A Multi-Stage Optimization Model for Flexibility in Engineering Design

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Engineering System Design

Power generation

25 de Abril bridge
Previous Works

• Flexibility in engineering system design:
  
  • Flexibility in system design and implications for aerospace systems (Saleh et.al 2003)
  • A flexible and robust approach for preliminary engineering design based on designer's preference (Nahm et.al, 2007)
  • A real options approach to hybrid electric vehicle architecture design for flexibility (Kang et.al 2016)
Our Research Contribution To The Engineering Design

• Challenges with flexible design:
  • Operation of engineered systems for long time
  • Evaluation of the objective function with the use of computationally expensive simulation

• Our contribution:
  Optimize the design when the objective function must be evaluated via simulation considering long range uncertainty and flexibility in design
Research Framework

Real world application

Simulation

Optimization

Black box simulation optimization

Identify key and long-range uncertainty (forecast and simulate future condition)

Optimization with long-range uncertainty

Optimal design without flexibility

Optimal design with flexibility
Application: Hybrid Renewable Energy System
Application: Hybrid Renewable Energy System

• Design of hybrid renewable energy system

• Hybrid renewable system includes: PV panels, wind turbine, battery storage, electrolyzer, and fuel cell

• Design variables: capacity of the components of the system

• Identify the optimal capacity of each component to minimize the expected discounted cost
Research Framework

Real world application

Simulation → Optimization
Black box simulation optimization

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Simulation of Energy Demand for California, 2017-2036

Historical demand

Forecasted demand
Research Framework

Real world application

Identify key and long-range uncertainty (forecast and simulate future condition)

Simulation
Optimization
Black box simulation optimization

Optimization with long-range uncertainty

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Mathematical Model

- Goal: Find the optimal design of hybrid renewable energy system
- Minimize expected discounted costs
  - Investment
  - Replacement
  - Maintenance
- Decision variables: Capacity of solar, wind, battery, fuel cells, electrolyzer, and hydrogen tank
Simulation Optimization

Randomly select decision variables → Monte Carlo simulation → Cost

New decision variables → Monte Carlo simulation → Cost

Update decision variables
Research Framework

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## Optimal Solution

<table>
<thead>
<tr>
<th>Components</th>
<th>Capacity (Giga Watt)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar panel</td>
<td>392</td>
<td>78</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>146</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>89</td>
<td>17</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>104</td>
<td>-</td>
</tr>
<tr>
<td>Hydrogen tank</td>
<td>322</td>
<td>-</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>138</td>
<td>4</td>
</tr>
<tr>
<td>Diesel</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Expected cost</td>
<td>$ 40.66 trillion</td>
<td>-</td>
</tr>
</tbody>
</table>
Demand Fulfillment Analysis: 1 Scenario
Parallel Coordinate Plot for Hybrid Renewable Design

Expected Cost ($ Trillion)

98.94

46.21

40.66
Research Framework

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Simulation

Optimization with long-range uncertainty

Optimization with long-range uncertainty

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Optimal design with flexibility

Identify key and long-range uncertainty (forecast and simulate future condition)

Black box simulation optimization
Design Optimization with Flexibility

**Case 1:** One time design modification at 2027

Optimize design over 2017-2027

- **High demand**
  - Optimize additional capacity for high demand profile

- **Medium demand**
  - Optimize additional capacity for medium demand profile

- **Low demand**
  - Optimize additional capacity for low demand profile
Design Optimization with Flexibility

- **Case 2**: Two times design modifications at 2027 and 2032
  - **Stage 1**: Optimize design for 2017-2027
  - **Stage 2**: Optimize additional capacity for 2027-2032, given the optimal initial design
  - **Stage 3**: Optimize additional capacity for 2032-2037, given the optimal initial design and each optimal expansion amounts of stage 2
  - Find the expected cost of design (initial design cost + average expansion cost at stage 2 + average expansion cost at stage 3)
Expected Cost of Design with and without Flexibility

![Graph showing expected cost with and without flexibility. The x-axis represents the number of design modifications, ranging from 0 to 2. The y-axis represents the expected cost in trillion dollars, ranging from 40.66 to 26.52. The graph shows a decrease in expected cost as the number of design modifications increases.]
Conclusions

• Design under long-range uncertainty

  • Hybrid renewable energy system
  • Monte Carlo simulation of uncertainties (e.g., demand)
  • Optimize design with and without flexibility
  • Compare the design without flexibility with design with flexibility

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Reference