Innovation in Modular Industries:
Implementing Energy-Efficient Innovations in US Buildings

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Oral Examination Committee:
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Agenda

- Problem
- Background
- Questions
- Method
- Results
- Contributions
  - Theory
  - Practice
Technology integration gone wrong

How likely is this technology to be included in the next project?
Existing energy saving building technologies represent an enormous opportunity

- The building industry is the largest single contributor to GHG emissions and global warming
  - 40% of USA energy
  - 70% of USA electricity
  - As much as 34% wasted!
- Significant unrealized energy savings for new and existing buildings
  - Existing technologies could lower energy use by 25-30% by 2030
  - Attractive investment opportunities
  - Opportunities worth $130 billion/yr foregone

Innovation diffusion in construction: Literature review

**Individual**
- Risk aversion$^{1,2,3,4}$
- Social heuristics$^5$
- Organizational cultures$^6$
- No “innovation champions”$^7$

**Contextual & Institutional**
- Codes and regulations$^{4,8}$
- Traditional procurement$^9$
- Competitive bidding$^4$
- Labor costs & labor unions$^{11}$

**Industry fragmentation$^{6,12,13}$**

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Objectives

• Develop and validate theory about effects of industry fragmentation on innovation diffusion
  • Innovation span (modular vs. integral innovations)
  • Supply chain integration

• A comprehensive model for structural barriers to innovation diffusion in construction
Definitions:
Vertical, Horizontal, and Longitudinal Fragmentation

Source: Fergusson 1993
Definitions:
Products, Modules, Modular Clusters

Modular Cluster
• Manufacturers
• Designers
• Installers
• Maintenance

Product
Module
Definitions:
Innovation Span (Modular vs. Integral Innovations)

**MODULES:**
- Plumbing
- Electrical
- Heating/AC
- Wall frames

**Modular Innovation** (Wall Truss)

**Integral Innovation** (Pre-fab Wall)

Sources: Illustration from Taylor & Levitt 2008, Revised definitions from Sheffer & Levitt 2010
Innovations that are misaligned are slower to diffuse

Source: Taylor & Levitt, 2004
Industry modularity – Beyond construction
Industries vary in their degree of fragmentation

**Integrated hierarchical organization**
- Coordinating mechanism: Central management

**Centralized Modular Cluster**
- Coordinating mechanism: Lead firm

**Decentralized Modular Cluster**
- Coordinating mechanism: Standardization (in AEC, also craft administration)

Source: Adapted from Langolis & Robertson, 2003
The introduction of integral innovations into various industry types

Integration  Fragmentation

Coordinating Agent:
• Mandate change
• Clarify procedures
• Establish training programs
• Manage new accumulated knowledge

No Strong Coordinating Agent:
• No one to mandate change
• No one to clarify procedures
• Not everyone undergoes training
• Difficult to accumulate knowledge
  • No central body
  • Social psychological barriers
Thus, in spite of the “Power of Modularity”...

... Modularity likely hinders the diffusion of integral innovations
Hypotheses

In decentralized modular clusters, integral innovations are less likely to be implemented than modular innovations.

Supply chain integration moderates the negative effect that innovation integrality has on the probability of implementation; the higher the degree of integration, the stronger the moderation effect.
Leadership in Energy and Environmental Design (LEED):

- Voluntary green building certification system
- Est. 1998 by USGBC

Sample Characteristics:

- 112 LEED-NC, 2000-2009
- Well distributed
- 23 technologies
- N=2,576 implementation opportunities (112 X 23)
## Measures

<table>
<thead>
<tr>
<th>Construct</th>
<th>Measure</th>
<th>Descriptives</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology implementation</td>
<td>1= Technology implemented</td>
<td>N= 2576, Ave = 28%</td>
</tr>
<tr>
<td>0 = Not</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>IV</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Innovation Span</td>
<td>0= Modular</td>
<td>11 modular, 12 integral, MEP-related, consensus by 4 LEED APs</td>
</tr>
<tr>
<td>1 = Integral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Chain Integration</td>
<td>Horizontal</td>
<td>Horizontal: MEP from same firm, Vertical: DB vs. DBB, info for 23 projects (N=528)</td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Med</td>
</tr>
<tr>
<td>Technology-Level</td>
<td>Added first costs in $/SF in comparison to standard alter.</td>
<td>Ave: integral $10.10/sf, modular $3.12/sf</td>
</tr>
<tr>
<td>• Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Controls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Building-Level</td>
<td>• MEP Firm</td>
<td>0-30, 2=medium</td>
</tr>
<tr>
<td>• Year (registration year)</td>
<td>• Core values</td>
<td>30-100, 3=large</td>
</tr>
<tr>
<td>• Overall LEED Score</td>
<td>(1=sustainability / innovation, 0=n/a)</td>
<td>100+)</td>
</tr>
<tr>
<td>• Owner type (1=profit org, 0=gov/NPO/indiv)</td>
<td>• Firm size (1=small</td>
<td></td>
</tr>
</tbody>
</table>
# Technologies – Sample coding

<table>
<thead>
<tr>
<th>Technology</th>
<th>Basic alternative</th>
<th>Changed interfaces?</th>
<th>Changed process?</th>
<th>Coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomass / biogas</td>
<td>Obtaining power from the grid and disposing of waste</td>
<td>Yes</td>
<td>Yes</td>
<td>Integral</td>
</tr>
<tr>
<td>alternative-fuel refueling stations</td>
<td>No charging stations</td>
<td>Yes</td>
<td>No</td>
<td>Integral</td>
</tr>
<tr>
<td>fixture sensors</td>
<td>Manual control of fixtures</td>
<td>No</td>
<td>No</td>
<td>Modular</td>
</tr>
</tbody>
</table>
# Technologies

<table>
<thead>
<tr>
<th><strong>Modular Technologies</strong></th>
<th><strong>Integral Technologies</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>ceiling fans</td>
<td>alternative-fuel refueling stations</td>
</tr>
<tr>
<td>CO2 monitoring equipment</td>
<td>biomass / biogas</td>
</tr>
<tr>
<td>daylight sensors / dimming controls</td>
<td>building monitoring system / direct digital control</td>
</tr>
<tr>
<td>fixture sensors</td>
<td>chilled beams</td>
</tr>
<tr>
<td>high efficiency appliances (Energy Star)</td>
<td>ground source heat pumps</td>
</tr>
<tr>
<td>high efficiency lighting</td>
<td>greywater reuse</td>
</tr>
<tr>
<td>individual thermostat controls</td>
<td>light shelves</td>
</tr>
<tr>
<td>low-flow, high efficiency fixtures</td>
<td>radiant heating / cooling</td>
</tr>
<tr>
<td>occupancy sensors</td>
<td>smart building façade / shading controls</td>
</tr>
<tr>
<td>operable windows</td>
<td>under floor air distribution (UFAD)</td>
</tr>
<tr>
<td>variable air volume systems</td>
<td>vegetated roof</td>
</tr>
<tr>
<td></td>
<td>waste heat recovery</td>
</tr>
</tbody>
</table>
Analytic Approach

- Binary logistic regressions with generalized estimating equations to analyze impacts of innovation span on likelihood of implementation, and moderating role of team integration
Results – Low correlations among variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>S.D.</th>
<th>N</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Implementation</td>
<td>0.28</td>
<td>0.45</td>
<td>2,599</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Innovation span</td>
<td>0.52</td>
<td>0.50</td>
<td>2,599</td>
<td>-0.25***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Integration</td>
<td>2.04</td>
<td>0.68</td>
<td>551</td>
<td>0.06</td>
<td>-0.002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Cost</td>
<td>5.86</td>
<td>6.66</td>
<td>2,599</td>
<td>-0.22***</td>
<td>0.38***</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 LEED score</td>
<td>39.12</td>
<td>8.96</td>
<td>2,599</td>
<td>0.07***</td>
<td>0</td>
<td>0.12**</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Profit organization</td>
<td>0.25</td>
<td>0.43</td>
<td>2,599</td>
<td>0.03</td>
<td>0</td>
<td>0.44***</td>
<td>0.003</td>
<td>-0.12***</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Year</td>
<td>2002</td>
<td>1.80</td>
<td>2,599</td>
<td>0.03</td>
<td>0</td>
<td>0.24***</td>
<td>0.04*</td>
<td>0.23***</td>
<td>0.10***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Firm size</td>
<td>1.66</td>
<td>0.74</td>
<td>2,116</td>
<td>-0.01</td>
<td>0</td>
<td>-0.25***</td>
<td>-0.003</td>
<td>0.07**</td>
<td>0.02</td>
<td>-0.05*</td>
<td></td>
</tr>
<tr>
<td>9 Firm core values</td>
<td>0.87</td>
<td>0.34</td>
<td>2,116</td>
<td>0.01</td>
<td>0</td>
<td>0.24***</td>
<td>0.003</td>
<td>0.07**</td>
<td>0.09***</td>
<td>0.07***</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* p<.1, ** p<.01, *** p<.001; two-tailed tests.
H1 results:
The effects of innovation span on adoption

H1 is Confirmed:
Integral innovations have a lower probability of implementation than modular innovations
H2 results:
The moderating role of supply chain integration

H2 is Confirmed:
Supply Chain Integration moderates the negative impact that a long innovation span (integrality) has on probability of implementation.
Effect Sizes

• Integral innovations have 84% lower odds of implementation than modular innovations

• Odds of implementation decrease by 8% with every increase in $1/SF of added cost

• Medium integration increases odds of implementation by 186% when compared to low integration

• High integration increases the odds by 542% when compared to low integration
Results Summary: Strong Support for Both Hypotheses

• The longer an innovation’s span, the less likely is the innovation to be implemented
  • True over and above a set of controls
  • To a degree, innovation span has larger effect than cost

• Supply chain integration moderates the negative effects that a long innovation span has on implementation
  • The more integrated the team, the greater the odds of implementation of integral innovations
  • Main effect not significant
Theoretical Contributions – Management Literature

1. Develop an integrated theory to explain the effects of innovation span on implementation. Empirical support to validate theory.

2. Introduce concept of innovation span into modularity literature. Caution about limits of modularity.

3. Suggest and validate positive moderating effect of supply chain integration in facilitating the adoption of integral innovations.
Theoretical Contributions – Construction Literature

1. Empirical support for the influence of innovation span on the likelihood of adoption and implementation over and above other factors
2. Resolve debate about innovativeness of industry
3. Empirical support for the moderating effect of integration, along with caution against “one size fits all” solution
4. Large-N statistical analyses are possible even in complex building projects
5. Comprehensive model of the structural barriers to innovation diffusion
Practical Implications – Building Efficiency

- Easier to implement modular innovations (low hanging fruit)
- Supply chain integration improves odds for integral innovations – but only at high levels
Practical Implications – Modular Industries

- Supply chain integration as a strategic tool for penetrating mature markets with integral innovations
Limitations and Directions for Future Research

• Deepen Analyses
  • Limitation: Small data set, only two types of integration
  • Future Research: Obtain more data. More integration types.

• Increase Breadth
  • Limitation: One tech subset, one industry, one country
  • Future Research: Additional countries. Additional industries.

• Toward a Dynamic Model
  • Limitation: Static model
  • Future Research: Dynamic model of firm strategies over various products’ lifecycles
So what can we suggest?

- Stronger coordinator (GC)
- Integration
  - Integrated MEP, greater vertical integration
  - Full integration (e.g., Johnson Controls)
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- Moshe Sheffer, Noya Sheffer
Framework for understanding structural barriers to innovation in construction

Characteristics of Construction Products

- Durable
- Costly
- Complex

Resulting Risk & Industry Structure

- Susceptibility to demand fluctuations
- System of tort liability
- Vertical fragmentation
- Horizontal fragmentation
- Longitudinal fragmentation

Effects on Innovation Diffusion

- Reluctance to invest
- Technological risk aversion
- Broken agency
- No cross-subsidies
- Diffusion of responsibility
- Learning disability

Liberal Market Economies

Standardization & Regulation

Highly institutionalized