- Supplier development and training/practices
- Employee development and training
- Customer satisfaction/awareness
- Community development
- Diversity and equal opportunity
- Compliance and product responsibility

### Sample metrics
- Anti-competitive behavior index
- Employee awareness on anti-competitive behavior
- Supplier compliance index
- Supplier training intensity index
- Employee training intensity index
- Employee reward ratio
- Repeat customer ratio
- Product customization ratio
- Local community hiring ratio
- Community contribution ratio
- Diversity ratio
- Employees conflict ratio
- Product compliance ratio
- Compliance incidence rate
Limitations:

- Slow progress and limited effectiveness in implementing sustainable practices --- Lack of economic benefit studies, standards, or best practices
- No comprehensive tools and techniques for total life-cycle evaluation
- Complexity in measuring and quantifying sustainability in products and processes, and greater difficulty in evaluating at system/enterprise level

Outlook and Opportunities:

- Metrics-based sustainability evaluation of products, processes and systems offers a new opportunity for implementation in manufacturing
- Innovative methods for achieving improved resource efficiency (energy, materials, water, etc.) and end-of-life (EOL) management
- Improved manufacturing productivity and greater economic returns through sustainable value creation for all stakeholders