An Enhanced Sequential Search Methodology for Identifying Cost-Optimal Building Pathways

SimBuild, IBPSA

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Objectives

Develop strategies to improve speed and robustness of the basic sequential search optimization methodology

Construct packages of strategies for potential implementation in the BEopt software.
Motivation

Robustness
  - Lower-cost building designs

Speed
  - Increasing size of parameter search space
  - DOE-2, TRNSYS -> EnergyPlus
I. Background

**BEopt – Building Energy Optimizer**

Identifies cost-optimal building designs over a range of energy savings from base case to zero net energy

Accurately accounts for interactions between measures (e.g. glass type and HVAC)

Evaluates realistic (discrete) measures

Runs hour-by-hour simulations (DOE2 and TRNSYS)

Employs sequential search optimization technique
## I. Background

**BEopt - Cost/Energy Graph**

<table>
<thead>
<tr>
<th>Cost (ΔMortgage + Utility Bills) ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility Bills</td>
<td>0</td>
</tr>
<tr>
<td>Δ Mortgage Cost for Efficiency</td>
<td>10</td>
</tr>
<tr>
<td>Δ Mortgage Cost for PV</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>50</td>
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<td></td>
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<td>80</td>
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<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

- **A** represents the current utility bills and mortgage cost for inefficiency.
- **B** represents the point where energy savings start to become cost-effective.
- **C** represents the optimal energy savings point.
- **D** represents the point where energy savings are significantly high, indicating cost savings.
I. Background

Basic Sequential Search

Cost ($) vs. Energy Savings (%)

N simulations
I. Background

Basic Sequential Search

Cost ($) vs. Energy Savings (%)

N simulations
I. Background

Basic Sequential Search
I. Background

Basic Sequential Search

![Graph showing cost vs. energy savings for N and N-1 simulations](image-url)
I. Background

Basic Sequential Search

![Graph showing the relationship between cost and energy savings through sequential simulations.](image)
I. Background

Basic Sequential Search

![Diagram showing Cost ($) vs Energy Savings (%)]

- N simulations
- N-1 simulations
- N-2 simulations
I. Background

Basic Sequential Search

Three goals:

– Discrete, realistic building designs
– Optimal designs for a range of energy savings
– Alternative near-optimal designs
II. Robustness Strategies

Overview of Strategies

Special Cases
1. Large-Step
2. Invest/Divest
3. Positive Interactions
II. Robustness Strategies

Large-Step Special Case

![Diagram showing Cost ($) vs. Energy Savings (%)]

Cost ($) vs. Energy Savings (%)

- Cost ($)
- Energy Savings (%)
II. Robustness Strategies

Large-Step Special Case

- Cost ($)
- Energy Savings (%)
II. Robustness Strategies

Large-Step Special Case

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
II. Robustness Strategies

Large-Step Special Case

- Cost ($)
- Energy Savings (%)
II. Robustness Strategies

Large-Step Special Case

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2'</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

Diagram showing the relationship between cost and energy savings.
II. Robustness Strategies

Large-Step Special Case

Cost ($) vs. Energy Savings (%)

Solution: Store all previous simulation results when searching for next optimal point
II. Robustness Strategies

Invest/Divest Special Case

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
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</tbody>
</table>

![Graph showing the relationship between cost and energy savings.](image-url)
II. Robustness Strategies

Invest/Divest Special Case

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Graph showing the relationship between cost and energy savings.
II. Robustness Strategies

Invest/Divest Special Case

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
II. Robustness Strategies

Invest/Divest Special Case
II. Robustness Strategies

Invest/Divest Special Case

Solution: Evaluate ALL options
II. Robustness Strategies

Positive Interactions Special Case

A – Shift window area to South façade
B – High thermal mass
II. Robustness Strategies

Positive Interactions Special Case

A – Shift window area to South façade
B – High thermal mass
II. Robustness Strategies

Positive Interactions Special Case

A – Shift window area to South façade
B – High thermal mass

Cost ($)

Energy Savings (%)
II. Robustness Strategies

Positive Interactions Special Case

Solution: Allow users to explicitly include combinations for evaluation

A – Shift window area to South façade
B – High thermal mass
II. Robustness Strategies

Parametric Validation

- Parametric points (2,000,000)
- Optimization points (2,000)
III. Speed Strategies

Overview of Strategies

Reducing Number of Simulations per Iteration
1. Modularized simulations
2. Skip superseded options (3)
3. Skip less efficient options (5)
4. Skip predicted outliers (4)
5. Mathematically filter points (3)
6. Skip fine points (2)
7. Skip extraneous options (2)
8. Simulate best ranked option (4)

Reducing Number of Iterations
9. Option lumping (5)
10. Forward progression
11. Build up simulations
12. Pre-optimization of child categories

( ) Number of variants
III. Speed Strategies

Overview of Strategies

Reducing Number of Simulations per Iteration
1. Modularized simulations
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8. Simulate best ranked option

Reducing Number of Iterations
9. Option lumping
10. Forward progression
11. Build up simulations
12. Pre-optimization of child categories
III. Speed Strategies

Skip Predicted Outliers

Reducing Simulations per Iteration
Strategy #4

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>Predicted</td>
</tr>
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</table>

Band Threshold

- Simulated
- Predicted
- Band Threshold

Diagram showing points A, B, C, D, and E with corresponding coordinates and labels.
III. Speed Strategies

Skip Predicted Outliers

Reducing Simulations per Iteration
Strategy #4

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
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</table>

- Simulated
- Predicted
- Band Threshold
III. Speed Strategies

Skip Predicted Outliers

Reducing Simulations per Iteration
Strategy #4

<table>
<thead>
<tr>
<th>Simulated</th>
<th>Predicted</th>
<th>Band Threshold</th>
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</thead>
<tbody>
<tr>
<td>E</td>
<td>D</td>
<td>E'</td>
</tr>
<tr>
<td>C</td>
<td>B</td>
<td>C'</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>A'</td>
</tr>
<tr>
<td></td>
<td>B'</td>
<td></td>
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</tbody>
</table>
III. Speed Strategies

Skip Fine Points

Reducing Simulations per Iteration
Strategy #6

![Graph showing Cost (\$) vs. Energy Savings (%) with points A, B, C, D, E, F](image-url)
III. Speed Strategies

Skip Fine Points

Reducing Simulations per Iteration
Strategy #6

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
<th>Tolerance For B</th>
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<tbody>
<tr>
<td>A</td>
<td></td>
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<tr>
<td>B</td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td></td>
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</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
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</table>
III. Speed Strategies

Skip Fine Points

Reducing Simulations per Iteration
Strategy #6

Energy Savings ($/\text{iteration}$) vs. Energy Savings (%)

- Cost ($)
- Energy Savings (%)

Energy Savings Tolerance For B
### III. Speed Strategies

**Skip Extraneous Points**

Reducing Simulations per Iteration

Strategy #7

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing Cost ($) vs. Energy Savings (%)](image-url)
III. Speed Strategies

Skip Extraneous Points

Reducing Simulations per Iteration
Strategy #7

![Graph showing cost vs. energy savings with points A, B, C, and D.](image-url)
III. Speed Strategies

Skip Extraneous Points

Reducing Simulations per Iteration
Strategy #7

Cost ($) vs. Energy Savings (%)

Points A, B, C, D

Diagram showing the relationship between cost and energy savings.
III. Speed Strategies

Skip Extraneous Points

Reducing Simulations per Iteration
Strategy #7

![Graph showing energy savings vs. cost with points A, B, C, and D.]

- A: Maximum Energy Savings and Maximum Cost
- B: Moderate Energy Savings and Moderate Cost
- C: Minimum Energy Savings and Moderate Cost
- D: Minimum Energy Savings and Minimum Cost
III. Speed Strategies

Option Lumping

Reducing Iterations
Strategy #9

Cost ($)

Energy Savings (%)
III. Speed Strategies

Option Lumping

Reducing Iterations
Strategy #9

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Energy Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
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<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
</tbody>
</table>
III. Speed Strategies

Option Lumping

Reducing Iterations
Strategy #9

Cost ($) vs. Energy Savings (%)

- Option 0: Cost 0, Energy Savings 0
- Option 1: Cost 2, Energy Savings 6
- Option 2: Cost 4, Energy Savings 5
- Option 3: Cost 6, Energy Savings 4
- Option 5: Cost 3, Energy Savings 2
- Option 6: Cost 1, Energy Savings 1
III. Speed Strategies

Option Lumping

Cost ($) vs. Energy Savings (%)

Reducing Iterations
Strategy #9
III. Speed Strategies

Option Lumping

Reducing Iterations
Strategy #9

Cost ($)

Energy Savings (%)
IV. Test Suite

Details for Test Suite

2500 sqft building, 2 stories, 2-car garage

Standard BEopt costs
  – RS Means, manufacturer’s data, etc.

18 optimizations
  – 6 climates
    • Phoenix, Houston, Atlanta, San Francisco, Boulder, Chicago
  – 3 optimization sizes
    • Large ~ 2100 simulations, 8 hours
    • Medium ~ 300 simulations, 1.5 hours
    • Small ~ 50 simulations, 10 minutes
IV. Test Suite

Results

Speed Gains
Percent reduction in number of simulations, relative to reference optimization

Robustness
Percent maximum deviation in cost-optimal path, relative to reference optimization

![Diagram showing results](image-url)
V. Packages

Results

<table>
<thead>
<tr>
<th>Speed Gains (%)</th>
<th>Max. Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>50%</td>
</tr>
<tr>
<td>50%</td>
<td>40%</td>
</tr>
<tr>
<td>40%</td>
<td>30%</td>
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<tr>
<td>30%</td>
<td>20%</td>
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<tr>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>10%</td>
<td>0%</td>
</tr>
<tr>
<td>0%</td>
<td>-10%</td>
</tr>
<tr>
<td>-10%</td>
<td>-20%</td>
</tr>
<tr>
<td>-20%</td>
<td>-5.0%</td>
</tr>
<tr>
<td>-5.0%</td>
<td>-7.5%</td>
</tr>
</tbody>
</table>

Legend:
- **All Optimizations**
- **Average**

Diagram showing speed gains and max. deviation for various packages (2a, 2b, 2c, 3a, 3b, 4a, 4b, 4c, 5a, 6a, 7a, 7b, 8a, 8b, 9a, 9b, 9c, 9d, 9e, 10, LS, I/D).
V. Packages

Package Selection

![Graph showing speed gains and maximum deviation for different packages.](image)

- Selected Pkgs
- 1 Strategy
- 2 Strategies
- 3 Strategies
- 4 Strategies
- 5 Strategies
V. Packages

Package Selection

[Graph showing speed gains and maximum deviation for different package combinations.]

- A (4a)
- B (4a, 6a)
- C (4a, 6a, 9a)
- D (4a, 6a, 9a, 3b)
- E (4a, 6a, 9a, 3b, 7b)
- F (4b, 6a, 9a, 3b, 7b)
- G (4b, 6a, 9a, 3a, 7b)
V. Packages

Final Results

![Graph showing speed gains and maximum deviation. The graph includes points labeled A, B, C, D, E, F, G, and indicates that the maximum limit is not 100%.]
### V. Packages

#### Final Results

<table>
<thead>
<tr>
<th>Pkg</th>
<th>Speed Gains (%)</th>
<th>Max Deviation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small Only</td>
<td>Medium Only</td>
</tr>
<tr>
<td>A</td>
<td>10.2</td>
<td>16.7</td>
</tr>
<tr>
<td>B</td>
<td>10.2</td>
<td>16.7</td>
</tr>
<tr>
<td>C</td>
<td>15.6</td>
<td>25.3</td>
</tr>
<tr>
<td>D</td>
<td>26.9</td>
<td>42.1</td>
</tr>
<tr>
<td>E</td>
<td>29.7</td>
<td>45.7</td>
</tr>
<tr>
<td>F</td>
<td>38.4</td>
<td>54.2</td>
</tr>
<tr>
<td>G</td>
<td>44.0</td>
<td>58.4</td>
</tr>
<tr>
<td>H</td>
<td>45.1</td>
<td>64.5</td>
</tr>
</tbody>
</table>
V. Packages

Final Results

Atlanta, Large Optimization
Package G

2440 points (8 hours)
683 points (2 hours)
Conclusions

Robustness
- Three deficiencies identified/implemented
- Validated against large parametric runs

Speed
- 11 strategies (31 variants) documented; 20 variants evaluated
- Better to supplement robustness strategies with speed strategies than to deactivate robustness strategies
- Most effective strategies: skip predicted outliers, skip fine points, option lumping, skip less efficient options, skip extraneous points

Packages
- 7 packages selected
- Range from 15% speed gains (0% maximum deviation) to 71% speed gains (1.2% maximum deviation)
Thank You!