Designing for Cost Reduction

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Introduction

We normally think of optimization in terms of reducing mass or increasing performance of a product, but often the underlying goal is to reduce product cost while achieving a target performance. Product cost may be a function of many factors such as material type, amount of material used, manufacturing process, number of parts, assembly details, and more.

The relationship between cost and design variables (e.g., shape, material, gauge thickness, location of features, etc.) is highly implicit. In other words, it is often difficult to understand the direct effect that changing one or more variables will have on cost. But mathematical design optimization has the ability to efficiently explore these complex relationships. For this reason, it is a powerful tool for achieving a cost effective product design.

It is tempting to reduce design complexity by focusing on just one type of design variable. For example, cost reduction efforts may consider only reducing gauge thickness, or changing material type, or changing shape to reduce material usage. By themselves, any of these approaches may yield some benefit in terms of cost reduction. But the biggest cost savings are usually achieved by taking advantage of the strong coupling among shape, material properties, gauge thickness, and other variables.

For example, the best part shape for one material may be very sub-optimal for another material because the stiffness and strength characteristics of each material are different. Considering both shape and material together during the design optimization process often leads to a more optimal design, one with significantly less cost.

Further, the least expensive material may not always lead to the lowest cost design, since performance and mass are often strongly affected by a change in material. Simultaneously optimizing the distribution and type of material within each component is the best way to achieve both high performance and low cost.

Here, we demonstrate how to couple a cost model and a finite element model within an optimization process to obtain a minimum cost design that also meets performance requirements. The application example is an office chair leg with both material and shape design variables. HEEDS Professional is used to automate the design evaluation and optimization process, Abaqus is used to perform finite element analysis, and Excel is used to calculate the cost of each proposed design.

Analysis Model

A single leg of a typical five-leg office chair was designed to minimize its cost. The baseline design is shown in Figure 1. The material and the shape of the chair leg are treated as design variables. The possible material choices are: Aluminum, Cast-Iron, Low Strength Steel, and High Strength Steel. The six shape design variables, as shown in Figure 2, are the height, thickness and location of the internal rib, the linearly varying side wall thickness profile and the floor thickness. The parametric geometry model and associated finite element model are developed within Abaqus CAE.

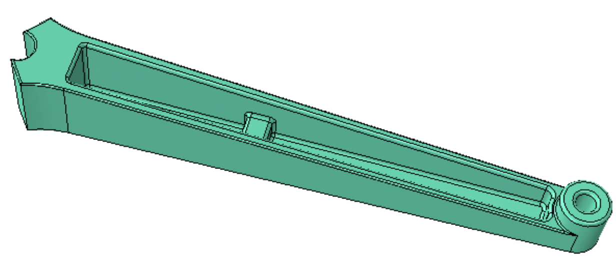

Figure 1. Chair leg to be optimized.

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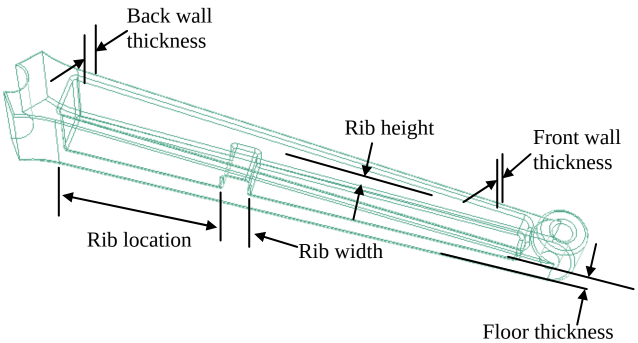

Figure 2. Chair leg shape parameters to be designed.

The nonlinear static finite element analysis is performed using Abaqus/Standard. For all materials except cast iron, mild nonlinearity is associated with material plasticity as the loading is allowed to exceed the material yield stress slightly in the most efficient designs. The leg is loaded as shown in Figure 3. It is fixed at the base of the chair, and a point force and a point moment are applied at the caster socket to simulate rolling of the chair on a frictional surface. Figure 4 shows the scaled deformation under loading. Table 1 contains the geometric details and analysis results for the baseline design.

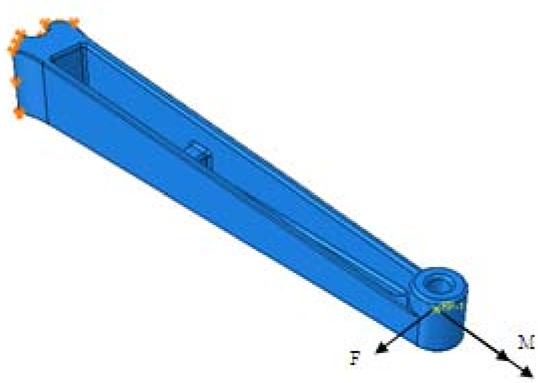

Figure 3. Chair leg loading and boundary conditions.

Figure 4. Scaled chair leg deformation.

Table 1. Baseline design finite element results.

Design Parameter	Value
Material	Steel_LowStrength
Rib Location (mm)	100
Rib Height (mm)	15
Rib Width (mm)	15
Floor Thickness (mm)	8
Front Wall Thickness (mm)	6
Back Wall Thickness (mm)	9
Response	**Value**
Volume (mm3)	2.848E5
Max Stress (MPa)	350.14
Max Displacement (mm)	1.005
Max Rotation (radians)	0.0216

Excel Model for Cost Analysis and Failure Index Computation

The cost of each design depends on the type of material, its density and the amount of material used. The relative cost of each design was calculated as the mass of the design multiplied by the relative material cost. The relative cost is a dimensionless (normalized) quantity that provides a relative, rather than an absolute, measure of cost. The density and relative material cost of each material are provided in Table 2.

The maximum stress in each design was calculated using the Abaqus finite element model. Because the allowable stress for a design depends on the material choice, a stress failure index was used to assess performance relative to the stress constraint. This index was defined as the maximum stress divided by the material's allowable stress. A value less than 1.0 for the stress failure index indicated a design that satisfied the stress constraint. The allowable stress was defined as the stress at 0.1% plastic strain for the given material (or for Cast Iron, the yield stress). This data is provided in Table 2.

Table 2. Material data used in the study.

Material	Density (10^{-6}*kg/mm^3)	Relative Material Cost (kg^{-1})	Allowable Stress (MPa)
Aluminum	2.71	7.9	162.2
Low Strength Steel	7.85	5.3	434.8
High Strength Steel	7.85	6.7	586.2
Cast Iron	7.30	4.7	379.0

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The cost and performance model was created using Microsoft Excel. A workbook was developed to calculate the relative cost, mass, and stress failure index for a given chair leg design. The workbook required as input the material type and the maximum stress and volume from the FE model. HEEDS provided these values to the workbook during optimization. Figure 5 shows the calculations for the baseline design defined in Table 1.

Microsoft Excel - Cost_Model.xls

	A	B	C
1	**Inputs:**		
2	Material=	Steel_LowStrength	
3	Volume=	2.85E+05	mm^3
4	Max Stress =	350.14	MPa
5			
6	**Outputs:**		
7	Relative Material Cost =	5.3	/kg
8	Relative Cost =	11.849104	
9	Material Allowable Stress =	434.8	MPa
10	Stress Failure Index =	0.805289788	
11	Material Density =	0.00000785	kg/mm^3
12	Mass =	2.23568	kg

Figure 5. Baseline design cost model.

Chair Leg Optimization

The optimization study considered both discrete (material) and continuous (shape) variables. The search was performed using the SHERPA algorithm within HEEDS Professional. The overall process flow is described in Figure 6. The goal of the study was to minimize the cost of the chair leg, with constraints on the stress failure index, deflection, and rotation. The mathematical optimization statement is:

Objective: minimize *relative cost*

Subject to: *stress failure index* $\le$ 1.0

max displacement $\le$ 5 mm

max rotation $\le$ 0.15 radians

By varying: 10 mm $\le$ *rib location* $\le$ 250 mm

4 mm $\le$ *rib height* $\le$ 20 mm

4 mm $\le$ *rib width* $\le$ 30 mm

1 mm $\le$ *floor thickness* $\le$ 10 mm

4 mm $\le$ *front wall thickness* $\le$ 10.75 mm

4 mm $\le$ back wall thickness $\le$ 10.75 mm

Material from the discrete set {Aluminum, Cast-Iron, Steel_HighStrength, Steel_LowStrength}

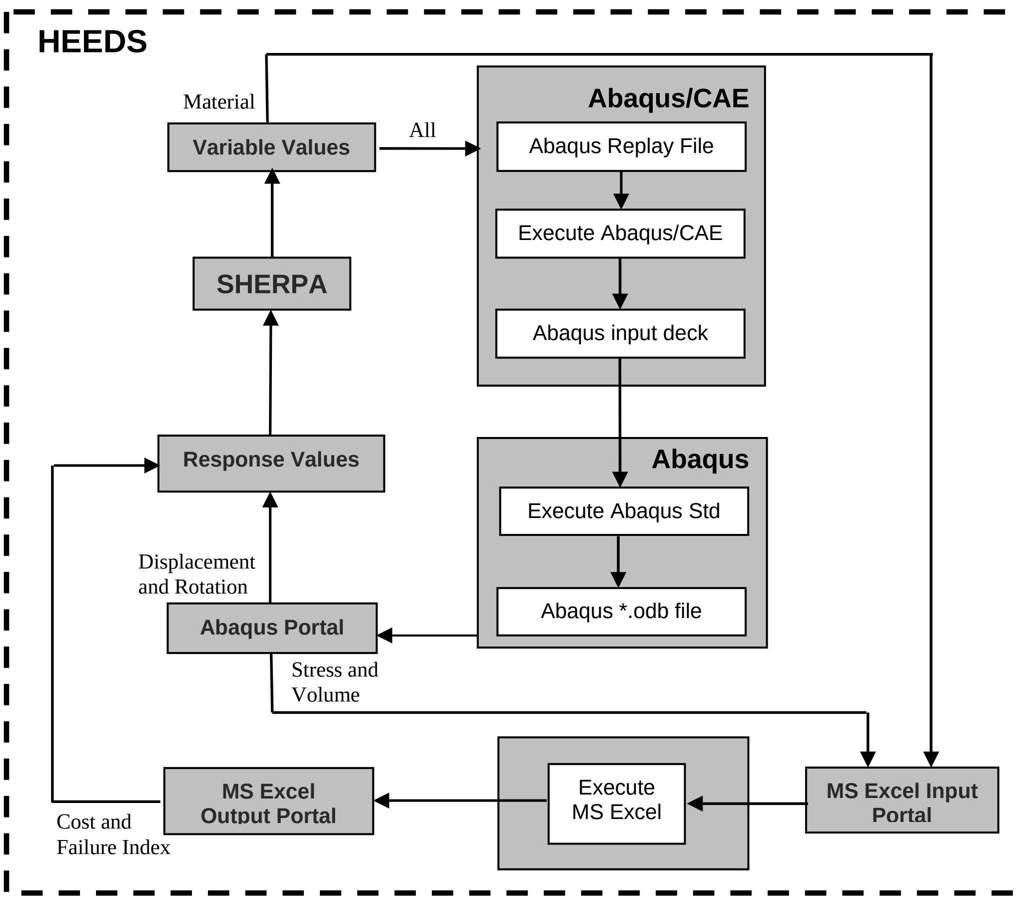

Figure 6. Process flow chart for optimization of the chair leg utilizing HEEDS with Abaqus and Excel.

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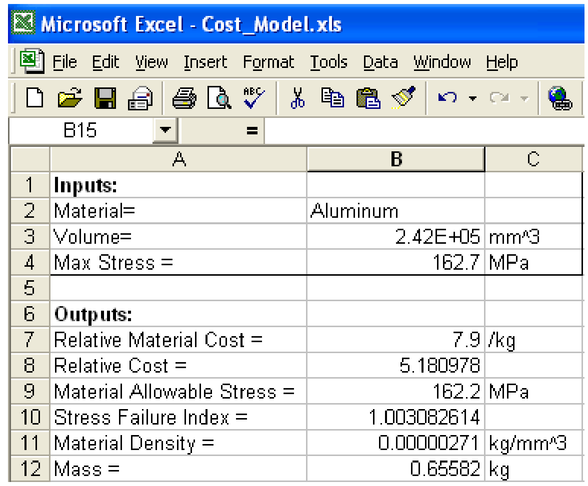
Optimized Design

HEEDS found a design that reduced the cost by 56% over the baseline design, while meeting all of the performance requirements. Though the baseline design was not considered to be a high-quality design, this result demonstrates, nonetheless, the ability of this approach to identify low cost designs that meet performance targets. The optimized design had the design characteristics of Table 3 and the cost model responses shown in Figure 7. Figure 8 shows the shape of the optimized design. In Figure 9, the properties of the optimized design are displayed in a parallel plot along with the results from other designs evaluated during the search. It should be noted that the height of the rib is at its minimum value, indicating that this rib is not needed in order to meet the performance criteria as defined here.

Table 3. Optimized design results from FEA with Abaqus.

Design Parameter	Value
Material	Aluminum
Rib Location (mm)	247.6
Rib Height (mm)	4.0
Rib Width (mm)	20.676
Floor Thickness (mm)	7.95
Front Wall Thickness (mm)	6.43
Back Wall Thickness (mm)	4.2
Response	**Value**
Volume (mm3)	2.42E5
Max Stress (MPa)	162.7
Max Displacement (mm)	4.57
Max Rotation (radians)	0.1



Microsoft Excel - Cost_Model.xls

	A	B	C
1	**Inputs:**		
2	Material=	Aluminum	
3	Volume=	2.42E+05	mm^3
4	Max Stress =	162.7	MPa
5			
6	**Outputs:**		
7	Relative Material Cost =	7.9	/kg
8	Relative Cost =	5.180978	
9	Material Allowable Stress =	162.2	MPa
10	Stress Failure Index =	1.003082614	
11	Material Density =	0.00000271	kg/mm^3
12	Mass =	0.65582	kg

Figure 7. Optimized design cost model.

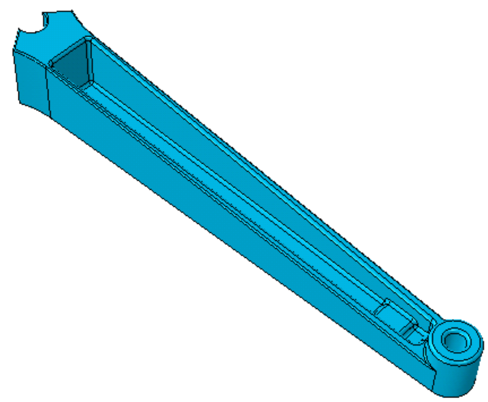


Figure 8. Optimized design shape.

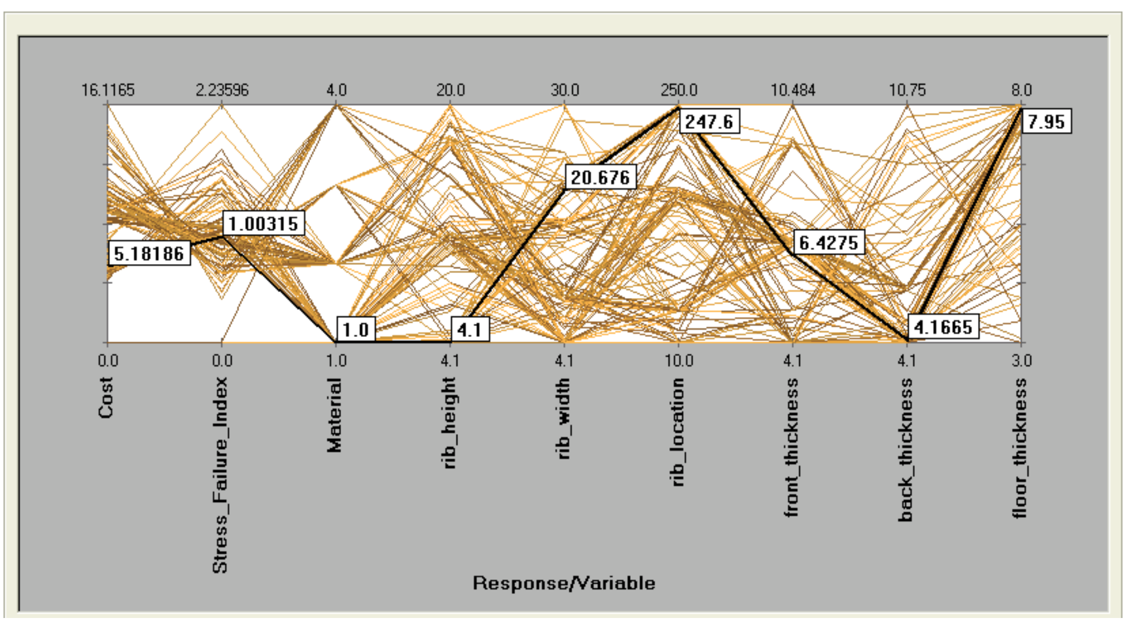


Figure 9. HEEDS parallel plot indicating the optimized design among all other designs evaluated during the search.

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