Sustainable Design of Industrial Processes: Integration of Sustainability into the Curriculum

Presenters:

**Yinlun Huang**
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Department of Chemical Engineering and Materials Science  
Director, Sustainable Engineering Graduate Certificate Program, College of Engineering  
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**Mario R. Eden**
Department Chair and Joe T. and Billie Carole McMillan Professor  
Director, NSF-IGERT on Integrated Biorefining  
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The Artie McFerrin Department of Chemical Engineering  
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2017 ASEE Summer School for Chemical Engineering Faculty

Wednesday, August 2, 2017 9:30 am-noon, Thursday August 3, 2017, 9:30 am-noon
Outline

• Overview of NSF Sustainable Manufacturing Advances in Research and Technology (SMART) Coordination Network (Huang)
• Overview of educational modules on sustainable manufacturing (Eden)
• Concepts, tools, and examples on sustainable design for inclusion in the senior-level design course(s) or an elective (El-Halwagi)
Workshop Learning Outcomes

By the end of the workshop, you should be able to perform the following:

• Introduce principles of sustainability and computer-aided modules into chemical engineering curriculum
• Evaluate overall mass targets (fresh usage, waste discharge, yield, etc.) for a given process
• Evaluate targets for minimum heating and cooling utilities
• Use integrated economic and other sustainability criteria in the assessment and screening of process design alternatives
Part I:
Overview of NSF Sustainable Manufacturing Advances in Research and Technology (SMART) Coordination Network

Yinlun Huang
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Wayne State University, Detroit, MI 48202
E-mail: yhuang@wayne.edu, Web:
http://chem1.eng.wayne.edu/~yhuang/
Centuries of Human Activities

- **Depleting resources** 😞
- **Increasing wealth** 😊
- **Damaging the Earth** 😞
Global Challenges

Megatrends

A growing and aging world population
Urbanization
Energy requirements and climate protection
Globalization and new markets

Energy and Resources
Housing and Construction
Health and Nutrition
Mobility and Communication
Demographic Change
Sustainability: What Does It Mean to Us

Definition (one of “hundreds”):

- “Development that meets needs of present without compromising ability of future generations to meet their own needs” – Brudtland, 1987

Sustainable Development

- A rich concept for helping shape human society’s interaction with the biosphere
- “Triple-bottom-lines” based balance
- Systems of interest: global to local, human to physical, macro to micro, etc.
- Features of systems: multiscale, complex, uncertain, unpredictable, moving target
Modern society: a highly heterogeneous system, experiencing numerous types of “reactions”, and having countless “transport phenomena” at all time and length scales.

Ergodicity: the tendency of a system to move towards equilibrium, maximizing entropy, and minimizing free energy.

Human society does not settle down into stable patterns for long; it constantly innovates, grows, and changes, posing a challenge for those trying to adjust human’s interactions with the biosphere.

Human societies are dynamic, open systems far from equilibrium and must evolve and adapt to survive.
Reality and Unacceptable Approach

- Economic prosperity first
- Social responsibility emphasized insufficiently
- Environmental quality suffered
Towards Balanced Development

We want to achieve simultaneously:

- economic prosperity &  
- environmental cleanness &  
- societal satisfaction
Engineering Sustainability: A Need to Re-engineer Engineering Systems

Socio-economic indicators

Economic aspects

Eco-efficiency indicators

Socio-ecological indicators

Environmental aspects

Infra-Structure Service

Cost

Waste

Sustainability Science & Engineering

Living standard

Environmental quality

Product, Process, Tech.
Accelerating U.S. Advanced Manufacturing
- PCAST, Oct. 27, 2014

- “The United States has been the leading producer of manufactured goods for more than 100 years.”
- “The United States has long thrived as a result of its ability to manufacture goods and sell them to global markets.”
- “U.S. strengths in manufacturing innovation and technologies that have sustained American leadership in manufacturing are under threat from new and growing competition abroad.”

A renewed national effort has been made to secure U.S. leadership in emerging technologies that will create high-quality jobs and enhance America’s global competitiveness.
• DOC and EPA Definition:

Sustainable manufacturing is “the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources”.

Sustainable manufacturing also “enhances employee, community, and product safety, which are all social issues.”
Overview of NSF Sustainable Manufacturing Advances in Research and Technology (SMART) Coordination Network

SMART CN – Leadership Team

Principal Investigators/Executive Committee

Y. Huang
Wayne State U

T. Edgar
U Texas

M. El-Halwagi
Texas A&M U

C. Davidson
Syracuse U

M. Eden
Auburn U

Development Director of Educational Modules

D. Sengupta
Gas and Fuels Research Center,
Texas A&M U

Steering Committee

L. Achenie
Virginia Tech.

D. Allen
U Texas

B. Bakshi
Ohio State U

B. English
U Tennessee

D. Fasenfast
Wayne State U

I. Grossmann
Carnegie Mellon U

K. High
Clemson U

I. Jawahir
U Kentucky

C. Maravelias
U Wisconsin

K. Ogden
U Arizona

M. Rezac
Kansas State U

F. Shadman
U Arizona
SMART CN – Collaboration Organizations

**Domestic**
- AIChE - Institute for Sustainability (IfS)
- CACHE Corporation
- Center for Sustainable Engineering, Syracuse U.
- Industrial and Urban Sustainability Group (I&US), Wayne State U.
- Institute for Sustainable Manufacturing (ISM), U. of Kentucky
- National Alliance for Advanced Biofuels and Bioproducts (NAABB)
- National Center for Manufacturing Sciences (NCMS)
- National Council for Advanced Manufacturing (NCFAM)
- NSF ISRC Engineering Center for Environmentally Benign Semiconductor Manufacturing, U. of Arizona
- Smart Manufacturing Leadership Coalition
- Texas-Wisconsin-California Control Consortium, Austin, TX
- The Industrial & Urban Sustainability (I&US) Group, Wayne State U.

**International**
- Denmark, Germany, China, Norway, Singapore, Japan, India
Project Tasks

1. To conduct comprehensive and in-depth review of the frontier research and technological development for sustainable manufacturing

2. To define roadmaps for manufacturing sustainability and identify bottlenecks in a number of focused research areas via workshops

3. To coordinate research through sharing knowledge, resources, software, and results

4. To establish partnerships with industrial groups to expedite technology innovation

5. To conduct education and outreach to a wide range of stakeholders
Academic and Industrial Collaboration on Sustainable Manufacturing

**Process-product Systems Studies**
- Modeling
- Process control
- Product quality
- Safety & security
- Energy efficiency
- Design
- Operation
- Management
- Material efficiency
- Optimization
- Education & workforce training
- Supply chain
- Waste reduction

**Sustainability Studies**
- Metrics
- LCA
- Industrial ecology
- Policy & regulations
- Sustainability assessment
- Economic
- Environmental
- Social
- Uncertainty
- Complex systems
- Multiscale systems
- Environ./health
- Sustainability decision making

**Manufacturing Technology Innovations**
- Material/alternative feedstock
- Energy/alternative energy
- Product & performance
- Process development
- Pollution prevention
- Supply chain
- Water conservation
- Business management

**Manufacturing Industries**
- Chemical
- Petrochemical
- Specialty chemical
- Pharmaceutical
- Automotive
- Electronics
- Iron & steel
- Energy/biofuels
- Construction
- Food

**Academic Research**
Part II: Overview of Educational Modules on Sustainable Manufacturing

Mario R. Eden
Department Chair and Joe T. and Billie Carole McMillan Professor
Director, NSF-IGERT on Integrated Biorefining
Department of Chemical Engineering, Auburn University, AL 36849-5127
Email: edenmar@auburn.edu, Web: wp.auburn.edu/eden
Tutorial on the SMART-CN Educational Modules for Incorporation in the Advanced Undergraduate or Graduate Engineering Curriculum

Debalina Sengupta1*, Yinlun Huang2, Thomas F. Edgar3, Cliff I. Davidson4, Mario R. Eden5, Mahmoud M. El-Halwagi1

1 Artie McFerrin Department of Chemical Engineering, Texas A&M University
2 Chemical Engineering and Materials Science, Wayne State University
3 McKetta Department of Chemical Engineering, University of Texas at Austin
4 Civil and Environmental Engineering, Syracuse University
5 Department of Chemical Engineering, Auburn University

Presented at the AIChE Annual Meeting,
San Francisco, November 14, 2016
Outline

• SMART – CN Education Vision
• Modules Development
• Future Modules
Sustainable Manufacturing Advances in Research and Technology (SMART) Coordination Network

SMART – CN Education Vision

Sustainable Manufacturing

Multiscale Framework Required for Information Exchange

Technology Development

Process and Systems Management

Enterprise Management

• **New Product Development** – Thermodynamics, chemistry, molecular modeling
• **Alternative Feedstock and Materials** – Chemical properties for new feedstock, seamless integration into design software
• **New Pathways and Processes** – Catalysis, reaction pathway synthesis, environmental releases

Learning criteria for students/workforce: Identify (develop if necessary) indicators and metrics for assessment and management of sustainable technologies.
Sustainable Manufacturing

Multiscale Framework Required for Information Exchange

- **Process Design** – process integration, process intensification, process optimization
- **Plant Operations** – advanced control systems, process safety, environmental control systems
- **Materials and Energy Management** – can be integrated into process design area through the integration and intensification methods

*Learning criteria for students/workforce:* Identify (develop if necessary) technologies, indicators and metrics for assessment and management of process systems. Incorporate this knowledge into various stages of design and operations.
Supply Chain Management and Logistics Optimization – life cycle assessment (for environmental impact assessment), optimization (for logistics, cost), life cycle optimization (for both economic and environmental assessment of supply chain)

Information Management – tools, data, information related to success stories, case studies for enterprise managers

Enterprise Framework – systems analysis for studying impacts of entire supply chain

Learning criteria for students/workforce: Identify (develop if necessary) methodologies for systematic analysis of sustainability of enterprise. Crucial to include all aspects of sustainability, such as economic, environmental, and social. Can be expanded to include cross-cutting areas such as safety.
Course Type 1 – Integrating into Existing Coursework

- The approach for this course is to develop modules which **COMPLEMENT** existing engineering discipline course curriculum with sustainability approaches.
- Instructors may choose to incorporate the case studies in these modules into the individual courses.
- Social criteria is not included in this section. It is expected to be incorporated into existing liberal arts coursework that students have to take in their degree.

<table>
<thead>
<tr>
<th>Thermodynamics</th>
<th>Molecular modeling</th>
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<tbody>
<tr>
<td>Mass Transfer</td>
<td>Green chemistry</td>
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<td>Heat Transfer</td>
<td>Environmental impact potential</td>
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<tr>
<td>Reaction Engineering</td>
<td>Resource use</td>
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<td>Transport Phenomena</td>
<td>Energy use</td>
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<table>
<thead>
<tr>
<th>Engineering Design</th>
<th>Process integration</th>
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<tbody>
<tr>
<td></td>
<td>Process intensification</td>
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<td></td>
<td>Process safety</td>
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<td>Metrics/Indicators/Indices</td>
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<table>
<thead>
<tr>
<th>Process Control and Optimization</th>
<th>Environmental control variables</th>
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<tbody>
<tr>
<td></td>
<td>Optimum points for economic and environmental issues</td>
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<tr>
<th>Supply Chain/Operations Management</th>
<th>Life Cycle Assessment</th>
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<tbody>
<tr>
<td></td>
<td>Supply Chain Optimization</td>
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</table>
Course Type 2 – Introducing New Coursework

• The approach in this course type is to **ADD** a topic to existing engineering discipline courses, at par with engineering design.
• Suggested title: “Sustainability approaches in Engineering”.
• Single instructor, or a group of instructors, specializing in the individual areas.
• Requires coordination among the instructors to time and devise homework/exams.
• Introduction of certain social aspects require interdisciplinary coordination from social sciences instructors.

<table>
<thead>
<tr>
<th>Increasing Scale</th>
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<tbody>
<tr>
<td>Molecular Modeling</td>
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<tr>
<td>Process integration</td>
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<tr>
<td>Process intensification</td>
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<tr>
<td>Life Cycle Assessment</td>
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</tbody>
</table>

Multiscale process systems modeling

| Environmental impacts methods – relevant at any scale |
| Safety/Risk assessment methods – relevant at some scales |
| Social impact methods – relevant after certain scales |
| Quantification: Metrics/Indicators/Indices – necessary for all scales |
Course Type 3 – Short Courses Directed towards Specific Manufacturing Sector

- The approach for this course is to **CATER** to the needs of existing industry professionals to understand, integrate, and measure sustainability approaches in their sector.
- This may be a classroom instruction course, **Massive Open Online Course (MOOC)**, or standard slideshow based course.
- Developing this will require the following knowledge and dissemination plan:

<table>
<thead>
<tr>
<th>Knowledge of Industrial Sectors</th>
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<tbody>
<tr>
<td>(can be categorized based on NAICS/SIC codes)</td>
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</table>

<table>
<thead>
<tr>
<th>Knowledge of Sustainability Implementation Areas</th>
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</thead>
<tbody>
<tr>
<td>(for example, petroleum refineries need to be profitable, safer, low emission, and built in areas such that environmental justice is not violated)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Develop Specific Module Based on the Knowledge of The Sustainability Implementation Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Course module takes an existing refinery, follows it through the various stages of design to implementation (Front End Engineering Design, Site Selection, HAZOP/HAZID studies, Environmental Permits and Regulations, Construction and Management, Operations)</td>
</tr>
<tr>
<td>- Plugs in the sustainability criteria knowledge (through modules) into the stages of design</td>
</tr>
<tr>
<td>- Identify a set of key indicators and metrics required to assess sustainability over the life cycle of the sector</td>
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</tbody>
</table>

**Example: Petroleum Refining Manufacturing Industry**
Course Type 1- Structure

Outline/Overview (Word® document)

– **Introduction** (max 500 words, excluding figures)
  
  Key aspects of module, e.g. “What is LCA?”, “Why is LCA needed?”, “Overview, framework for LCA”

– **Rationale: <Life Cycle Assessment> for ensuring Sustainable Engineering (max 300 words)**
  
  e.g. Why do we need LCA for sustainable engineering/manufacturing?

– **Course Content: <LCA theory, methods, tools and databases> (max 3000 words to ensure most important information is provided in the text, excludes figures, use of appendices for additional information)**

– **Connections to Existing Core Curriculum (max 200 words)**
  
  e.g. Which areas in existing courses can LCA fit into? Who should know about LCA?

– **Case study** (max 300 words, short description)

– **References and Websites for Further Reading**

– **Appendices**
Course Type 1- Structure

Classroom Presentation (Powerpoint® slides)
- ~ 40-50 slides, including case study
- Ready for use by instructor, specific delivery instructions (e.g. when to administer a certain case problem) provided in the notes
- Can also be used by individuals seeking self-study options

Case Study (Word® document)
- No word limits
- Case study can be describing a single problem with multiple example options
- The solutions are provided in most cases, with specific instructions on the solution methods used

Supporting Material
- All supporting material provided (spreadsheets, solution manuals, computer programs, design files)
Module Categories

Methods for Sustainable Manufacturing
Focus on the method of assessment of sustainability

Sustainable Manufacturing Processes
Focus on the process(es) for manufacturing

Dedicated Assessment Tools
Assessment platforms for Sustainable Manufacturing
## Modules

<table>
<thead>
<tr>
<th>Module Name</th>
<th>Developer/University</th>
<th>Module Content</th>
</tr>
</thead>
</table>
| Assessment of the Presidential Green Chemistry Award Winners using Green Chemistry Metrics | Christopher L. Kitchens/Clemson University | **Method Topic:** This module evaluates the work that has received the Presidential Green Chemistry Challenge Award using green chemistry metrics, principles, and design strategies.  
**Assessment Tools:** The first part is to perform a critical review of the awarded technology. The second part of the assignment requires students to contact the award winners by whatever means necessary, and interview them on 1) what the PGCC Award has meant to them and their career and 2) what personal benefit have they gained from working the award winning technology  
**Supporting Documents:** Sample interview responses, assessment of Ibuprofen production by green technology, awarded Green Chemistry award in 1997  
**Learning Outcomes:** Develop an appreciation of the Green Chemistry pathways and challenges through a case study based approach on the awarded winners |
# Modules

<table>
<thead>
<tr>
<th>Module Name</th>
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</thead>
</table>
| Life Cycle Assessment for Sustainable Manufacturing | Debalina Sengupta, Texas A&M University | **Method topic:** Provides overview of life cycle assessment methodology as outlined in the ISO standards, Emphasize the utility for the LCA methods for manufacturing sustainability  
**Assessment tools:** Case study for a chemical production process choice for methanol, assignment set  
**Supporting documents:** spreadsheet tool demonstrating case study  
**Learning Outcomes:** Understand the role of process engineers in providing effective inventory data for LCA, conduct screening level LCA studies for sustainable manufacturing |
LCA Module Example
## Modules

<table>
<thead>
<tr>
<th>Module Name</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Sustainability Metrics and Sustainability</td>
<td>Debalina Sengupta, Texas A&amp;M University</td>
<td><strong>Method topic:</strong> Provides overview of methods to compute sustainability metrics. It also gives a method compute overall sustainability by aggregating metrics. <strong>Assessment tools:</strong> Two case studies are presented on automotive shredder residue treatment method and on automobile fender formulation. <strong>Supporting documents:</strong> spreadsheet tool demonstrating case study <strong>Learning Outcomes:</strong> Understand the metrics used for measuring sustainability, compute these metrics, and then use the sustainability footprint method to decide which is the best option among these.</td>
</tr>
</tbody>
</table>
### Modules

<table>
<thead>
<tr>
<th>Module Name</th>
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</table>
| Green Chemistry to Manufacture Specialty Chemicals from Renewable Resources | Jeffrey R. Seay, Assistant Professor, University of Kentucky | **Method Topic:** Introduces the concept of green chemistry for green design of processes, gives three methods for assessing “greener” processes: The WAR Algorithm for computing the potential environmental impact (PEI) of a process, Life Cycle Assessment for assessing environmental and other impacts, and inherently safe process design.  
**Assessment Tools:** Case study for assessing sustainability of acrolein production, assignment set for pre-test on sustainability and five guided enquiry activities.  
**Supporting Documents:** Aspen Plus design files for acrolein production  
**Learning Outcomes:** Learn the theory for green chemistry, green engineering, and sustainability assessment methods |
<table>
<thead>
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</table>
| Sustainability Root Cause Analysis (SRCA)       | Helen H. Lou, Professor, Lamar University| **Method Topic**: Demonstrates Sustainability Root Cause Analysis (SRCA) as a tool to determine the bottlenecks for a system’s progress towards sustainability. The framework is built on the combination of Pareto chart and the Fishbone diagram, in conjunction with a set of sustainability metrics (economics, environmental and safety).  
**Assessment Tools**: Three case studies with assignment set on steam reforming of methane, polygeneration, and LNG process  
**Supporting Documents**: ASPEN Plus design files for the case studies  
**Learning Outcomes**: Learn how to combine quality assessment method of Root Cause Analysis (RCA) and sustainability metrics to determine a sustainable manufacturing process |
## Modules

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<tbody>
<tr>
<td>Optimization and Uncertainty for Green Design</td>
<td>Dr. Urmila Diwekar,</td>
<td><strong>Method Topic:</strong> Demonstrates the use of optimization methods for sustainable manufacturing. Incorporates systems theory as a valuable tool to</td>
</tr>
<tr>
<td>and Industrial Symbiosis</td>
<td>Vishwamitra Research</td>
<td>enable the integration of multi-scale, multi-disciplinary components using an informational and computational platform.</td>
</tr>
<tr>
<td></td>
<td>Institute and Dr.</td>
<td><strong>Assessment Tools:</strong> A case study on mercury waste management from coal power plants, divided into several sub-modules to demonstrate model</td>
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<td></td>
<td>Yogendra Shastri,</td>
<td>formulation and solving.</td>
</tr>
<tr>
<td></td>
<td>IIT Bombay</td>
<td><strong>Supporting Documents:</strong> GAMS codes, solution files</td>
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<td><strong>Learning Outcomes:</strong> Learn how to use optimization methods as a tool to formulate and solve issues related to sustainable manufacturing</td>
</tr>
</tbody>
</table>

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</table>
| Early Stage Sustainability Analysis Tool - EarlySim | Akshay Patel/SustAnalyze/Utrecht University | **Tool:** This module provides an early stage chemical process assessment tool. The tool can be used for sustainability assessment in the areas of economic constraints, environmental impact of raw materials, process costs and environmental impact, EHS index, and Risk aspects.  
**Assessment Tools:** The module provides a link to a tool available online, instructions on how to use the tool and learning modules.  
**Supporting Documents:** Dedicated tool online access, Learning modules, walkthrough for case studies  
**Learning Outcomes:** Learn to analyze sustainability issues through a tool based learning environment |
EarlySim Tool

![Process Flow Diagram](Diagram.png)

**Index Ratio = 0.90**

Bioethanol Score / Naphtha score

**Lower scores are better**

- **Economic constraint (EC)** (0.3)
  - Price ratio
  - Practical yields
  - Allocated raw material costs
  - Market price

- **Environmental impact of raw materials (EIR)** (0.2)
  - Cumulative energy demand
  - GHG emissions

- **Process costs and environmental impacts (PCEI)** (0.2)
  - Energy loss index
  - Product concentration
  - Water content
  - Boiling point difference
  - Mass loss index
  - Reaction energy
  - No. of co-products
  - Pre-treatment

- **EHS index (EHSI)** (0.2)
  - Environment
  - Persistency
  - Air hazard
  - Water hazard
  - Solid waste
  - Health
  - Irritation
  - Chronic toxicity
  - Safety
    - Mobility
    - Fire/explosion
    - Reactivity
    - Acute toxicity

**Total score**

- **Conventional process**

**Risk aspects (RA)** (0.1)
  - Feedstock supply risk
  - Market risk
  - Infrastructure (availability) risk
  - Regional feedstock availability
  - Application-technical aspects

**Process concept**

- **Laboratory experiments**
- **Process design**
- **Pilot trials**
- **Commercial production**

**Early stage assessment (ESA)**

**Ex-ante sustainability assessment**
## Modules

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</table>
| Atomic Layer Deposition Nano-Manufacturing Technology | Chris Yuan/University of Wisconsin, Milwaukee | **Process Topic:** This module on atomic layer deposition (ALD) focuses on the study of energy usage and exergy efficiency, simulate reactions inside ALD system and analyze ALD deposition and emissions.  
**Assessment Tools:** A design of experiments based assessment of ALD process with sustainability considerations, Minitab example to run DOE  
**Supporting Documents:** Detailed process description, experimental requirements, and design of experiments description for sustainability assessment of ALD process  
**Learning Outcomes:** Learn details of ALD concept, manufacturing steps, model formulation for DOE, and benefits of sustainable manufacturing principles applied to ALD |
<table>
<thead>
<tr>
<th>Module Name</th>
<th>Developer/ University</th>
<th>Module Content</th>
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</thead>
</table>
| Optimal Design and Operation of Reverse Osmosis Desalination | Mingheng Li/California State Polytechnic | **Process Topic:** Specific energy consumption (SEC) in reverse osmosis (RO) desalination is considered for sustainability of the water treatment process. The module focuses on case studies that help in the optimal design for RO with the sustainability concerns in energy consumption addressed.  
**Assessment Tools:** GAMS program files  
**Supporting Documents:** Supporting documentation on RO, homework problems  
**Learning Outcomes:** Learn about RO water treatment as a means to provide desalinated water, understand the key sustainability issues with RO desalination, and |
## Modules

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</table>
| Sustainable Additive Manufacturing | Karl Haapala/Oregon State University | **Process topic:** Provides a module that covers additive manufacturing as a means for sustainable manufacturing. This module explains the basics of additive manufacturing, and explores energy analysis as a metric to establish the benefits of AM.  
**Assessment tools:** Case study in the form of a hands-on laboratory that will educate students about the use of CAD and CAM tools in AM for developing a keychain.  
**Supporting documents:** CAD exercise file, Powerpoint presentations for different topics covered  
**Learning Outcomes:** Understand the basics of the new trend in additive manufacturing, have sustainability considerations in design, create effective low cost and low energy consuming manufactured goods. |
Additive Manufacturing Module Example

Think-Pair-Share

- What can be done to improve the efficiency of AM processes?
  - Process:
  - Problem:
  - Research:
  - Action:
## Modules

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</table>
| Sustainable Mitigation of Carbon Dioxide  | Debalina Sengupta and | **Process Topic:** this module explores CO2 mitigation strategies through the utilization of CO2 into high value chemicals. A superstructure optimization model is formulated and solved for different scenarios.  
**Assessment Tools:** GAMS program files for several scenarios, homeworks  
**Supporting Documents:** Case study explanation files, background information documents  
**Learning Outcomes:** The module is intended to expand the knowledge on CO2 mitigation methods as a means to tackle climate change. |
| to Chemicals                              | Sherif Khalifa/Texas | University and Drexel University                                                                                                                |
Future Modules

• Currently following modules are under development:
  
  – Tool:
    • Chemical Complex Analysis tool for Sustainability Analysis
    • Process Modeling and Life Cycle Analysis of 1,3-Propanediol from Fossils and Biomass: Instructor Materials
  
  – Process:
    • Sustainability of Battery Manufacturing
    • Characterizing and Managing Hydraulic Fracturing Water and Gas Production
    • Sustainable Shale Gas Monetization
    • Electrodialysis Membrane Distillation
  
  – Method:
    • Process Integration
    • Sustainability Cost Assessment for Manufacturing
    • Water-Energy Nexus
    • Biomass Feedstock Properties

• Help is sought in the academic community for knowledge dissemination and utilization of the modules
Web Resources and Additional Readings

Modules are made available through the following website: Computer Aids in Chemical Engineering “CACHE”:
http://cache.org/super-store

Acknowledgement

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The SMART education modules provide complete classroom ready material for instructors. Each module contains an overview, a set of slides for instructional use, and homework with solutions. Instructors may modify the material as needed. The modules are categorized as learning tools, methods for sustainable manufacturing with case studies, and process examples.

<table>
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<tr>
<th>Module Name</th>
<th>Module Developer</th>
<th>Module Content</th>
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<tr>
<td>Early Stage Sustainability Analysis Tool - EarlySim</td>
<td>Akshay Patel/Sustainalyze/University</td>
<td>Provides an early stage chemical process assessment tool. The tool can be used for sustainability assessment in the areas of economic constraints, environmental impact of raw materials, process costs and environmental impact, EHS index, and Risk aspects.</td>
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<tr>
<td>Assessment of the Presidential Green Chemistry Award Winners using Green Chemistry Metrics</td>
<td>Christopher L. Kitchens/Clemson University</td>
<td>Evaluates the work that has received the Presidential Green Chemistry Challenge Award using green chemistry metrics, principles, and design strategies.</td>
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<tr>
<td>Life Cycle Assessment for Sustainable Manufacturing</td>
<td>Debalina Sengupta, Texas A&amp;M University</td>
<td>Provides overview of life cycle assessment methodology as outlined in the ISO standards, Emphasize the utility for the LCA methods for manufacturing sustainability</td>
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<tr>
<td>Sustainability Metrics and Sustainability Footprint Method</td>
<td>Debalina Sengupta, Texas A&amp;M University</td>
<td>Provides overview of methods to compute sustainability metrics. It also gives a method compute overall sustainability by aggregating metrics.</td>
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<tr>
<td>Green Chemistry to Manufacture Specialty Chemicals from Renewable Resources</td>
<td>Jeffrey R. Seay, Assistant Professor, University of Kentucky</td>
<td>Introduces the concept of green chemistry for green design of processes, gives three methods for assessing “greener” processes: The WAR Algorithm for potential environmental impact (PEI) of a process, Life Cycle Assessment, and inherently safe process design.</td>
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<tr>
<td>Sustainability Root Cause Analysis (SRCA)</td>
<td>Helen H. Lou, Professor, Lamar University</td>
<td>Demonstrates Sustainability Root Cause Analysis (SRCA) as a tool to determine the bottlenecks for a system’s progress towards sustainability. The framework is built on the combination of Pareto chart and the Fishbone diagram, in conjunction with a set of sustainability metrics (economics, environmental and safety).</td>
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<tr>
<td>Optimization and Uncertainty for Green Design and Industrial Symbiosis</td>
<td>Dr. Urmila Diwekar, VRI and Dr. Yogendra Shastri, IIT Bombay</td>
<td>Demonstrates the use of optimization methods for sustainable manufacturing. Incorporates systems theory as a valuable tool to enable the integration of multi-scale, multi-disciplinary components using an informational and computational platform.</td>
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<tr>
<td>Atomic Layer Deposition Nano-Manufacturing Technology</td>
<td>Chris Yuan/University of Wisconsin, Milwaukee</td>
<td>Module on atomic layer deposition (ALD) focuses on the study of energy usage and exergy efficiency, simulate reactions inside ALD system and analyze ALD deposition and emissions.</td>
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<tr>
<td>Optimal Design and Operation of Reverse Osmosis Desalination</td>
<td>Mingheng Li/California State Polytechnic</td>
<td>Specific energy consumption (SEC) in reverse osmosis (RO) desalination is considered for sustainability of the water treatment process. The module focuses on case studies that help in the optimal design for RO with the sustainability concerns in energy consumption addressed.</td>
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<tr>
<td>Sustainable Additive Manufacturing</td>
<td>Karl Haapala/Oregon State University</td>
<td>Provides a module that covers additive manufacturing as a means for sustainable manufacturing. This module explains the basics of additive manufacturing, and explores energy analysis as a metric to establish the benefits of AM.</td>
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<tr>
<td>Sustainable Mitigation of Carbon Dioxide to Chemicals</td>
<td>Debalina Sengupta, Texas A&amp;M University and Sherif Khalifa, Drexel University</td>
<td>This module explores CO2 mitigation strategies through the utilization of CO2 into high value chemicals. A superstructure optimization model is formulated and solved for different scenarios.</td>
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Modules Available at: [https://cache.org/super-store](https://cache.org/super-store) or [http://www.research.che.utexas.edu/susman/edu.html](http://www.research.che.utexas.edu/susman/edu.html)

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