Target Cascading in Optimal System Design

An Academic Example:
Half-Vehicle Design

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Target Cascading Problem Statement

Given

• a set of vehicle targets, and

• models for systems, subsystems and components,

Determine system, subsystem and component targets by

• partitioning the vehicle design problem,

• satisfying feasibility/optimality of system, subsystem and component designs, and

• achieving vehicle targets.
Proposed Approach

1. Model Development/Verification
   - Identify optimal design objectives, variables and constraints and formulate design optimization problem.
   - Build approximate models.

2. Optimal Decomposition
   - Model-Based Decomposition (Michelena & Papalambros)
   - Integer Programming-Based Decomposition (Krishnamachari & Papalambros)

3. Cascading Targets (Multiple Levels)
   - Formulate Design Optimization Problems at each level.

4. Coordination
   - Ensure convergent solution to the optimum.
Vehicle Design Optimization

All-At-Once (AAO) approach

VEHICLE TARGETS

Minimize Deviation from Vehicle Targets

Vehicle Parameters
Vehicle Level Design Analysis

System Parameters
System Level Design Analysis

Subsystem Parameters
Subsystem Level Design Analysis

Component Parameters
Component Level Design Analysis
Vehicle Decomposition

Vehicle

Systems
- POWERTRAIN
- ELECTRONICS
- BODY
- CHASSIS
- CLIMATE CONTROL

Subsystem
- GLASS
- BODY-IN-WHITE
- CLOSURE

Components
- JOINTS
- ...
Hierarchical Optimization for Target Cascading

Vehicle Targets

Minimize Deviation vehicle targets/responses
subject to compatibility constraints for system linking variables/responses

Minimize Deviation system targets/responses and linking variables
subject to compatibility constraints for subsystem linking variables/responses

Minimize Deviation system targets/responses and linking variables
subject to compatibility constraints for component linking variables/responses

Minimize Deviation component targets/responses and linking variables

system linking variables
subsystem linking variables
component linking variables
system responses
subsystem responses
component responses
Half Car Model (Chassis+Body)

**Vehicle → System → Subsystem**

Vehicle Responses:
- NVH ($z''_b$),
- Packaging ($z_s - z_{us}$),
- Body Weight ($m_b$)

System Responses:
- Suspension Stiffness ($k_s$),
- Body Weight ($m_b$)

Body Model Deflections

$k_s = k_{s1} + k_{s2}$

$k_{s1} = 2k_{s2}$
Vehicle to System: Dynamics Model

Original Problem
Minimize the acceleration of body mass and the displacement between sprung mass and unsprung mass.

Target Cascading Formulation
Minimize the acceleration of body mass and the displacement between sprung mass and unsprung mass with the minimum deviations from the target values.

\[
\text{Minimize } w_1 \left\| z_b'' - T_1 \right\| + w_2 \left\| (z_s - z_{us}) - T_2 \right\| + w_3 \left\| m_b - T_3 \right\|
\]

subject to
\[
\left\| m_b - m_b^\dagger \right\| \leq \varepsilon_1
\]
\[
\left\| k_s - k_s^\dagger \right\| \leq \varepsilon_2
\]
\[
25 \leq c_b \leq 500
\]
\[
18000 \leq k_b \leq 36000
\]
\[
100 \leq m_b \leq 150
\]
\[
125 \leq c_s \leq 2500
\]
\[
6000 \leq k_s \leq 12000
\]
\[
400 \leq m_s \leq 500
\]
System to Subsystem: FEA Model

Design Objectives:
Minimize deviation from the weight target.

Design Variables:
Section thicknesses for 8 different beam sections

Design Constraints:
Strain energy for each beam should be less than allowable limit.
## Optimization Results (1)

### Vehicle Level: Target Variables

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>Targets</th>
<th>Initial Design</th>
<th>Optimal Design</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>NVH (m/s^2)</td>
<td>0.01</td>
<td>0.0227</td>
<td>0.0112</td>
<td>-50.7%</td>
</tr>
<tr>
<td>Packaging (m)</td>
<td>0.002</td>
<td>0.0016</td>
<td>0.0017</td>
<td>+6.3%</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>100</td>
<td>150</td>
<td>100</td>
<td>-33.3%</td>
</tr>
</tbody>
</table>

### Vehicle to System: Dynamics Model

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>Initial Design</th>
<th>Lower Bounds</th>
<th>Upper Bounds</th>
<th>Optimal Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>max suspension stroke</td>
<td>0.01</td>
<td>-Inf</td>
<td>Inf</td>
<td>0.0017</td>
</tr>
<tr>
<td>max body mass accel.</td>
<td>0.01</td>
<td>-Inf</td>
<td>Inf</td>
<td>0.0112</td>
</tr>
<tr>
<td>damping of suspension</td>
<td>500</td>
<td>125</td>
<td>2500</td>
<td>286</td>
</tr>
<tr>
<td>stiffness of suspension</td>
<td>9000</td>
<td>3000</td>
<td>12000</td>
<td>4000</td>
</tr>
<tr>
<td>damping of body</td>
<td>250</td>
<td>25</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>stiffness of body</td>
<td>24000</td>
<td>18000</td>
<td>36000</td>
<td>18000</td>
</tr>
<tr>
<td>sprung mass w/o body</td>
<td>450</td>
<td>400</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>vehicle body mass</td>
<td>150</td>
<td>100</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>
Optimization Results (2)

- Ground velocity
- Suspension Stroke
- Sprung Mass Acceleration
- Tire Deflection
- Body Stroke
- Body Acceleration

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### Optimization Results (3)

#### System to Subsystem: FEA Model

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>Initial Design</th>
<th>Lower Bounds</th>
<th>Upper Bounds</th>
<th>Optimal Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness of section type 1</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.4066</td>
</tr>
<tr>
<td>thickness of section type 2</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.3597</td>
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<tr>
<td>thickness of section type 3</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.2931</td>
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<tr>
<td>thickness of section type 4</td>
<td>0.3</td>
<td>0.001</td>
<td>0.3</td>
<td>0.2988</td>
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<tr>
<td>thickness of section type 5</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.4110</td>
</tr>
<tr>
<td>thickness of section type 6</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.3117</td>
</tr>
<tr>
<td>thickness of section type 7</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.5000</td>
</tr>
<tr>
<td>thickness of section type 8</td>
<td>0.5</td>
<td>0.001</td>
<td>0.5</td>
<td>0.2947</td>
</tr>
<tr>
<td>vehicle body mass</td>
<td>150</td>
<td>100</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

#### System to Subsystem: Suspension Model

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>Initial Design</th>
<th>Lower Bounds</th>
<th>Upper Bounds</th>
<th>Optimal Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>suspension spring 1</td>
<td>2000</td>
<td>1000</td>
<td>12000</td>
<td>2667</td>
</tr>
<tr>
<td>suspension spring 2</td>
<td>2000</td>
<td>1000</td>
<td>12000</td>
<td>1333</td>
</tr>
</tbody>
</table>
Conclusions

• Rigorous approach to cascade/achieve targets for large scale system design was proposed.

• Hierarchical optimization problem structure for target cascading was presented.

• Example problem with three-level hierarchy for vehicle was developed to implement target cascading approach.