Outline

1 Motivation
2 Intuition
3 Research Approach
4 Validation
5 Next Steps
Motivation

Impact

Conceptual Design
Design Development
Construction Administration
Operation

1. Ability to impact cost
2. Cost of design changes
3. Traditional design process
4. Preferred design process

Design Stage
Motivation

1/2" GWB, PTD.
1/2" CEMENTITIOUS BACKER BOARD + CERAMIC WALL TILE
2X4 @ 24" OC
CELLULOSE INSUL, TOTAL R-33
2" CAIITY (W/ INSUL)
2X4 @ 24" OC
SHEATHING, SEE STRUCT NOTES
2" RIGID INSULATION, R-10
ALL SEAMS TAPED
GALVANIZED FURRING STRIPS
5/16" FIBER CEMENT BOARD

PARTITION TYPE:
TYP. EXT. ASSEMBLY
SCALE [1-1/2"=1'-0"]
<table>
<thead>
<tr>
<th>Building Component</th>
<th>Level 1 (class)</th>
<th>Level 2 (sub-component)</th>
<th>Level 3 (category)</th>
<th>Level 4 (property)</th>
<th>Level 5 (type)</th>
<th>Level 6 (processing)</th>
<th>Level 7 (specific database entry)</th>
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<td>Steel coil</td>
<td>Steel, converter, chromium steel 18/8</td>
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<td>Steel unalloyed</td>
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<td>Aluminum primary</td>
<td>Steel, converter, unalloyed, at plant</td>
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<td>Non-ferrous metals</td>
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<td>Aluminum extrusion profile</td>
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<td>Aluminum sheet, primary prod., semi-finished sheet product</td>
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<td>Aluminum, primary, at plant</td>
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<td>Aluminum</td>
<td>Aluminum, primary, liquid, at plant</td>
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<td>Aluminum, primary, ingot, at plant</td>
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<td>Aluminum</td>
<td>Aluminum, primary, smelt, at plant</td>
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</tbody>
</table>
Life cycle assessment integrated with optimization methods can help designers understand which design parameters drive a building’s impacts.
Which design elements drive a building’s life cycle impacts?

1. Determine scope of decisions
   - materials
   - sizes
   - design variables
   - life cycle phases

2. Develop material quantity heuristics

3. Provide feedback

4. Perform sensitivity analysis

5. Validate
   - retrospective case studies
Research Approach

1. Determine scope of decisions
   - materials
   - sizes
   - design variables
   - life cycle phases

2. Develop material quantity heuristics

3. Provide feedback

4. Perform sensitivity analysis

5. Validate
3 Material and Size Choices

• Uniformat 2010
  (A) Substructure
  (B) Shell
  (C) Interiors
  (D) Services
  (E) Equipment and Furnishings
  (F) Special Construction and Demolition
  (G) Sitework

• RSMeans

• equipment supplier documentation
## Building Component Classification Framework

<table>
<thead>
<tr>
<th>Uniformat element</th>
<th>Assembly</th>
<th>Sub-components</th>
<th>Number of material choices</th>
<th>Min (m)</th>
<th>Max (m)</th>
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<tbody>
<tr>
<td>A: Substructure</td>
<td>piles</td>
<td>piles, vapor barrier, caps, slab-on-grade, grade beam, rebar, formwork</td>
<td>2, 2, 1, 1, 1, 1</td>
<td>0.1</td>
<td>0.4</td>
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</tbody>
</table>
Design Variables

• parameterized

• literature review
  (1) window-to-wall ratio (WWR)
  (2) orientation
  (3) massing parameters: length, width, height
  (4) materials
  (5) building component size ranges
3 Life Cycle Phases

- Raw material acquisition
- Building material production
- On-site construction
- Operation
- Demolition

Transportation

MRR
3 Research Approach

1. Determine scope of decisions
   - materials
   - sizes
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   - life cycle phases

2. Develop material quantity heuristics

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Material Quantity Heuristics

- estimators at Beck Technology
- material quantity equations (231)
- building components (21)
  - required inputs (2)
    - gross floor area, location
  - independent variables (7)
    - length, width, orientation, WWR, # floors, materials, size ranges
  - dependent variables (9)
    - perimeter, slab perimeter, slab area, roof area, height, glazing area, # interior grid intersections, # exterior grid intersections, floor GFA
  - assumptions (6)
    - floor-to-floor height, bay spacing, door area, material densities, building lifetime, building type
## Material Quantity Heuristics

<table>
<thead>
<tr>
<th>Uniformat Code</th>
<th>Material</th>
<th>Equation</th>
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<tbody>
<tr>
<td><strong>A10 Foundations</strong></td>
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<tr>
<td>A1010.90200.PC</td>
<td>poured concrete footing</td>
<td>$0.2 \times \text{density} \times \text{slab area}$</td>
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<tr>
<td>A1020.8010.FW</td>
<td>wood formwork for grade beams</td>
<td>$4 \times \text{thickness} \times \text{perimeter}$</td>
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<td><strong>B20 Exterior vertical enclosures</strong></td>
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<td>B2010.2010.ST</td>
<td>steel cladding</td>
<td>$\text{density} \times \text{thickness} \times (1 - \text{WWR}) \times \text{perimeter} \times \text{height}$</td>
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<td>B2010.2040.WG</td>
<td>WF column/glulam beam</td>
<td>$10.76 \times (\text{GFA} + \text{roof area})$</td>
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<tr>
<td><strong>C10 Interior Construction</strong></td>
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<tr>
<td>C2030.2010.CR</td>
<td>ceramic floor tile</td>
<td>$\text{density} \times \text{thickness} \times \text{GFA}$</td>
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<tr>
<td>C2030.2010.ST</td>
<td>stone floor tile</td>
<td>$\text{density} \times \text{thickness} \times \text{GFA}$</td>
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<tr>
<td>C2030.2010.CM</td>
<td>cement facing tile with fiber</td>
<td>$\text{density} \times \text{thickness} \times \text{GFA}$</td>
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</tbody>
</table>
Research Approach

1. Determine scope of decisions
   - materials
   - sizes
   - design variables
   - life cycle phases

2. Develop material quantity heuristics

3. Provide feedback

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5. Validate
Design-Feedback Method

Software Implementation Key

1 = DProfiler
2 = Athena, SimaPro
3 = eQUEST
4 = CostLab
5 = Excel
6 = ModelCenter
3 Research Phases

Building information model

Pre-operational CO₂e

Pre-operational cost

MRR Schedule

Energy simulation

Operational CO₂e

Operational cost

Life-cycle CO₂e

Life-cycle cost

Optimizer

Impacts by Phase
1: Embodied
2: Operational
3: Cost

Software Implementation Key
1 = DProfiler
2 = Athena, SimaPro
3 = eQUEST
4 = CostLab
5 = Excel
6 = ModelCenter
### BUILDING SYSTEM

<table>
<thead>
<tr>
<th>A: Substructure</th>
<th>B: Shell</th>
<th>C: Interiors</th>
<th>D: Services</th>
<th>E: Equipment &amp; Furnishings</th>
<th>G: Building Sitework</th>
</tr>
</thead>
</table>

#### BUILDING LIFE CYCLE PHASE

**Pre-Operational**

- **Cost**
  - Beck Technology

- **Impact**
  - Athena / SimaPro

**Operational**

- **Cost**
  - Utilities
  - MRR
  - Beck Technology
  - Cost Lab

- **Impact**
  - Utilities
  - MRR
  - eQuest
  - Athena / SimaPro

#### Impacts by Phase

- Green: 1: Embodied
- Blue: 2: Operational
- Orange: 3: Cost

**Data Sources**

- Athena / SimaPro
- Beck Technology
- Cost Lab
- eQuest
Research Approach

1. Determine scope of decisions
   - materials
   - sizes
   - design variables
   - life cycle phases

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5. Validate
Which design parameters consistently drive building impacts?

**Impact Allocation:** determines where building impacts lie

**Impact Reduction:** shows degree to which changes to design parameters affect impacts

→ sampling very large number of building design alternatives

→ by phase

### Impacts by Phase

- 1: Embodied
- 2: Operational
- 3: Cost
Research Approach

1. Determine scope of decisions
   - materials
   - sizes
   - design variables
   - life cycle phases

2. Develop material quantity heuristics

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5. Validate
Case Study: US Government Building, Middle East
Case Study

**SCOPE**

(1) Housing buildings

**OBJECTIVES**

(1) Minimize life-cycle cost
(2) Minimize carbon footprint

**CONSTRAINTS**

(1) Gross floor area
(2) Location
(3) Building type

**DESIGN SPACE SIZE**

Possible design configurations: $1.46E11$
4 Sensitivity Analysis

**VARIABLES**

1. Number of buildings: 3 or 4
2. Orientation
3. Number of stories: 5, 6, 7, or 8
4. Building footprint: H-shape
5. WWR
4 Results: Life Cycle Cost vs. Carbon Footprint

KEY

Baseline
Lowest Cost
Lowest Carbon Footprint

3 Buildings, 5 Stories
3 Buildings, 6 Stories
3 Buildings, 7 Stories
3 Buildings, 8 Stories
4 Buildings, 5 Stories
4 Buildings, 6 Stories
4 Buildings, 7 Stories
4 Buildings, 8 Stories
Results: Base Design

Configuration
- Number of buildings: 4
- Number of floors: 8
- Glazing: 15%

Process Efficiency
- Design Cycle Duration: 4 wks
- Number of cycles: 1

Life-Cycle Performance
- COST (USD, Millions): 198
- IMPACT (metric ktns. CO2e): 286

Baseline
- Capital: 58
- Operational: 140

Baseline
- Capital: 259
- Operational: 27
Results: Design 1560

Configuration
Number of buildings: 3
Number of floors: 6

Process Efficiency
Design Cycle Duration: 7 s
Number of cycles: 21,360

Life-Cycle Performance
COST (USD, Millions)

Baseline   Design 1560
Capital      140     58       (-14%)
Operational 122     48

IMPACT (met ktns. CO2e)
Baseline   Design 1560
259       250       (-5%)
### Sensitivity Analysis

#### SCOPE
1. Housing buildings

#### OBJECTIVES
1. Calculate impact allocation scheme
2. Calculate impact reduction scheme

#### VARIABLES
1. Number of buildings (3 or 4)
2. Number of stories (5, 6, 7, or 8)
3. Building orientation (0°-360°)
4. Building shape
5. Window-to-wall ratio (0.15-0.50)
6. Materials
7. Sizes

#### CONSTRAINTS
1. Gross floor area
2. Location
3. Building type

#### DESIGN SPACE SIZE
1. Materials: $1.24 \times 10^{14}$
2. Sizes: $5.66 \times 10^{10}$
3. Total design space: $2.38 \times 10^{16}$
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<th>Decision number</th>
<th>Assembly</th>
<th>Impact Reduction (% max embodied impact)</th>
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<td><strong>Whole building</strong></td>
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<tr>
<td>22</td>
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<td>Exterior doors</td>
<td><strong>Max</strong></td>
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<td>74.94</td>
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**Sensitivity Analysis Results (phase 1: embodied)**
Next Steps

1. Determine scope of decisions
   - materials
   - sizes
   - design variables
   - life cycle phases

2. Develop material quantity heuristics

3. Provide feedback

4. Perform sensitivity analysis

5. Validate

Impacts by Phase

- 1: Embodied
- 2: Operational
- 3: Cost

- case study
- charrette
Next Steps

**SCOPE**
- entire building
- WWR
- orientation
- length
- cladding material

**SAMPLING METHODS**
1. orthogonal array
2. Latin hypercube

**DESIGN SPACE SIZE**
2.38E16
Next Steps

Impact Reduc/$

 SCOPE

A: Substructure
B: Shell
C: Interiors
D: Services

SAMPLING METHODS

(1) orthogonal array
(2) Latin hypercube

DESIGN SPACE SIZE

> 2.38E16
Questions?