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

Presenters:

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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

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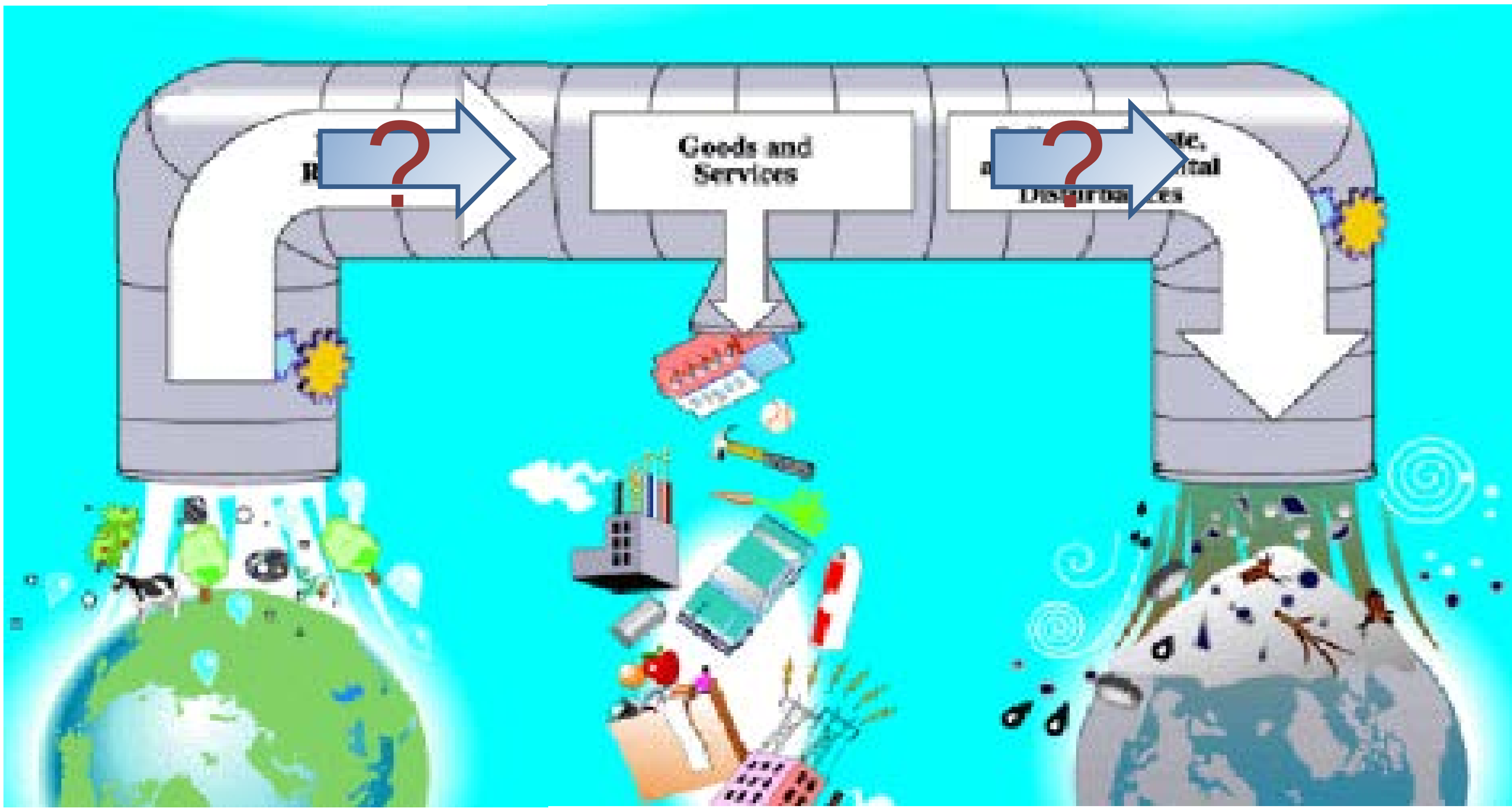
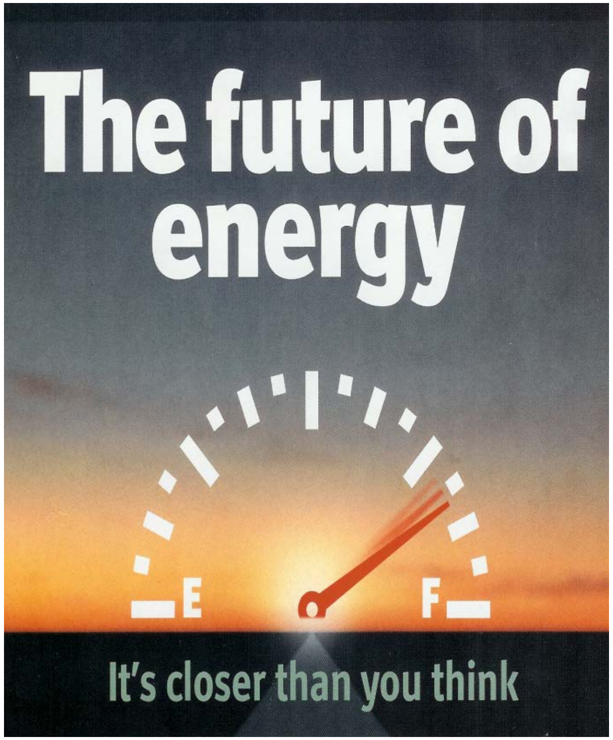
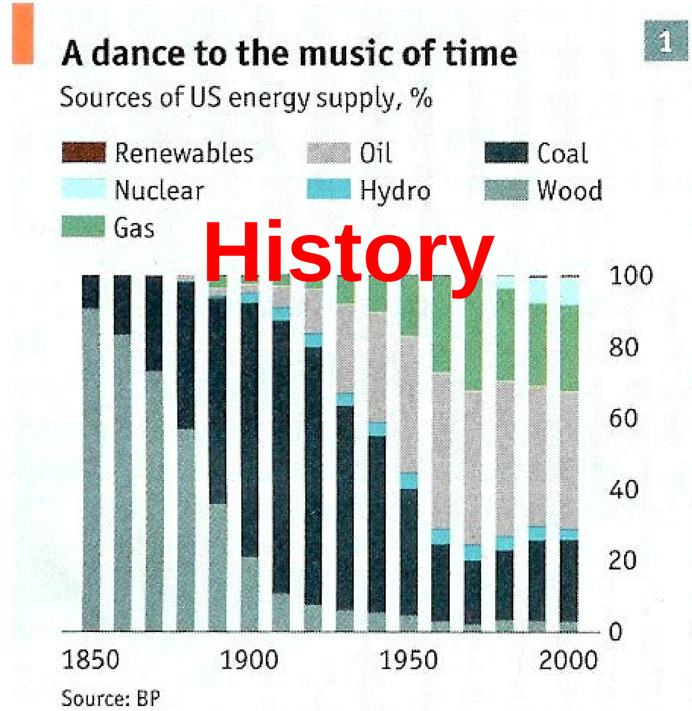
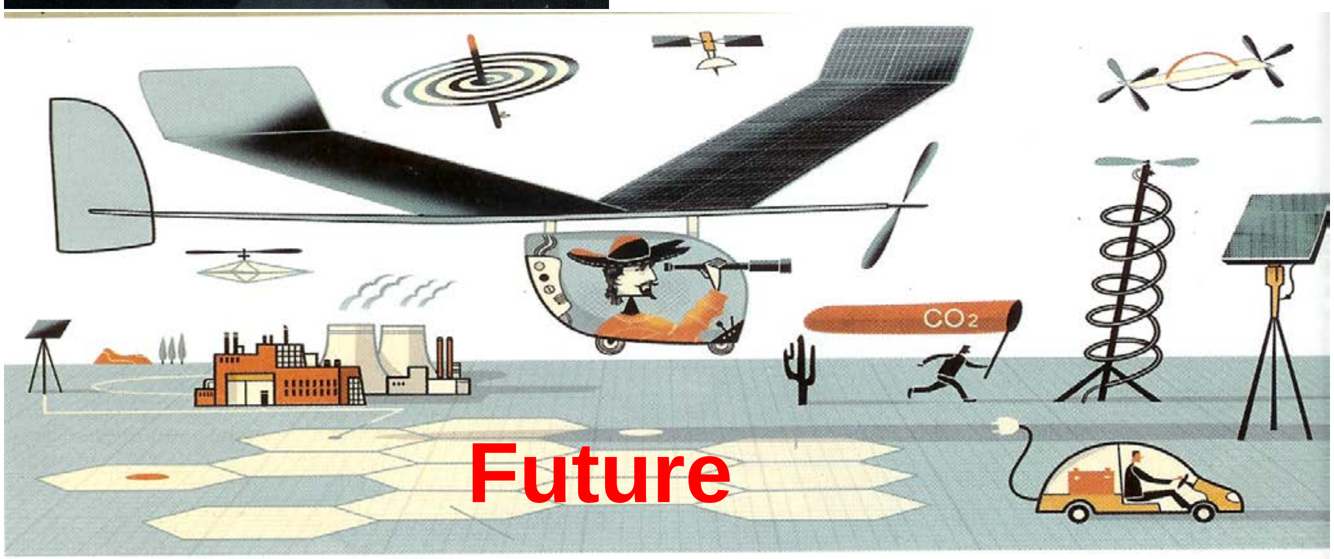
Centuries of Human Activities

Depleting resources | **Increasing wealth** | ***Damaging the Earth***




The future of energy
E
F
It's closer than you think


A dance to the music of time
1
Sources of US energy supply, %
Renewables
Oil
Coal
Nuclear
Hydro
Wood
Gas
History
100
80
60
40
20
0
1850
1900
1950
2000
Source: BP


CO2
Future


Today

Global Challenges

A growing and aging world population

Urbanization

Energy requirements and climate protection

Globalization and new markets

Megatrends

- 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

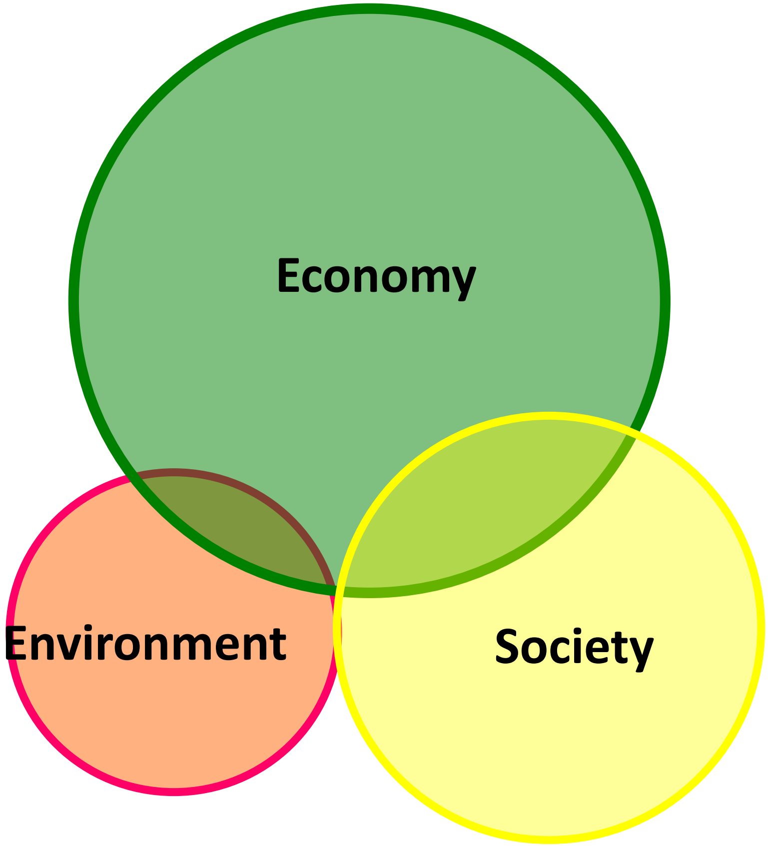
Sustainable Development

- 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

SD: An Engineer's View

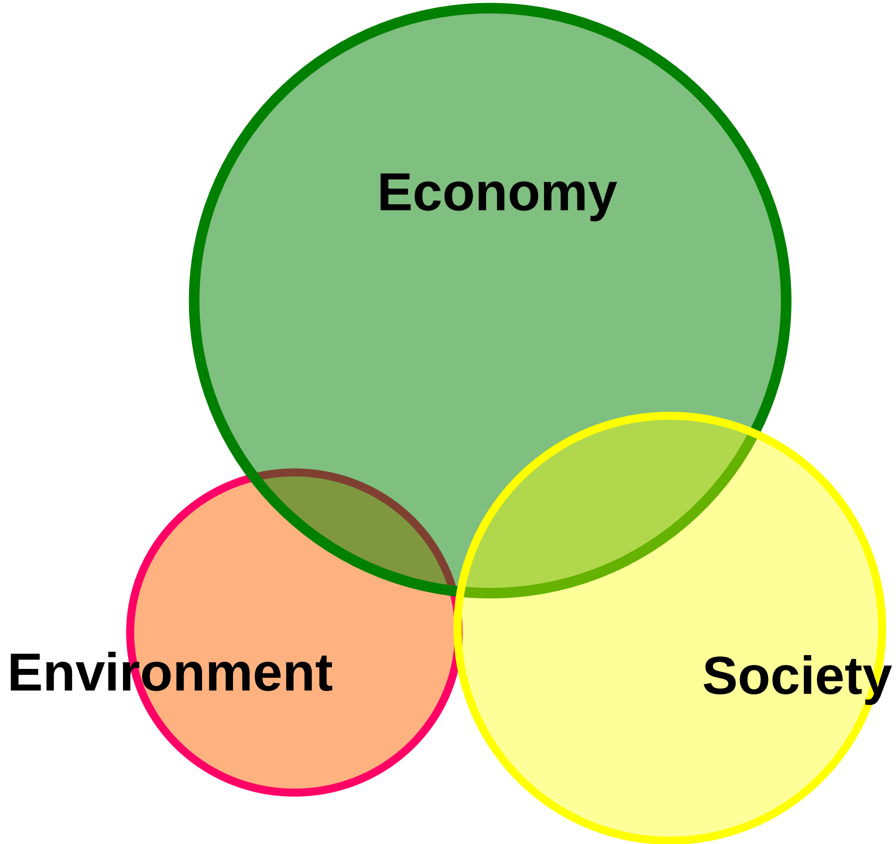
- Modern society: a highly heterogeneous system, experiencing numerous types of "reactions", and having countless "transport phenomena" at all time and length scales
- Ergodicity: the tendency of a system to move towards equilibrium, maximizing entropy, and minimizing free energy
- Human society does 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

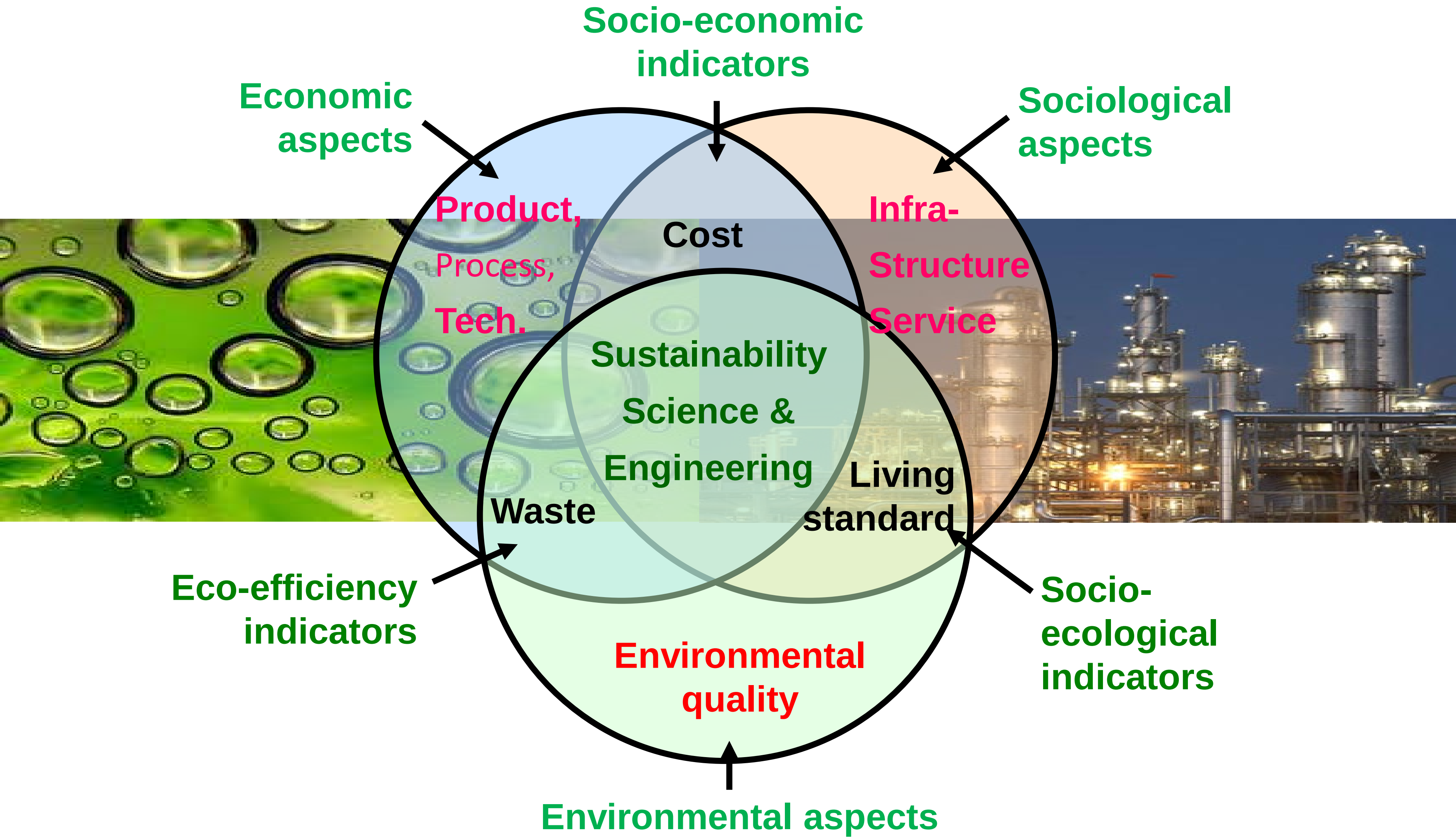
Towards Balanced Development



We want to achieve simultaneously

- economic prosperity
  &
- environmental cleanness
  &
- societal satisfaction

Engineering Sustainability:
A Need to Re-engineer Engineering Systems



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.

Sustainable Manufacturing

- **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."

SMART CN – Leadership Team

Principal Investigators/Executive Committee


Y. Huang
Wayne State U

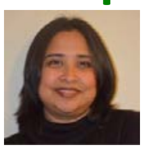

T. Edgar
U Texas


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
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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 Advanced Process Decision-Making, Carnegie Mellon U.
- 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.

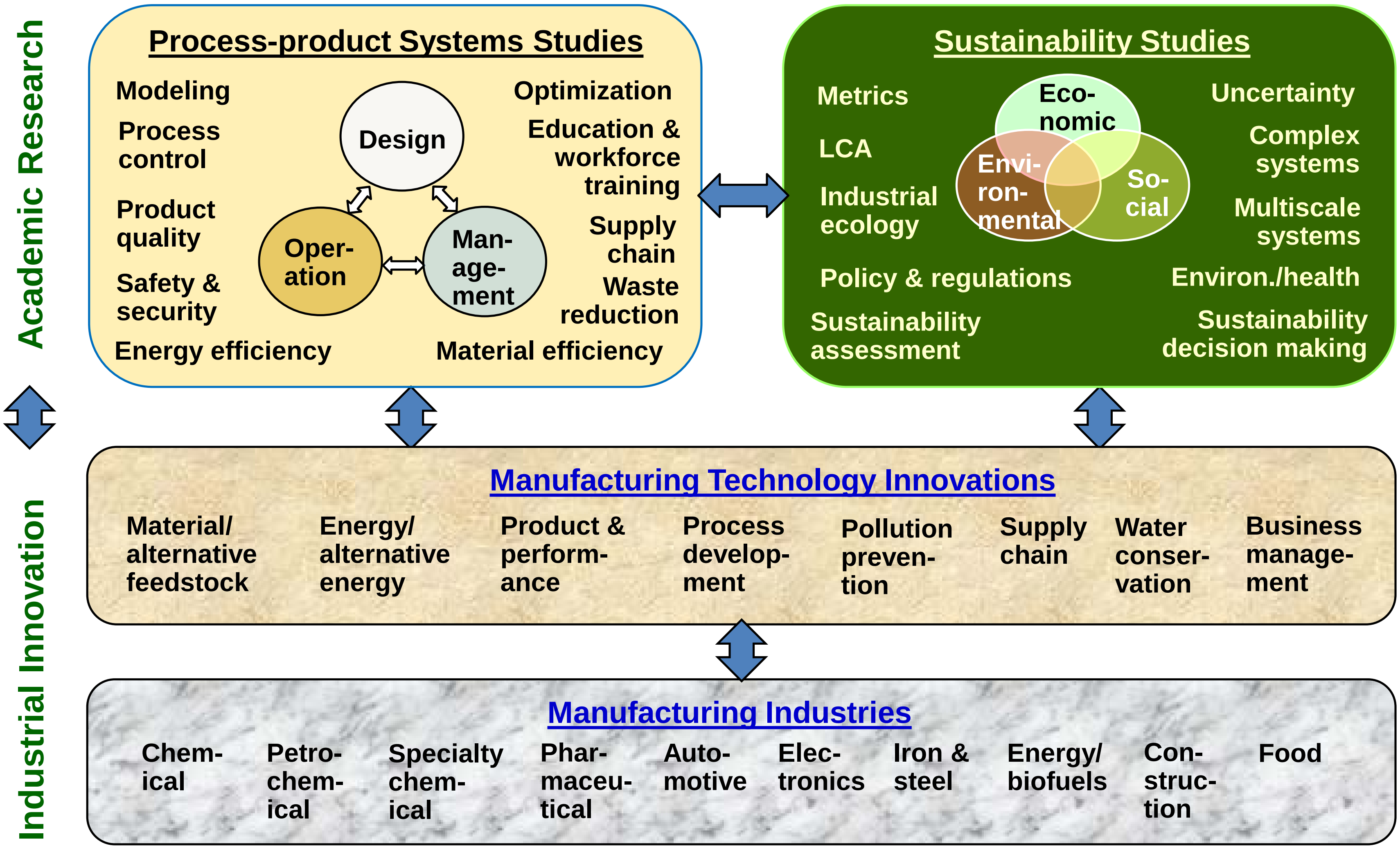
International

- 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



Part II:
Overview of Educational Modules on Sustainable Manufacturing

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Tutorial on the SMART-CN Educational Modules for Incorporation in the Advanced Undergraduate or Graduate Engineering Curriculum

Debalina Sengupta[1]*, Yinlun Huang[2], Thomas F. Edgar[3], Cliff I. Davidson[4], Mario R. Eden[5], Mahmoud M. El-Halwagi[1]

[1] Artie McFerrin Department of Chemical Engineering, Texas A&M University
[2] Chemical Engineering and Materials Science, Wayne State University
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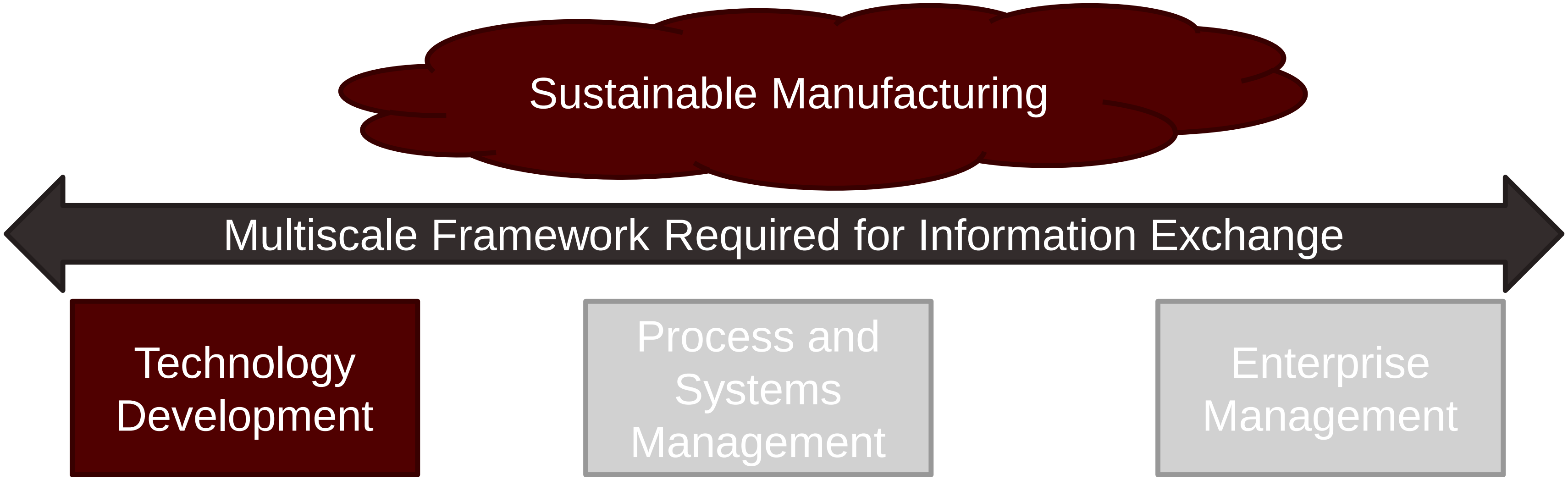
[5] Department of Chemical Engineering, Auburn University

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

Outline

- SMART – CN Education Vision
- Modules Development
- Future Modules

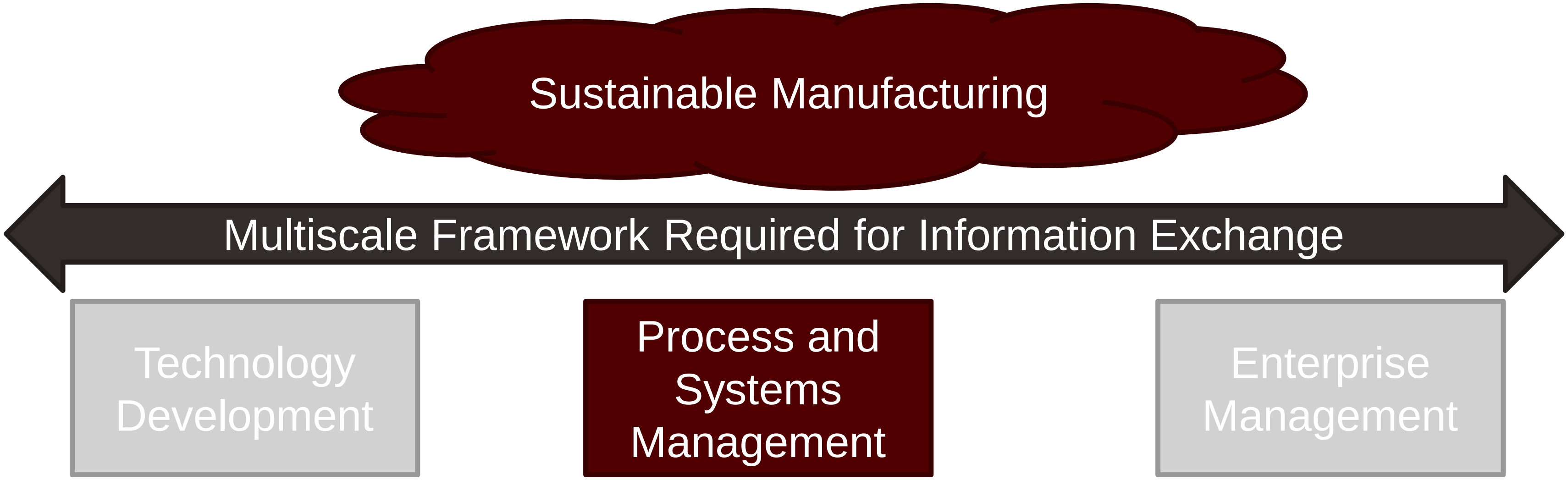
SMART – CN Education Vision



- **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*

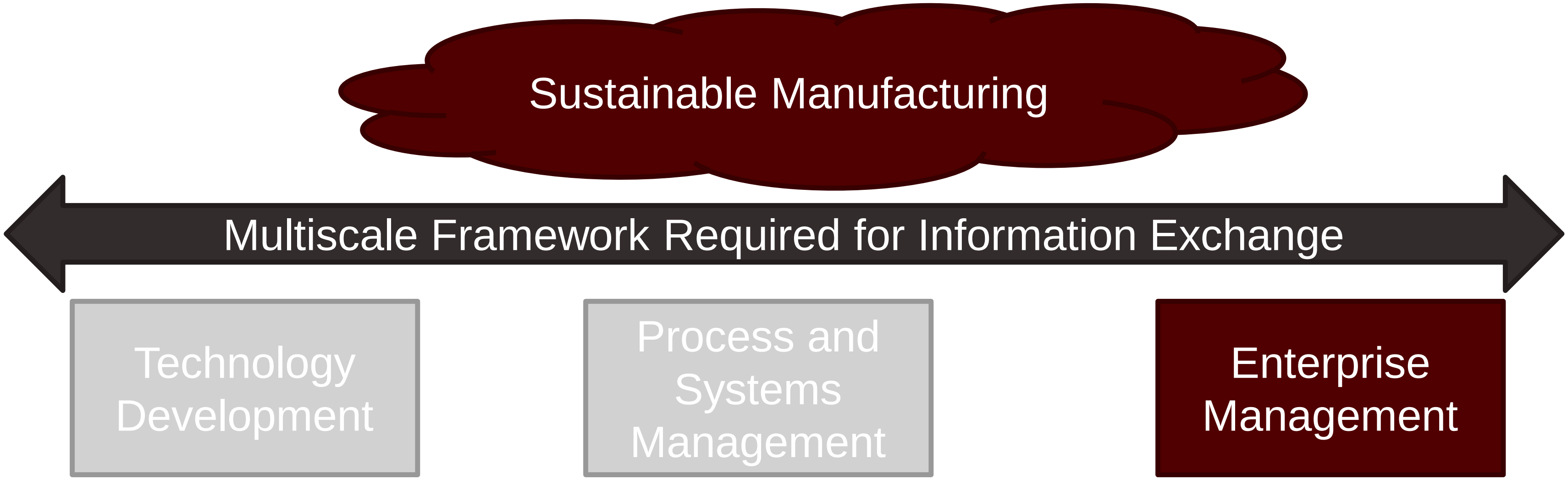
SMART – CN Education Vision



- **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*

SMART – CN Education Vision



- **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.*

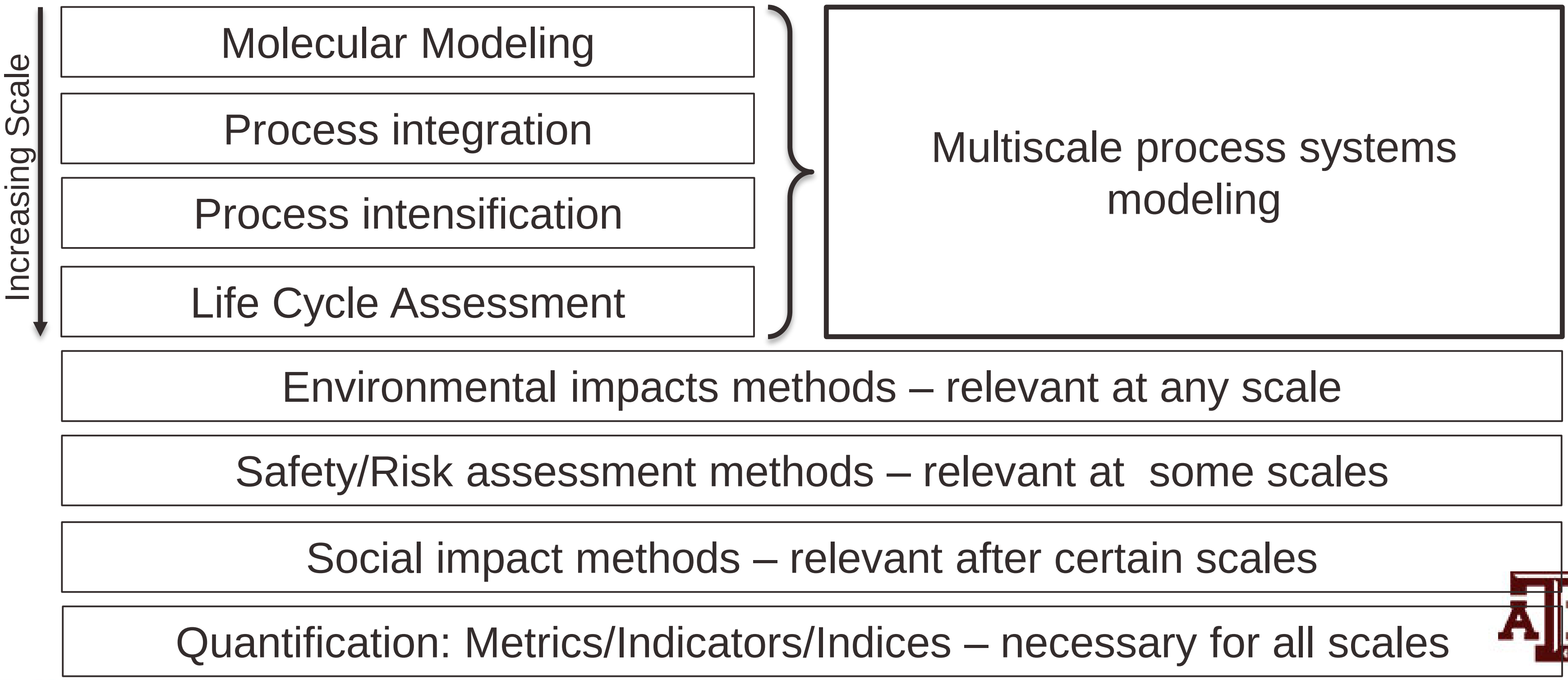
Course Type 1 – Integrating into Existing Coursework

- 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.

Thermodynamics Mass Transfer Heat Transfer Reaction Engineering Transport Phenomena	Molecular modeling Green chemistry Environmental impact potential Resource use Energy use
Engineering Design	Process integration Process intensification Process safety Metrics/Indicators/Indices
Process Control and Optimization	Environmental control variables Optimum points for economic and environmental issues
Supply Chain/Operations Management	Life Cycle Assessment Supply Chain Optimization

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.



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:

Knowledge of Industrial Sectors
(can be categorized based on NAICS/SIC codes)

Knowledge of Sustainability Implementation Areas
(for example, petroleum refineries need to be profitable, safer, low emission, and built in areas such that environmental justice is not violated)

Develop Specific Module Based on the Knowledge of The Sustainability Implementation Area

- 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)
- Plugs in the sustainability criteria knowledge (through modules) into the stages of design
- Identify a set of key indicators and metrics required to assess sustainability over the life cycle of the sector

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

Module Name	Developer/ University	Module Content
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

Module Name	Developer/ University	Module Content
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

Inventory of Inputs and Outputs

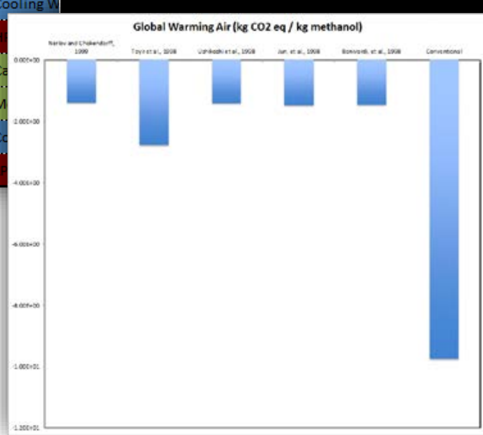
Process	Input Streams	Flow Rate (Kg/hr)	Flow Rate (kg/kg methanol)	Output Streams	Flow Rate (Kg/hr)	Flow Rate (kg/kg methanol)
Nerlov and Chokendorff, 1999	Carbon Dioxide	75,540	1.38E+0			
	Hydrogen	10,380	1.90E-0			
	Cooling Water	18,160,000	3.32E+0			
	HP Steam	776,000	1.42E+0			
Toyir et al., 1998	Carbon Dioxide	151,400	2.76E+0			
	Hydrogen	13,870	2.53E-0			
	Cooling Water	26,740,000	4.87E+0			
	HP Steam	1,205,000	2.20E+0			
Ushikoshi, 2002	Carbon Dioxide	76,450	1.40E+0			
	Hydrogen	10,420	1.90E-0			
	Cooling Water	16,510,000	3.02E+0			
	HP Steam	693,000	1.27E+0			
Jun, et al., 1998	Carbon Dioxide	79,740	1.46E+00	Methanol	54,700	1.00E+00
	Hydrogen					
	Cooling W					
	HP Steam					
Bonivardi, et al., 1998	Carbon Di					
	Hydrogen					
	Cooling W					
	H					
Conventional Process	Ca					
	M					
	Co					
	LP					

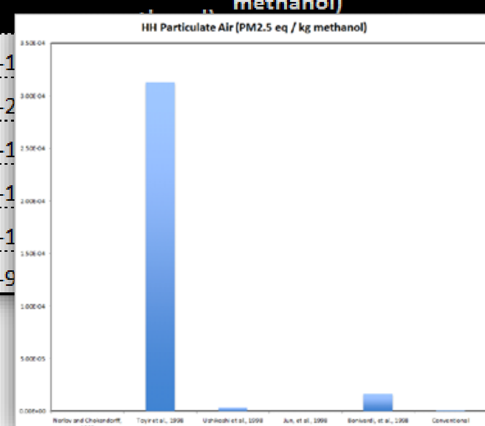
TRACI Characterization Factors

Compound	Global Warming Air (kg CO_2 eq / kg substance)	HH Particulate Air (PM2.5 eq / kg substance)	Smog Air (kg O_3 eq / kg substance)
Carbon Dioxide	1	-	-
Methanol	25		
Carbon Monoxide	-	3.56E-04	5.56E-02
Methanol	-	-	6.72E-01

Impact Assessment

	Global Warming Air (kg CO2 eq / kg methanol)	HH Particulate Air (PM2.5 eq / kg methanol)	Smog Air (kg O3 eq / kg methanol)	Energy Intensity (kJ/kg methanol)	Water Intensity (kg/kg methanol)	Material Intensity (kg/kg methanol)
	-1			E+04	3.32E+02	1.57E+00
	-2			E+04	4.87E+02	3.01E+00
	-1			E+04	3.02E+02	1.59E+00
	-1			E+04	2.71E+03	1.66E+00
	-1			E+04	2.41E+02	1.65E+00
	-9			E+04	1.21E+02	7.23E-01





Modules

Module Name	**Developer/ University**	**Module Content**
Sustainability Metrics and Sustainability Footprint Method	Debalina Sengupta, Texas A&M University	***Method topic*****:** Provides overview of methods to compute sustainability metrics. It also gives a method compute overall sustainability by aggregating metrics. ***Assessment tools*****:** Two case studies are presented on automotive shredder residue treatment method and on automobile fender formulation. ***Supporting documents*****:** spreadsheet tool demonstrating case study ***Learning Outcomes*****:** 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.

Modules

Module Name	Developer/ University	Module Content
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

Modules

Module Name	Developer/ University	Module Content
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

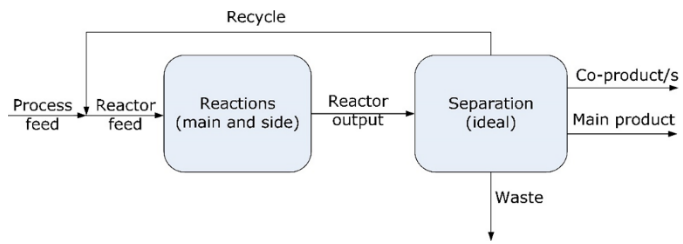
Modules

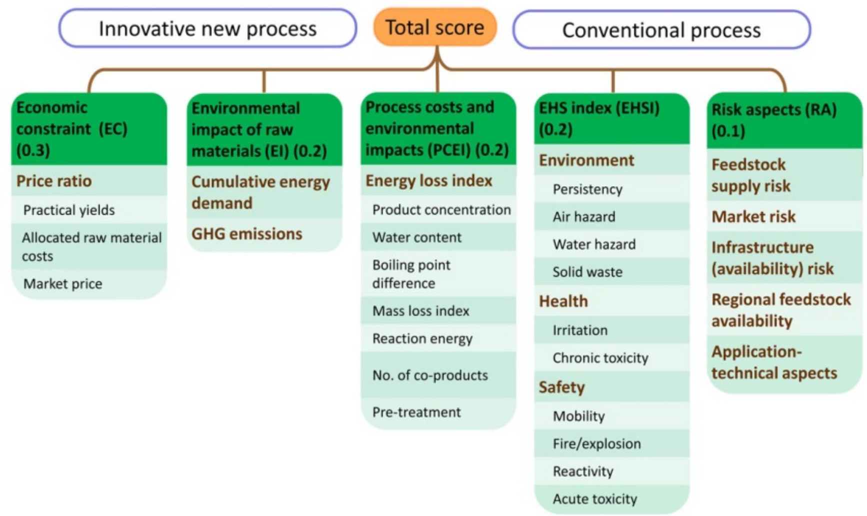
Module Name	Developer/ University	Module Content
Optimization and Uncertainty for Green Design and Industrial Symbiosis	Dr. Urmila Diwekar, Vishwamitra Research Institute and Dr. Yogendra Shastri, IIT Bombay	***Method Topic*****:** Demonstrates the use of optimization methods for sustainable manufacturing.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

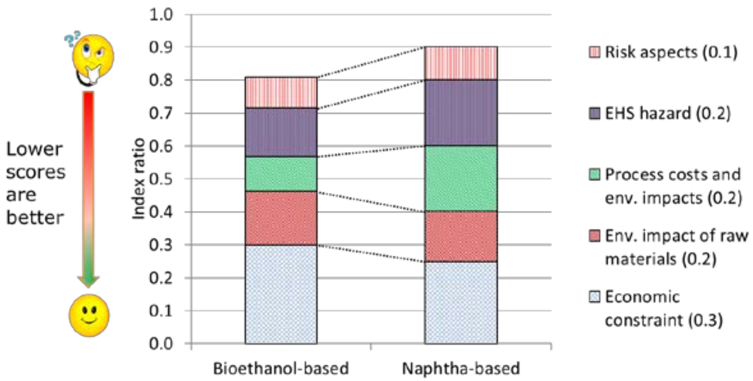
Modules

Module Name	Developer/ University	Module Content
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







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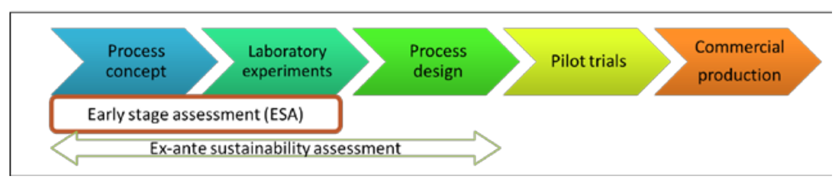


Modules

Module Name	Developer/University	Module Content
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

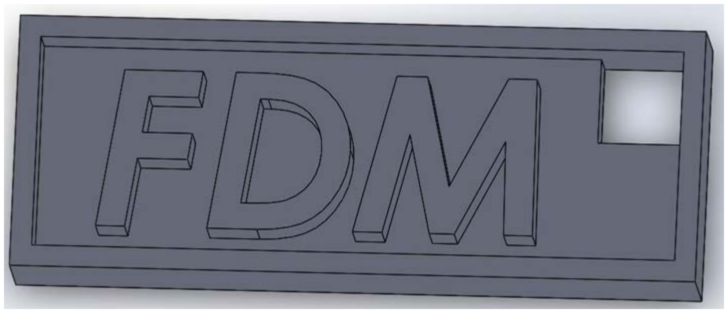
Modules

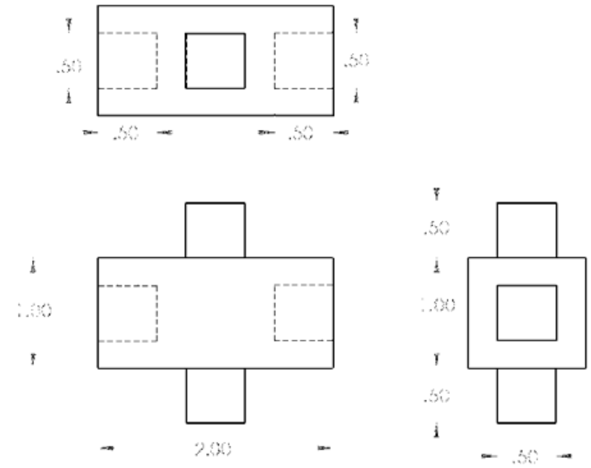
Module Name	Developer/ University	Module Content
Optimal Design and Operation of Reverse Osmosis Desalination	Mingheng Li/California State Polytechnic	***Process Topic*:** Specific energy consumption (SEC) in reverse osmosis (RO) desalination is considered for sustainability of the water treatment process. The module focuses on case studies that help in the optimal design for RO with the sustainability concerns in energy cosumption 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

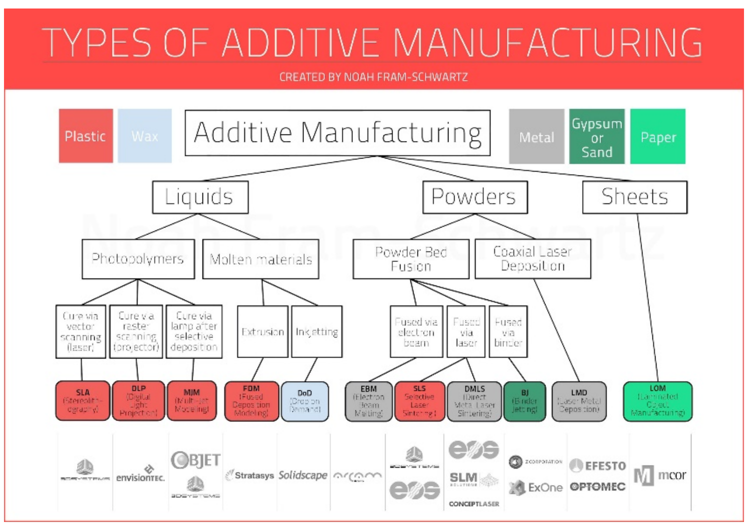
Modules

Module Name	Developer/ University	Module Content
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

Module Name	Developer/ University	Module Content
Sustainable Mitigation of Carbon Dioxide to Chemicals	Debalina Sengupta and Sherif Khalifa/Texas A&M University and Drexel University	***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.

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

Additional Reading: Sengupta, D., Y. Huang, C. I. Davidson, T. F. Edgar, M. Eden, and M. M. El-Halwagi, “Using Module-Based Learning Methods to Introduce Sustainable Manufacturing in Engineering Curriculum”, Int. J. Sustainability in Higher Education 18(3), 307-328 (2017)

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TEXAS A&M UNIVERSITY

The SMART education modules provides 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.

Module Name	Module Developer	Module Content
	Learning Tools	
Early Stage Sustainability Analysis Tool - EarlySim	Akshay Patel/SustAnalyze/Utrecht University	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.
	Case Studies and Methods	
Assessment of the Presidential Green Chemistry Award Winners using Green Chemistry Metrics	Christopher L. Kitchens/Clemson University	Evaluates the work that has received the Presidential Green Chemistry Challenge Award using green chemistry metrics, principles, and design strategies.
Life Cycle Assessment for Sustainable Manufacturing	Debalina Sengupta, Texas A&M University	Provides overview of life cycle assessment methodology as outlined in the ISO standards, Emphasize the utility for the LCA methods for manufacturing sustainability
Sustainability Metrics and Sustainability Footprint Method	Debalina Sengupta, Texas A&M University	Provides overview of methods to compute sustainability metrics. It also gives a method compute overall sustainability by aggregating metrics.
Green Chemistry to Manufacture Specialty Chemicals from Renewable Resources	Jeffrey R. Seay, Assistant Professor, University of Kentucky	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.
Sustainability Root Cause Analysis (SRCA)	Helen H. Lou, Professor, Lamar University	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).
Optimization and Uncertainty for Green Design and Industrial Symbiosis	Dr. Urmila Diwekar, VRI and Dr. Yogendra Shastri, IIT Bombay	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.
Atomic Layer Deposition Nano-Manufacturing Technology	Chris Yuan/University of Wisconsin, Milwaukee	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.
	Process Examples	
Optimal Design and Operation of Reverse Osmosis Desalination	Mingheng Li/California State Polytechnic	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.
Sustainable Additive Manufacturing	Karl Haapala/Oregon State University	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.
Sustainable Mitigation of Carbon Dioxide to Chemicals	Debalina Sengupta, Texas A&M University and Sherif Khalifa, Drexel University	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.

Modules Available at: https://cache.org/super-store; http://www.research.che.utexas.edu/susman/edu.html

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Reference to Journal Article: Debalina Sengupta, Yinlun Huang, Cliff I. Davidson, Thomas F. Edgar, Mario R. Eden, Mahmoud M. El-Halwagi, (2017) "Using module-based learning methods to introduce sustainable manufacturing in engineering curriculum", International Journal of Sustainability in Higher Education, Vol. 18 Issue: 3, pp.307-328, https://doi.org/10.1108/IJSHE-05-2015-0100