Structural Optimization of a Refrigerator Cabinet

Curtis R. Niemeier, P.E.

Whirlpool Corp., Evansville, IN

Abstract

An optimization study was performed on a refrigerator cabinet to minimize the material cost of the cabinet structure while maintaining the same structural performance.

A refrigerator cabinet is constructed primarily of sheet metal parts with a plastic liner and a foam core. All of the parts were created and meshed in Pro/ENGINEER. APDL was used to assemble and load the model, define cost functions for each design variable, and perform the optimization. Component thicknesses were defined as design variables.

The optimization resulted in nearly a $2 savings per product to be applied to approximately 1.2 million products per year.

Introduction

The refrigerator cabinet in this study is from a 25 cubic foot side by side refrigerator. It is a mature design having been in production for over twelve years. Many cost reductions have been implemented over the years but never had there been a comprehensive attempt to optimize the overall structure. Typically, cost reductions of the cabinet's structural components have been accomplished as follows. Several prototype cabinets are built implementing the proposed change (smaller bracket, thinner gage of some component, etc). These products are then stiffness tested and the results are compared to current production cabinets. If the change is small or not discernable then the change is approved. Obviously, this leads to only incremental cost improvements and provides very limited understanding of the overall structural behavior. There are other issues. These incremental changes may accumulate to cause significant structural degradation. There also tends to be significant cabinet to cabinet variation that may overwhelm the factor one is attempting to measure.

This study takes a more comprehensive approach and assumes that there exists an optimum combination of steel component thicknesses that will provide the same overall cabinet stiffness at a minimum cost.

The first step in performing the optimization study was to build a detailed finite element model of the entire cabinet assembly. The model was then correlated to test results.

Five design variables were considered in the optimization. These were the thicknesses of the most significant structural components. Two state variables were defined. These were the cabinet deflection under two different boundary conditions. The cabinet deflection was defined in terms of door misalignment. For a side by side cabinet, the doors become vertically misaligned with respect to each other as a cabinet racks and twists under load. Misalignment is a significant quality issue and is a primary driver of cabinet stiffness requirements. The state variables were defined such that the door misalignment could not exceed that of a nominal cabinet. The objective was to minimize the cost. For each design variable an equation was generated that defined the component cost as a function of thickness. The sum of these costs was defined as the objective variable.

An optimization was then performed using the subproblem approximation method. The optimization resulted in savings of approximately $2 per product or about a 10% reduction in the cost of the components under consideration.

Cabinet Description

Primary Structure

The primary structure is a sandwich of steel on the outer surface, a foam core, and plastic inner liners. The outer steel is comprised of a wrapper with roll-formed front and rear flanges, corner bracket reinforcements, a back panel, and a deck. The inner liners are made from thermoformed high impact polystyrene (HIPS) and form the freezer compartment and the refrigerator compartment. The inner and outer layers adhere to the polyurethane foam core.

Support Structure

The bottom support structure is made from six formed sheet metal parts: front rail, back rail, two s-channels, and glider rails (left and right). The cabinet sits on four rollers that are attached to the front and back rails.

Connections/ Assembly

The steel components are joined with a variety of fastening methods: welds, lance locks, toggle locks, screws, and foam adhesion. The deck subassembly consists of a deck rail and glider rails welded to a deck panel. The deck subassembly is welded to the back panel, then the wrapper is folded around these parts and welded to the back panel and lance locked to the glider rails. All of the above assembly is automated. The plastic liners are then manually inserted into the steel cabinet assembly to create the prefoam assembly. The cabinet is then fixtured and the expanding polyurethane foam is injected. The remaining structure (front rail, back rail, and s-channels) is added in subsequent operations. Figure 1 shows an exploded view of the structural components of a refrigerator cabinet.

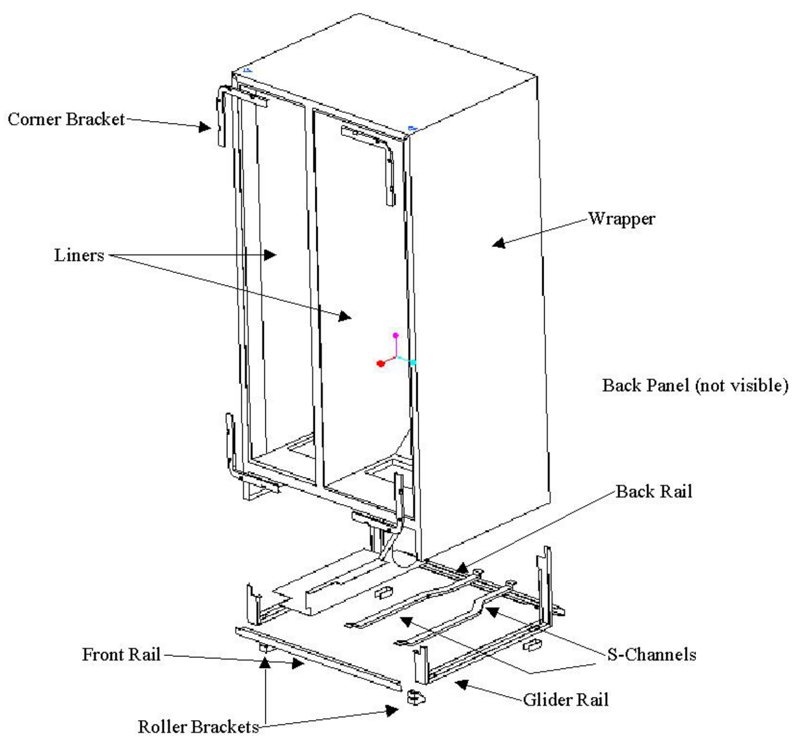

Figure 1 - Exploded View of Pro/Engineer Cabinet Model

The main function of the cabinet is to maintain the food in a sealed refrigerated compartment. In order to do this, the deflection must be small enough that the door seal is retained. There is also the aesthetic issue of door alignment. Heavily loaded doors and nonplanar floors are the primary causes of cabinet deflection/ door misalignment.

Model Description and Modeling Techniques

Model Description

The finite element model is comprised of a mixed mesh of solid elements, shells, and beams. The foam is meshed with tetrahedrons. The plastic liners and all sheet metal components are meshed with shells. The connections of welds, lance locks, toggle locks, and screws are all modeled with beams.

Geometry Creation

All of the model geometry was created in Pro/Engineer. The first step was to create a solid model part of the foam geometry. The formed sheet metal components that make up the support structure (glider rails, front rail, etc.) were each modeled as a separate part. The parts were then combined into a Pro/Engineer assembly. Beams were added to represent each individual weld, lance lock, etc. The freezer and refrigerator doors were modeled with stiff beams and used to apply loads to the model and provide geometry points to measure the door misalignment caused by the cabinet deformation.

Mesh Creation

The assembly was then meshed within Pro/Engineer using Pro/Mesh. The foam was meshed with tetrahedrons while all of the sheet metal components of the support structure were meshed with shells. The meshed model was then saved as a ".ans" file.

Detailed Model Definition

At this point the .ans file is just a crude representation of the cabinet. An extensive APDL input file was used to manipulate the .ans file and create final model. A plot of the completed finite element model is shown in Figure 2. Use of the input file also allowed the finite element model creation to be almost completely automated. The input file performed the following:

Material Property Definition

The tetrahedron foam model was "esurfed" with shell elements. The Pro/Engineer model was loaded with dummy boundary conditions (constraints, loads, and temperatures). The input file used these boundary conditions to select the appropriate shell elements and define the correct material properties to represent wrapper, back panel, deck, liners, mullion, front flange, and back flange.

Geometry Manipulation

In order for the Pro/Engineer assembly to mesh correctly the parts could not contact or interfere. This required the assembled geometry to have an "exploded" appearance. The input file selected each component, defined its material properties and real constants, and moved it into the correct location.

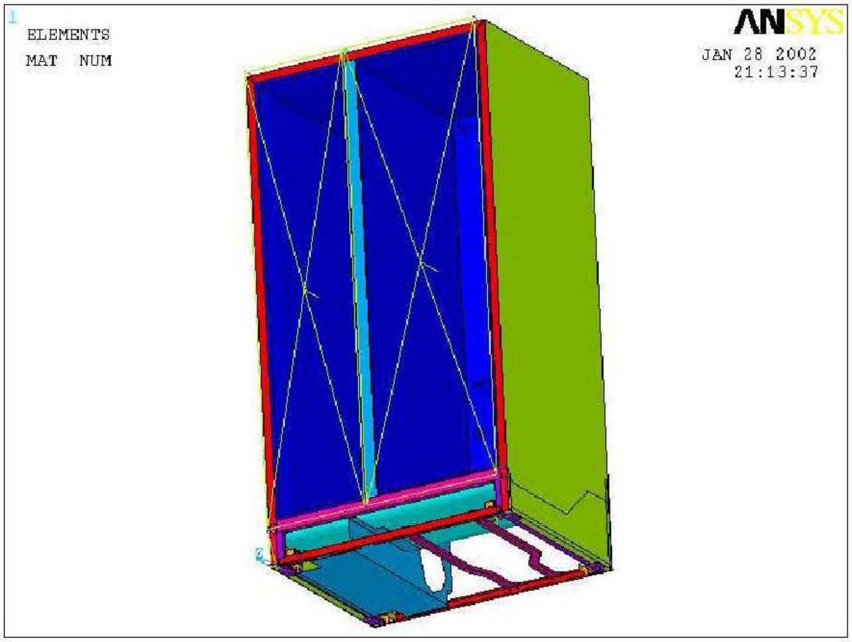

Figure 2 - Isometric View of Ansys FE Cabinet Model

Boundary Conditions

Under nominal conditions the cabinet sits on four rollers. There may also however be a situation where an uneven floor would cause the cabinet to sit on three rollers. Both conditions are considered. A large force representing fully loaded shelves is applied to the refrigerator door. This condition produces the largest cabinet deformation and corresponding door misalignment.

Model Correlation

There are many challenges in creating a model that accurately simulates the cabinet structure. The cabinet design is driven by the need to be assembled on a high-speed production line and to meet aesthetic requirements. Creating a structure with well-defined load paths for ease of analysis is certainly not a consideration. The construction methods of the cabinet require many modeling assumptions (Reference 1).

1. Foam Adhesion - Much of the cabinet is held together with foam adhesion. The foam is modeled as linear and isotropic. The foam is actually somewhat orthotropic (stiffer in the direction of flow) and may change stiffness dramatically if it cracks or loses adhesion.
2. Wrapper Front Flange - Simplifying assumptions were made in this area for the purpose of model size. Also, the liner flange slips inside the wrapper flange but it is assumed to be not connected and the load must be carried through the foam. See the wrapper front flange detail in Figure 3.

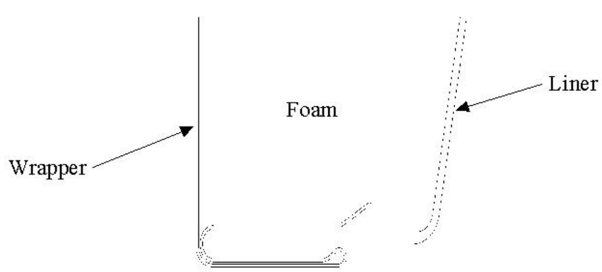

Figure 3 - Detail of Wrapper Front Flange and Liner Flange

3. Fasteners - All fasteners are modeled with beams. It is assumed that all connections maintain their integrity and do not gap or lose stiffness.

Correlating the model to test data is complicated by large cabinet to cabinet variation. This variation has many sources. The foam can crack, lose adhesion, have voids, and exhibit anisotropic behavior. Variation can be caused by different lots of material, different foam fixtures, varying ambient conditions at different times of the day or year, etc. Steel properties (stiffness, strength) can vary within a coil, from coil to coil, or between suppliers. Thickness variation will affect stiffness. Yield strength variation can affect the integrity of the lance locks and toggle locks.

Side by Side cabinets as well as several other styles of cabinets have been modeled over the last several years. These models have all been correlated to test data and thus some history has been developed to build confidence that these structures can be modeled effectively.

A special test was set up for the purpose of correlation to the side by side cabinet model. Cabinets were fixtured with dial indicators to monitor the deflection in the x, y, and z directions at all four of the top corners of the cabinet and to measure the door misalignment. The results correlate quite well as shown in Figure 4 and Figure 5. Figure 4 is a graph of door misalignment and displacements of the cabinet corners. Figure 5 compares displacement plots of the cabinet model to the measured displacements from the test.

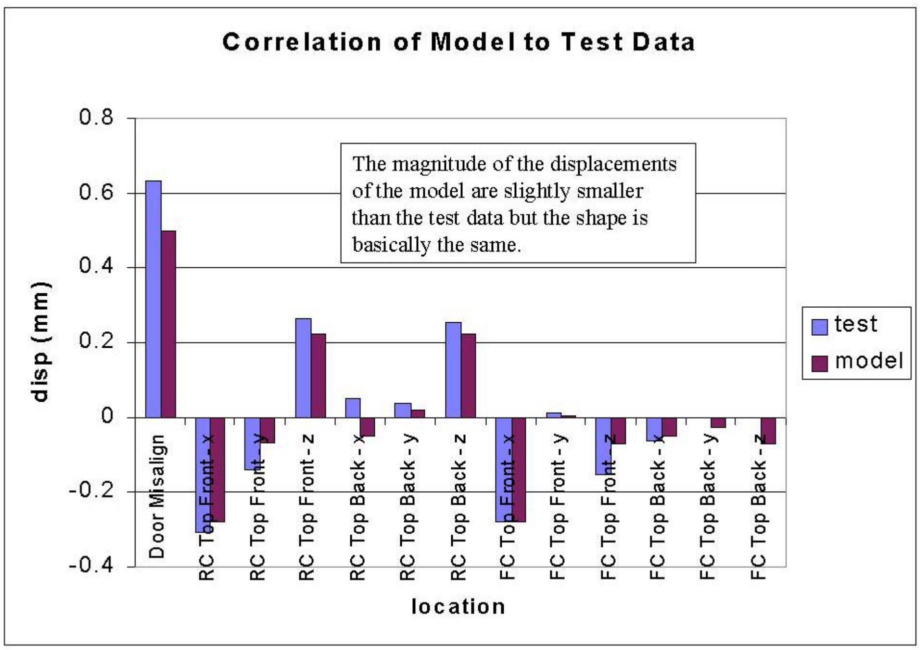

Figure 4 - Graph Showing Correlation of Model to Test

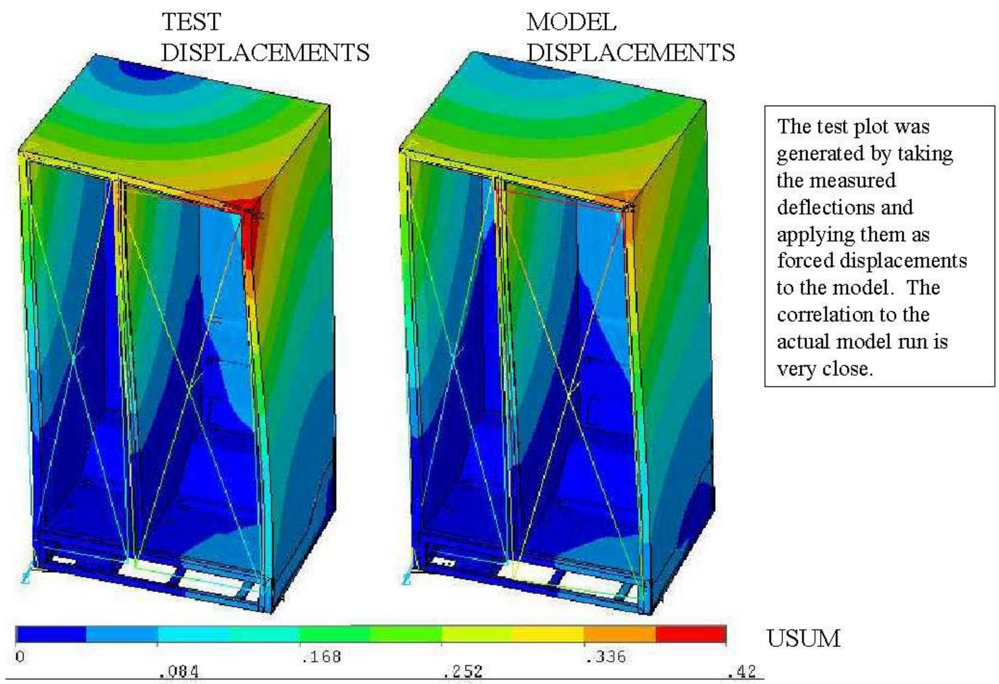

Figure 5 - Plot Showing Correlation of Model to Test

Optimization Description

Advantages of Optimization over Testing and DOE's

Optimization using a finite element model offers tremendous advantages over traditional testing and design of experiments methods (DOE's).

Traditional testing of physical prototypes where one factor is changed at a time leads to only limited understanding of structural behavior and only incremental improvements can be made. Additionally, large cabinet to cabinet variation may overwhelm the effect of the change being measured. Large sample sizes can help this situation but is costly and time consuming.

Use of DOE's can facilitate much greater understanding of the cabinet's structural behavior. One can gain understanding of important factors and interactions. Typically, standard DOE's are based on a linear fit of empirical data. This data however can also be plagued with noise requiring many cabinets to be built and tested. Again, this is expensive and time consuming. DOE's can be performed on the finite element model instead of physical cabinets. One can explore the design space and learn about important factors and interactions in an experiment that is free of noise and limited only by computation time. Additionally, a finite element model based on first principals provides greater insight into physics of the problem than just performing a linear fit through empirical data.

DOE's however are not the best tool for design optimization given that one can adequately simulate the behavior of the cabinet with a finite element model. The optimization tools available in ANSYS are much more powerful. It would be difficult if not impossible to cost optimize the refrigerator cabinet using a series of sequential DOE's.

The subproblem approximation method is more sophisticated in that it is based on a fully quadratic function and accounts for interactions by including cross terms. (See Equation 1) It also iterates automatically to an optimum solution by minimizing a penalized function. (Reference 2)

$$\hat{f} = a_0 + \sum_i^n a_i x_i + \sum_i^n \sum_j^n b_{ij} x_i x_j \qquad \text{(Eq. 1)}$$

Design Variables

Five design variables were considered in the optimization. These were the thicknesses of the most significant structural components. Their ranges are shown in Table 1. Manufacturing involvement was crucial in determining the design variable ranges. The upper and lower limits are based on manufacturing equipment capability and engineering judgement. The thinness of the wrapper is limited by the ability of the equipment to handle thinner stock and by quality concerns such as susceptibility to dents and demarcations. The back panel was limited to .015" because the material must be drawn. The glider rails, front and back rails, and s-channels were limited by their ability to survive shipping, impact, and handling loads.

The optimization was performed twice, with the wrapper lower limit at .019" and at .017". A .017" wrapper carries more manufacturing risk than a .019" wrapper however additional savings may warrant assuming more risk.

Design Variable	Name	Range	
Wrapper Thickness	wrapt	.019"	.022"
Back Panel Thickness	bkpant	.015"	.018"
Glider Rail Thickness	gldt	.043"	.096"
Rails (front, back, s-channels) Thickness	fbst	.043"	.096"
Corner Bracket Thickness	cbrktt	.022"	.096"

Table 1: Design Variables and Ranges

State Variables

Two state variables were defined. These were the cabinet deflection (door misalignment) under two different boundary conditions. Case 1 constrains the cabinet on all four rollers. With a level floor, relatively heavy cabinet load, and a small door load, the cabinet would sit on all four rollers. Case 2 constrains the cabinet on three rollers. A lightly loaded cabinet, heavily loaded door, and/or an uneven floor may produce this condition. The state variables were defined such that the door misalignment could not exceed that of a nominal cabinet for these two load cases. In other words, no degradation in cabinet stiffness was allowed.

Objective Function

The objective was to minimize the cost. For each design variable an equation was generated that defined the component cost as a function of thickness. Steel is paid for by weight. Therefore, the current price of a component was ratioed by the change in thickness to determine the new price. The wrapper is an exception since it is made from prepainted material and the paint is a fixed cost. Therefore only a percentage of the wrapper price was ratioed by the change in thickness. The sum of these costs was defined as the objective variable.

Optimization Results

The results showed approximately $2 in materials could be removed from the cabinet with no degradation in cabinet stiffness. This is a 10% reduction in the cost of the components under consideration. The current cost is $20.13. The optimization saved $2.07. If the wrapper is allowed to go to .017" instead of .019" then the savings grows to $2.41.

Figure 6 shows the current and optimized thickness of each component. (Refer to Table 1 for a description of component names.) Figure 7 illustrates the change in cost of each component. The savings is achieved by reducing the thickness of the wrapper, back panel, and the bottom rail system (fbst). The cabinet stiffness is regained by thickening the glider rails and corner brackets. Both the wrapper and the back panel bottom out against their lower limits. The rails are near the lower limit when the wrapper is at .019" but must be slightly thicker for a .017" wrapper. Figure 8 is a plot of the model illustrating the thickness and cost change of component.

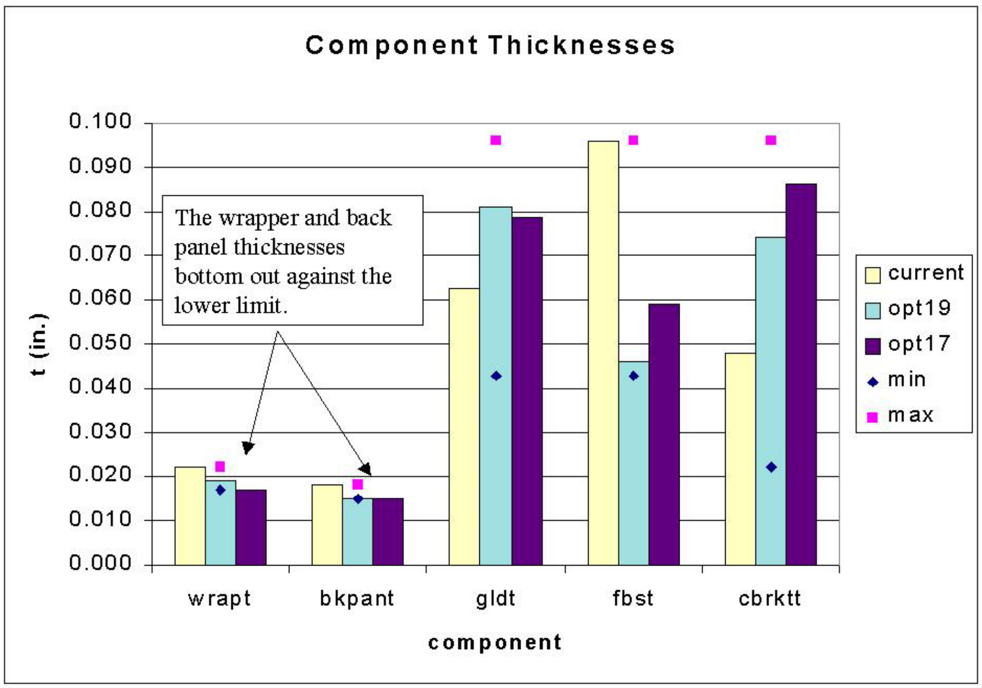

Figure 6 - Graph of Current and Optimized Thicknesses

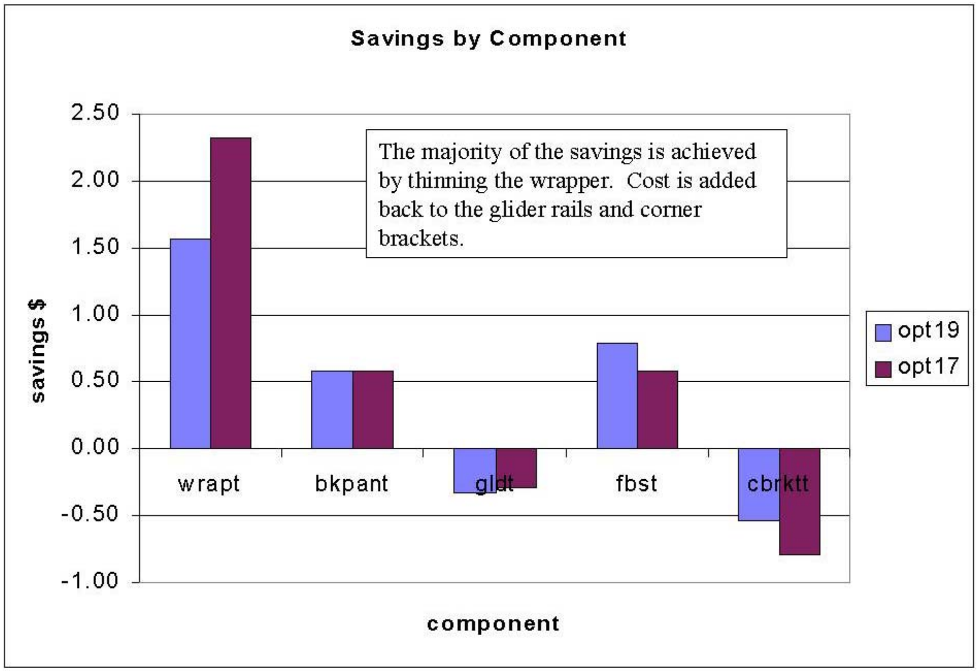

Figure 7 - Graph of Savings by Component

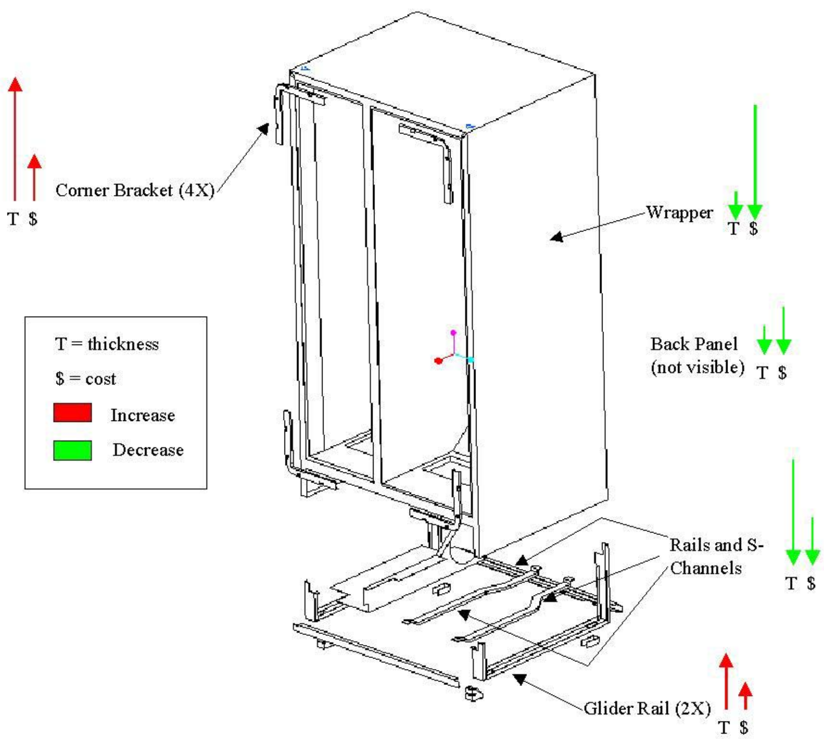

Figure 8 - Thickness and Cost Changes of Optimized Cabinet

Conclusions

This study shows that a complex structure such as a refrigerator cabinet can be adequately simulated with a finite element model and that this is a very valuable tool in understanding a cabinet's structural behavior.

Through the use of the optimization tool, significant cost reductions were achieved without diminishing product quality. The savings were $2 per product and could potentially be applied to approximately 1.2 million products per year. These types of savings are simply not possible using traditional testing methods.

The appliance industry is a difficult business with ever increasing price pressures and demands for quality. This environment demands increasingly sophisticated design and analysis methods.

References

1) K. J. Rasche, P.E., "Cost/Structural Optimization of a Complex and Composite Foamed Cabinet Structure", Proceedings of NAFEMS World Congress '99 on Effective Engineering Analysis, Volume 2, pp. 841-852, April 25-28, 1999, Newport, RI.
2) Ansys Theory Reference, Release 5.6, Subproblem Approximation Method, Ansys Inc., 1999