A system dynamics model of early-stage transition dynamics in the bioproducts industry

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Technology Development Process

- How do developer-investor interactions and other factors impact low TRL stages of bioproduct development?
- (How) Can the likelihood that a bioproduct reaches commercial production, or is sold as IP, be influenced, and by whom?

**Technology Readiness Level (TRL):** Numeric representation of technology maturity, from 1 (beginning of applied R&D) through 9 (technology fully developed and at operational scale)
Bioproduct Transition Dynamics Project

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Understand the environment and drivers that impact bioproducts industry growth: investor decision-making, bioproduct techno-economics, and end use factors</td>
<td>Transparent, analytic system dynamics model of early-stage industrial transition dynamics in the bioproducts industry</td>
</tr>
<tr>
<td>Identify synergies between the bioproduct and biofuel industries</td>
<td></td>
</tr>
</tbody>
</table>
# Why System Dynamics Modeling?

<table>
<thead>
<tr>
<th>While systems are...</th>
<th>...our thinking processes often...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constantly changing</td>
<td>...are static, equilibrium oriented</td>
</tr>
<tr>
<td>Tightly coupled/interdependent</td>
<td>...draw very narrow boundaries around issues and problems</td>
</tr>
<tr>
<td>Rich in feedback</td>
<td>...treat drivers of performance as external and independent</td>
</tr>
<tr>
<td>Nonlinear</td>
<td>...assume linear responses</td>
</tr>
<tr>
<td>History dependent</td>
<td>...neglect to consider path dependence, accumulations, and delays</td>
</tr>
<tr>
<td>Adaptive and evolving</td>
<td>...fail to pay sufficient attention to the sources of unintended consequences</td>
</tr>
</tbody>
</table>

Introduction to System Dynamics

- SD models are based on system structures and capture patterns of behavior

System Dynamics Model
A system of coupled, nonlinear, first-order differential or integral equations

- Flows (births, deaths) are the rates of change of stocks
- Stocks (Population) are the integrals over time of flows
- Feedback loops (A, B) exist among stocks, flows and model parameters
- Feedback loops are either reinforcing or balancing
  - A is reinforcing
  - B is balancing

\[
\begin{align*}
\text{births}(t + dt) &= \text{birth rate} \times \text{Population}(t) \\
\text{deaths}(t + dt) &= \text{death rate} \times \text{Population}(t) \\
\text{Population} &= \int_{t_0}^{t} [\text{births}(t) - \text{deaths}(t)] dt
\end{align*}
\]
BTD Model Structure

Model structure was derived from...
- Interviews with bioproduct industry experts
- Research on investor decision-making and innovation processes
- Shared learning models
- End use structure research

Actors include...
- Bioproduct developers
- Investors
- Bioproduct purchasers
- Government agencies

- Initial Seed Investment
- Basic and Applied Research
- Piloting
- Demoing
- Commercial Production

- Next Investment
- Bioproduct Techno-Economics
- Investor Requirements
- Exogenous and End Use Factors
Investor Decision Making

Investor requirements vary by development stage. (Damodaran, 2009)
Effectiveness of researching controls the rate at which TRL is gained during research.

Research management effectiveness controls how much of each dollar spent is available for conversion into TRL gains.
Piloting and Demoing Process

**Piloting effectiveness and demoing effectiveness** (not shown in diagram) control the rate at which TRL is gained during piloting and demoing.

![Graph showing TRL gain/operating hour](image)

- **Piloting Effectiveness**
- **Demoing Effectiveness**

*Pilot and demo management effectiveness are both analogous to the research management effectiveness parameter.*
Sample TRL Path and Events

- Failures trigger additional research
- Pilot-stage failure sends project back to researching stage
- Rate of TRL gain slows as research nears completion
- Project stalls while funds accumulate
- Development process completes

Graph showing the TRL path from 2015 to 2040, with key events labeled:
- Researching
- Piloting
- Demoing
Sensitivity Analysis and Model Verification

• 14.8 million simulations
• Assess sensitivity to investor, developer decision-making parameters and bioproduct (succinic acid) techno-economics

• **Selling price potential**
  • Selling price
  • Size of green premium

• **Government policy**
  • Research cost share
  • Capital cost share
  • Production incentive

• **Developer effectiveness**
  • Research stage

**Investor behavior**
• Optimism
• Bioproduct strategic value
• Expected government policy continuity

**Management effectiveness**
• Research stage
• Pilot stage
• Demo stage
The three pathways differ significantly in their cost structure.

### N<sup>th</sup> Plant Parameters

<table>
<thead>
<tr>
<th></th>
<th>Lignocellulosic</th>
<th>Commodity Sugar</th>
<th>Maleic Anhydride (fossil)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Large</td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td><strong>Capacity</strong></td>
<td>Ton product/year</td>
<td>286,300</td>
<td>28,630</td>
</tr>
<tr>
<td><strong>Capital cost</strong></td>
<td>USD</td>
<td>$1,253M</td>
<td>$462M</td>
</tr>
<tr>
<td><strong>Feedstock cost</strong></td>
<td>USD/ton</td>
<td>$100</td>
<td>$263</td>
</tr>
<tr>
<td><strong>Fixed operating cost</strong></td>
<td>USD/year</td>
<td>$27.0M</td>
<td>$12.8M</td>
</tr>
<tr>
<td><strong>Variable operating cost</strong></td>
<td>USD/ton product</td>
<td>$494</td>
<td>$815</td>
</tr>
<tr>
<td><strong>Process yield</strong></td>
<td>Ton product/ton feed</td>
<td>0.409</td>
<td>0.770</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>Years</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Feedstock

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Capital Cost</th>
<th>Operating Cost</th>
<th>Feedstock Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignocellulosic</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Commodity Sugar</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Maleic Anhydride (fossil)</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
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</table>
Results: Highest TRL Reached

- Color indicates TRL at end of model run for each simulation
- Failure to progress to higher TRLs results from inability to raise new investor funds.

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<th>lignocellulosic</th>
<th>commodity-sugar</th>
<th>fossil</th>
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Technology Readiness Level

Stage
- 😞 Researching
- 🤖 Pilot Completed
- 😄 Demonstration Completed
- 😊 Commercial Production
Results: Success Likelihoods

- The interaction of grants and policy continuity is more impactful than either alone.
- Bioproduct selling price and expected green premium are good predictors of success.
Conclusions and Next Steps

The Bioproduct Transition Dynamics model captures the bioproduct technology development process from basic research through commercial production, including interactions between developers and investors.

• BTD workshop will be held July 16, 2018 to solicit guidance on model logic, enhancements and validation
• BTD model development and validation will continue through 2019
• An NREL technical report is planned for release in September 2018, with the potential for additional publications in the future
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