Reinventing Project Delivery Through Modular Chemical Process Intensification

James O’Connor, The University of Texas at Austin
Olivier J. LeNormand, The Dow Chemical Company
**What is MCPI?**

Modular Chemical Processing Intensification (MCPI) makes use of new technology that’s smaller, safer, and more energy-efficient, and/or combining multiple operations into fewer ones

– Argonne National Laboratory
Modularization:
Moving work-hours to a beneficial fabrication site
Prior Modularization Research: Five Solution Elements (RT-283)

- Business Case
- Execution Plan Differences
- 21 CRITICAL SUCCESS FACTORS
- MAXIMIZATION ENABLERS

Levels:
- Business Unit Level
- Project Level
- Industry Level
Top 4 (of 21) Modularization Critical Success Factors

- Preliminary Transportation Evaluation
- Alignment on Drivers
- Owner’s Planning Resources and Processes
- Timely Design Freeze
21 Critical Success Factors by Implementation Responsibility and Timing

**RESPONSIBLE LEAD**
- Owner: 57%
- Contractor: 33%
- Vendors & Tech Lic.: 7%
- Others: 3%

**PROJECT PHASE**
- Opportunity Framing: 12%
- Basic Design: 23%
- Selection: 20%
- Assessment: 31%
- Execution: 10%
- Startup: 5%

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2021 ECC Perspectives Conference
Timing of Modularization Commitment

<table>
<thead>
<tr>
<th>PHASE</th>
<th>Opportunity Framing</th>
<th>Assessment</th>
<th>Selection</th>
<th>Basic Design</th>
<th>EPC</th>
<th>Startup</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRAME OF REFERENCE</td>
<td>Gate 1</td>
<td>Gate 2</td>
<td>Gate 3</td>
<td>Gate 4</td>
<td>Gate 5</td>
<td></td>
</tr>
<tr>
<td>EPC CONTRACTOR</td>
<td></td>
<td>PRE-FEED</td>
<td>FEED</td>
<td></td>
<td>EPC</td>
<td></td>
</tr>
<tr>
<td>COST ESTIMATE ACCURACY</td>
<td>±50%</td>
<td>±30%</td>
<td>±10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BUSINESS CASE EVALUATIONS</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
</tr>
</tbody>
</table>

Potential Benefits at Time of Decision

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Execution Planning Differences

Ways of doing business can be very different with Modularization.

107 items pertaining to 21 topics
Process Intensification
Benefits of Process Intensification

Process intensification is just innovation at the chemical process level

- Reduced capital investment
- Improved process safety
- Reduced energy use
- Lowered materials costs
- Increased process flexibility and inventory reduction
- Increased attention to quality
- Better environmental performance

Modular Chemical Process Intensification
Solar Thermochemical Processing

Plant construction is changing from conventional stick-built to the centralized manufacturing, transport, and delivery of manifold modules.
## Chemical Process Intensification

### Conventional Heat Exchanger

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>µChannel HX</th>
<th>Commercial HX</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX mass</td>
<td>Kg</td>
<td>5</td>
<td>70</td>
</tr>
<tr>
<td>HX volume</td>
<td>L</td>
<td>1.25</td>
<td>35</td>
</tr>
<tr>
<td>Duty</td>
<td>Watts</td>
<td>3500</td>
<td>3500</td>
</tr>
<tr>
<td>Effectiveness</td>
<td>%</td>
<td>87</td>
<td>&lt;80</td>
</tr>
<tr>
<td>Side 1, Air dP</td>
<td>in H2O</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Side 2, Air dP</td>
<td>in H2O</td>
<td>3.1</td>
<td>3.1</td>
</tr>
</tbody>
</table>

### PNNL Heat Exchanger

- 14X reduction in mass
- 28X reduction in volume
- Higher effectiveness

*Reaction Nacelle*
Chemical Process Intensification

Conventional Heat Exchanger

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>PNNL HX</th>
<th>Commercial HX</th>
</tr>
</thead>
<tbody>
<tr>
<td>HX mass [1]</td>
<td>g</td>
<td>432</td>
<td>2285</td>
</tr>
<tr>
<td>HX volume [2]</td>
<td>cm³</td>
<td>134</td>
<td>~1278</td>
</tr>
<tr>
<td>Duty</td>
<td>W</td>
<td>155</td>
<td>136</td>
</tr>
<tr>
<td>Effectiveness</td>
<td>%</td>
<td>92.2</td>
<td>80.0</td>
</tr>
<tr>
<td>Side 1, Air dP</td>
<td>psi</td>
<td>0.3</td>
<td>&lt;1 psi</td>
</tr>
<tr>
<td>Side 2, Air dP</td>
<td>psi</td>
<td>0.9</td>
<td>&lt;1 psi</td>
</tr>
</tbody>
</table>


PNNL Heat Exchanger

5X reduction in mass
10X reduction in volume
Higher effectiveness
Chemical Process Intensification

- **Methods**
  - Multi-Function Processes
    - Reactive Extraction
    - Reactive Extrusion
    - Reactive Distillation
    - Reactive Separation
    - Membrane Reaction
  - Hybridized Separations
  - Alternative Energy Sources
    - Microwaves
    - Ultrasonics
    - Vibrations
    - Electric/Magnetic Fields
    - Centrifugal Fields
    - Solar Energy
  - Other

- **Equipment**
  - Separators and Mixers
    - Dividing Wall Column
    - Static Mixer
    - Rotor/Stator Mixer
    - Rotating Packed
  - Reactors
    - Micro-Reactor
    - Static Mixer Reactor (SMR)
    - Spinning Disk Reactor (SDR)
    - Rotating Packed
  - Heat and Mass Transfer
    - Compact Heat Exchanger
    - Micro-Channel Heat Exchanger
    - Other Micro-Geometry Heat
  - Multi-Function Devices
    - Reactive Extractor
    - Reactive Extruder
    - Reactive Distiller
    - Reactive Separator
    - Membrane Reactor
    - Reverse Flow Reactor
  - Other
Guiding Principles for Process Intensification

• Maximize effectiveness of intramolecular and intermolecular events.

• Give each molecule the same processing experience.

• Optimize driving forces at all scales and maximize the specific surface areas to which they apply.

• Maximize synergistic effects from partial processes.

Symbioses between Modularization and Process Intensification: Mutually Beneficial Linkages

• Smaller process intensification equipment and denser process intensification plant layouts facilitate modularization.

• Module mobility provides advantages:
  – geographically distributed customers/markets
  – energy sources/feedstocks
  – distribution challenges

• Capacity flexibility is possible with module numbering-up.
## Background of Case Studies

<table>
<thead>
<tr>
<th>CASE STUDY 1</th>
<th>CASE STUDY 2</th>
<th>CASE STUDY 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specialty chemical driven by manufacturer-operator with the goal of reducing CAPEX</td>
<td>Commodity chemical driven by developer-supplier with the goal of providing cheaper feedstock</td>
<td>Commodity chemical driven by developer-supplier to address storage and distribution challenges</td>
</tr>
</tbody>
</table>
Case Study 1
## Case Study 1

<table>
<thead>
<tr>
<th>Perspective</th>
<th>Manufacturer-operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geography</td>
<td>Customer</td>
</tr>
<tr>
<td>Specialty</td>
<td>Specialty chemical</td>
</tr>
<tr>
<td>Chemical</td>
<td>OTS Tubular RX</td>
</tr>
<tr>
<td>Batch to Continuous</td>
<td>Vol = 250 x</td>
</tr>
<tr>
<td>Client Motivation</td>
<td>Reduced CAPEX</td>
</tr>
<tr>
<td>Plant Size Reduction</td>
<td>1 year post-Pilot</td>
</tr>
<tr>
<td>Numbering-up?</td>
<td>No numbering-up</td>
</tr>
</tbody>
</table>
### Specialty Chemical Production

#### (ISBL) CAPEX-Driver Differences

<table>
<thead>
<tr>
<th></th>
<th>Number of modules per train</th>
<th>Height</th>
<th>Brownfield SIMOPS impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSB</td>
<td>N/A</td>
<td>30</td>
<td>High</td>
</tr>
<tr>
<td>MCPI</td>
<td>1</td>
<td>6</td>
<td>Minimal</td>
</tr>
</tbody>
</table>
Specialty Chemical Production

CASE STUDY 1

Site and module footprint

CSB
10,000 ft²

MCPI
200 ft²
# Specialty Chemical Production

## Project Frame and Basis

<table>
<thead>
<tr>
<th>Mode</th>
<th>Reactor</th>
<th>Cycle time (hours)</th>
<th>Heat transfer area (ft²)</th>
<th>Heating time (hours)</th>
<th>Heat loss (kW)</th>
<th>Flushing material (gallons/batch)</th>
<th>Nitrogen purge (SCF/batch)</th>
<th>Cooling system</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSB</td>
<td>Batch 12,000 gal. paddle mixer</td>
<td>48</td>
<td>628</td>
<td>10</td>
<td>17</td>
<td>1500</td>
<td>2800</td>
<td>water</td>
</tr>
<tr>
<td>MCPI</td>
<td>Continuous Tubular reactor</td>
<td>N/A</td>
<td>39</td>
<td>N/A</td>
<td>1.2</td>
<td>N/A</td>
<td>N/A</td>
<td>air</td>
</tr>
</tbody>
</table>
# Specialty Chemical Production

**CAPEX**

<table>
<thead>
<tr>
<th></th>
<th>Total Installed Cost</th>
<th>Engineering Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSB</td>
<td>$3,500,000</td>
<td>$350,000</td>
</tr>
<tr>
<td>MCPI</td>
<td>$450,000</td>
<td>$55,000</td>
</tr>
</tbody>
</table>
## Specialty Chemical Production

### Time until Production (weeks)

<table>
<thead>
<tr>
<th></th>
<th>CSB</th>
<th>MCPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prod.</td>
<td>74%</td>
<td></td>
</tr>
<tr>
<td>PI/De</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Pro</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Mfab</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>In/Con/CSU</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

**CASE STUDY 1**

*70% Shorter time to operations and revenue*
## Specialty Chemical Production

### CAPEX, OPEX, NPV, and Payback Period

<table>
<thead>
<tr>
<th>Cost Category</th>
<th>MCPI Change</th>
<th>CSB (MCPI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CAPEX (USD/MT)</strong></td>
<td>87% lower</td>
<td>CSB: 714</td>
</tr>
<tr>
<td><strong>O&amp;M FTE</strong></td>
<td>91% lower</td>
<td>CBS: 9</td>
</tr>
<tr>
<td><strong>COST OF POWER &amp; UTILITIES</strong></td>
<td>40% lower</td>
<td>CSB: $40 K</td>
</tr>
<tr>
<td><strong>NPV</strong></td>
<td>91% lower</td>
<td>CSB: $6.23 M</td>
</tr>
<tr>
<td><strong>OPEX (USD/MT)</strong></td>
<td>14% lower</td>
<td>CSB: $40 K</td>
</tr>
<tr>
<td><strong>PAYBACK PERIOD (MONTHS)</strong></td>
<td>80% shorter</td>
<td>CSB: 12.3</td>
</tr>
</tbody>
</table>
Specialty Chemical Production

Six Top Drivers of Superior MCPI Capital Efficiency:

- PI equipment is smaller, cheaper, and available off the shelf
- Unit productivity rate improvements for module fabrication
- Pre-shipment testing of modules enhances performance assurance
- Lower weight of MCPI means simpler and lower-cost foundations, support structure
- Reduced module installation time and effort (SIMOPS)
- Earlier recovery of investment from early production and sales
Specialty Chemical Production

Backup MCPI train is a very attractive option

NPV Comparison... given MCPI has a 2nd Backup Train

CASE STUDY 1
Case Study 2
## Leveraging Cheap Distributed Energy

### Case Study 2

<table>
<thead>
<tr>
<th></th>
<th>Conventional Stick-Built (CSB)</th>
<th>MCPI*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plant Area</strong></td>
<td></td>
<td><strong>(146k MTPY Capacity)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>*MCPI has 5 modules within a single train</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale-up rate</th>
<th>Footprint</th>
<th>Brownfield SIMOPS impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSB</td>
<td>Full capacity in 3 years</td>
<td>141 K</td>
</tr>
<tr>
<td>MCPI</td>
<td>2X increase in capacity year-to-year</td>
<td>18 K</td>
</tr>
</tbody>
</table>
## Leveraging Cheap Distributed Energy

**Comparison: PI / Process / OPEX Features**

- Same rated capacity (18,250 MTPY)
- Same production rate (76 lbs/min)

<table>
<thead>
<tr>
<th></th>
<th>Raw Material Preprocessing</th>
<th>Waste Management</th>
<th>Operations Staff</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSB</td>
<td>De-sulfurization required</td>
<td>Needs a separate waste management unit</td>
<td>Scales with plant size</td>
</tr>
<tr>
<td>MCPI</td>
<td>None</td>
<td>Minimal waste</td>
<td>8 FTE (any # of trains)</td>
</tr>
</tbody>
</table>
# Leveraging Cheap Distributed Energy

## Other Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Total Installed Cost (TIC) (1 train = 18,250 MTPY)</th>
<th>Numbering-up Learning Rate</th>
<th>NPV comparison at lifetime of plant (25 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CSB</strong></td>
<td>$66M (based on industry data)</td>
<td>80%</td>
<td>Scenario 1: higher</td>
</tr>
<tr>
<td><strong>MCPI</strong></td>
<td>$44.5M (based on Sievers model)</td>
<td>N/A</td>
<td>Scenario 2: same</td>
</tr>
</tbody>
</table>
Utility costs > feedstock gains even with lower utility rates
Lower cost of innovative PI equipment
Faster time-to-market
Leveraging Cheap Distributed Energy

SIX TOP DRIVERS

• Increased efforts for engineering of new technologies
• Higher capital expenditures for new advanced equipment
• Reduced time of fabrication of equipment (parallel fabrication, reduced size, piping, etc.)
• Lower energy demand (i.e., reduced energy input and losses for reactions)
• Faster-time to market for new investments; earlier product sales due to shorter processing times
• Economic benefits from earlier completion; Earlier recovery of investment from early production and sales

Key drivers that were NOT indicated as top drivers by the case study partner
Case Study 3
## Distributed Commodity Production

### CAPEX (ISBL) Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>CSB</th>
<th>MCPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployment Schedule</td>
<td>Full capacity in 3 years</td>
<td>2x increase in capacity year-to-year</td>
</tr>
<tr>
<td>Footprint</td>
<td>Smallest 24,000 ft²</td>
<td>460 ft²</td>
</tr>
<tr>
<td>Brownfield SIMOPS impact</td>
<td>High</td>
<td>Minimal</td>
</tr>
</tbody>
</table>

- **Conventional Stick-Built (CSB)**: 52X reduction in plant area

CASE STUDY 3
## Distributed Commodity Production

### OPEX Features and Other Assumptions

Same rated capacity, 1 train = 11,200 MMSCF (300 Nm$^3$/h)
Same production rate (244 lbs./min.)

<table>
<thead>
<tr>
<th>PI Technology</th>
<th>Operations Staff</th>
<th>Design Maturity</th>
<th>Maximum Numbered-up Skids</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSB</td>
<td>None</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>MCPI</td>
<td>Modified reactor and PSA system</td>
<td>1 FTE (1-2 skids), 2 FTE (3-5 skids)</td>
<td>7 years into production (~230+ deployments)</td>
</tr>
</tbody>
</table>
Distributed Commodity Production
Total Production Cost: MCPI vs. CSB

- Total production cost for MCPI is relatively lower up to three trains
- Findings align with the case study partner’s deployment strategy of numbering-up to three trains; thereafter moving to a mid-sized or a large-sized CSB plant
- **Interconnection systems (piping and electrical)** are the primary drivers for reduced MCPI CAPEX.
- Equipment costs for CSB become lower than those for MCPI above a 2-train capacity.
- Other costs (engineering, buildings, instrumentation, and contingency) are lower for MCPI relative to CSB – with one exception: instrumentation for a 5-train capacity is greater than for CSB.
Distributed Commodity Production

26 Drivers from the Literature / 6 Top Drivers

• Design effort reduction from DOBM for second, third, fourth, etc. modules
• Reduced CapEx due to reduced number of components
• Module fabricator learning curve benefits from standardization (DOBM)
• Reduced equipment assembly/installation time and labor effort
• PI equipment requires fewer interconnecting systems
• Reduced construction footprint, less land, less infrastructure, etc.
Case Study Key Learnings

1. Conversion from **batch-to-continuous** chemical processing enhances CAPEX reduction and time-to-market

2. **Cost of process intensification technology** is important

3. PI technology can significantly reduce the cost of **interconnecting systems**
Recap / Closure

MCPI challenges old plant design paradigms and offers new opportunities

Substantial benefits may be realized, if managed

Visionary champion is critical to advance MCPI within large organizations
Questions?