10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference
30 August - 1 September 2004, Albany, New York

AIAA 2004-4310

Design for Flexibility: Performance and Economic Optimization of Product Platform Components

Eun Suk Suh,* Il Yong Kim,† and Olivier de Weck‡
Massachusetts Institute of Technology, Cambridge, MA, 02139

and

David Chang§
GM Research and Development, Warren, MI, 48090

Embedding flexibility into physical products or manufacturing processes has been a research topic of great interest. Embedding such flexibility allows manufacturers to respond to changing market preferences or regulations with minimum increase in product complexity and investment cost. In this paper, a multidisciplinary optimization design process for embedding and evaluating flexibility in product components is introduced. The components are assumed to be part of an existing or planned product platform. The design process starts with generation of multiple design alternatives for embedding flexibility into product components. The generated flexible designs are then optimized for component performance maximization and cost minimization. The optimized designs are then evaluated for economic profitability using a Monte Carlo simulation. At the end, the most profitable flexible component design is selected. The proposed design process is demonstrated through a detailed case study, where flexible design alternatives for an automotive floor pan are generated and optimized.

Nomenclature

C	=	Total Variable Cost, $
CF	=	Cash Flow, $
D	=	Demand for the Product, units
F	=	Set of Economic Variables
J	=	Set of Performance Variables
K	=	Total Capital Investment Cost, $
NPV	=	Net Present Value, $
P	=	Price of the Component, $
R	=	Total Revenue, $
T	=	Planning Horizon, years
V	=	Individual Design Alternative
WB	=	Wheelbase
Y	=	Total Number of Flexible Design Alternatives
c	=	Unit Cost of the Component, $
c_a	=	Unit Assembly Cost of the Component, $
c_f	=	Unit Fabrication Cost of the Component, $
k_{at}	=	Capital Investment Cost (Assembly), $
k_{sa}	=	Auxiliary Stamping Equipment Cost, $
k_{st}	=	Capital Investment Cost (Stamping Tools), $

* PhD Candidate, Engineering Systems Division, MIT {essuh@mit.edu}, AIAA Student Member
† Postdoctoral Researcher, Department of Aeronautics & Astronautics, MIT {kiy@mit.edu}
‡ Assistant Professor, Engineering Systems Division, MIT, AIAA Member, {deweck@mit.edu}
§ Chief Scientist, Math Tools, GM Research and Development, {david.chang@gm.com}

m	=	Mass of the Floor Pan, kg
n	=	Total Number of Observed Past Time Period, years
q	=	Number of Component Variants
r	=	Discount Rate, %
s	=	Total Number of Spot Welds
t	=	Time
x	=	Set of Design Variables
α	=	Drift Coefficient
δ	=	Maximum Floor Pan Deflection, mm
ε	=	Random Number ~ $N(0,1)$
Δt	=	Finite Time Step, years
σ	=	Volatility Coefficient
τ	=	Torsion Stiffness, Nm/degree
V	=	Set of Flexible Design Alternatives

I. Introduction

IN the age of mass customization,[1] customers demand and expect more personalized products, creating a need for more product variation. However, increasing variety in the product family leads to increases in product complexity and development cost. In order to reduce the product complexity and the development cost while offering more product variants, many innovative product design and manufacturing strategies have been proposed and implemented.

A widely implemented strategy among various companies is the product platform strategy.[2] According to Meyer and Lehnerd, a *product platform* is "the set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched." A benefit of the product platform strategy is pointed out by Robertson and Ulrich, who stated "by sharing components and production processes across a platform of products, companies can develop differentiated products efficiently, increase the flexibility and responsiveness of their manufacturing processes, and take market share away from competitors that develop only one product at a time.[3]" In industry, the product platform concept has been implemented in many products including portable Walkman®,[4] power tools[2] and automobiles.[5] Active research for product platform design and optimization has been carried out during the last decade. Research topics include platform design process development,[6, 7] optimum platform component selection,[8, 9] and platform portfolio optimization and valuation,[10, 11] to name a few.

Even though the product platform strategy has many advantages, it also has some disadvantages. Increasing the degree of commonality in the product family can lead to loss of performance competitiveness. Also, sharing common components between high end products and low end products can lead to cannibalization,[12] where brands of the same manufacturer compete with each other, causing loss of sales for one brand. Finally, the platform strategy can deter the implementation of new technological innovations, since the investment cost and the switch-over cost to implement such technical innovations would be very large.

A good systematic solution to overcome such disadvantages is to embed flexibility into the product platform. The word *flexibility* is defined as "the ease of changing the system's requirements with a relatively small increase in complexity (and rework).[13]" By embedding flexibility into the product platform itself, the manufacturer can produce variants from the platform with sufficient distinctiveness, and implement new technological innovations to the platform with minimum investment in facilities, tooling, and labor training. The flexible platform can also respond to changing market preferences quickly and efficiently.

However, embedding flexibility in *all* platform elements (components, interfaces, processes, etc.) can be very costly and inefficient. It would be ideal to identify critical elements of the platform, ones that are highly sensitive to product performance attributes, and embed flexibility in those elements. Flexibility can be embedded into various levels of manufacturing from a single machine to the entire manufacturing plant.[14] Flexibility can also be embedded in physical components directly. Finally, the managerial flexibility to exercise "platform flexibility" can be analyzed using Real Options theory,[15] which is an extension of classic financial option theory developed by Black and Scholes.[16]

In this paper, a multidisciplinary design process for optimizing and evaluating flexibility built into a critical platform component is introduced. Previous research on multidisciplinary processes includes a publication by Georgiopoulos et. al.,[17] where a product portfolio is optimized to gain maximum economic benefit subject to performance and production capacity constraints. Subsequent sections outline the proposed design process for optimizing and evaluating multiple designs for embedding flexibility in a single component of the product platform. The design process is demonstrated through a detailed case study, where numerous flexible design alternatives for an automotive floor pan are structurally and economically optimized.

II. Design Process Overview

Figure 1 shows a general overview of the proposed design process for optimizing and evaluating flexible component designs.

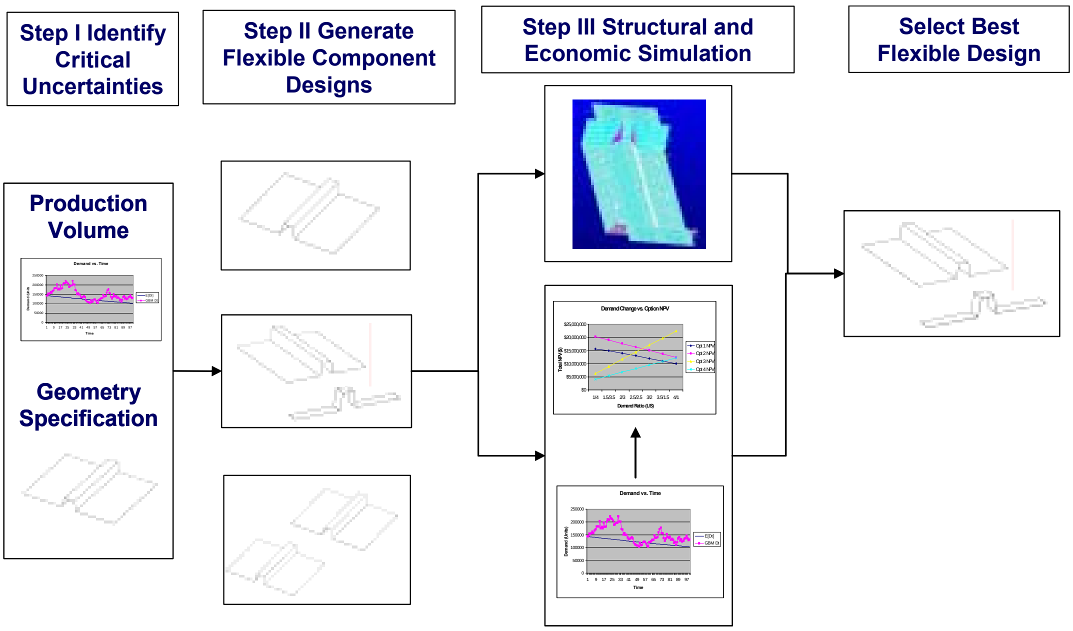

Figure 1: Proposed Optimization Design Process

First, critical uncertainties for a component must be identified. Second, various component design alternatives for incorporating flexibility are generated. The generated designs are then optimized to minimize development and manufacturing costs, while satisfying performance requirements. Optimized designs are evaluated in terms of long term economic gain by calculating the expected Net Present Value (NPV) over the lifetime of component production, accounting for future uncertainties. Monte Carlo simulation is used to evaluate the expected NPV over the total production lifetime. The mathematical problem statements for each design process step are stated below.

A. Define a set of flexible component design alternatives $\mathcal{V}$.

$$\mathcal{V} = \{V^1, V^2, \ldots V^Y\} \tag{1}$$

where

$$V^v = \left[\mathbf{J}^v, \mathbf{F}^v\right];\ v \in \mathcal{V} \tag{2}$$

$\mathbf{J}^v$ is a set of component's functional requirement values and $\mathbf{F}^v$ is a set of component economic metrics for a particular flexible design alternative. Functional requirements in $\mathbf{J}^v$ can be different depending on type of the component, but economic variables in $\mathbf{F}^v$ are mostly the same for all components types. The set $\mathbf{F}^v$ is defined as

$$\mathbf{F}^{v} = [c_i^{v}, K^{v}]; \;\; i \in q,\; v \in V \tag{3}$$

where c_i^v is the unit cost of the i^{th} component variant for q variants and K^v is the total investment cost for all variants in each design alternative.

B. Each design alternative in the flexible component design alternative set V is optimized for minimum production cost while the set of functional requirements $\mathbf{J}^v$ satisfies constraint requirements.

$$\begin{aligned} \min_{x^v} \quad & \{\mathbf{F}^v(\boldsymbol{x}^v)\};\; v \in V \\ \text{subject to} \quad & h^v(\boldsymbol{x}^v), g^v(\boldsymbol{x}^v) \end{aligned} \tag{4}$$

$\boldsymbol{x}^v$ is a set of design variables and $\boldsymbol{h}^v(\boldsymbol{x}^v), \boldsymbol{g}^v(\boldsymbol{x}^v)$ are equality and inequality constraints that $\mathbf{J}^v$ must satisfy.

C. Once all flexible design alternatives in V are optimized, they are economically evaluated to select the most profitable flexible component strategy over its lifetime.

$$\begin{aligned} \max_{V} \quad & NPV(V) \\ \text{subject to} \quad & r, D(\alpha, \sigma, t, \varepsilon) \end{aligned} \tag{5}$$

Through calculating the maximum expected net present value (NPV) achieved for optimized flexible design alternatives in V, one can identify the best flexible design, given the discount rate ($\boldsymbol{r}$) and the uncertainty in component demand $\boldsymbol{D}$, which is a function of the drift trend coefficient ($\boldsymbol{\alpha}$), volatility ($\boldsymbol{\sigma}$), time ($\boldsymbol{t}$) and the normally distributed random variable ($\boldsymbol{\varepsilon}$).

The proposed multidisciplinary optimization process is demonstrated through a detailed case study of a vehicle floor pan, an important vehicle platform component that requires dimensional flexibility to accommodate vehicles with different wheelbase configurations.

III. Automotive Floor Pan Case Study

A. Case Study Overview

A major automotive manufacturer is developing a new vehicle platform for multiple variants. Several critical vehicle platform decisions are made *a priori*. The proposed vehicle platform strategy is to share a common underbody structure, which consists of front and rear compartments and the floor pan. Wheelbase (***WB***) will be adjusted by embedding dimensional flexibility in the floor pan, a part of the vehicle platform. The floor pan is an important component which connects the front compartment and the rear compartment of the automotive underbody. Figure 2 shows a CAD representation of the vehicle underbody and the floor pan. In this case study, all floor pans are to be fabricated from steel, using tandem stamping press machines. The objective is to create the most profitable "flexible design" to achieve dimensional flexibility in vehicle length by embedding geometric flexibility in the floor pan.

Several flexible design alternatives are generated. The flexible designs are optimized structurally and economically to achieve the maximum expected net present value over the lifetime of the platform, while satisfying imposed structural criteria. The overall optimization process is shown in Fig. 3. As a part of vehicle platform decisions made *a priori*, width and height of the floor pan are fixed and cannot be changed. Using the floor pan shape, thickness, and number of spot welding connections ($\boldsymbol{s}$) as user controlled design variables, structural simulation is performed to yield the floor pan's mass ($\boldsymbol{m}$) and to verify that all structural criteria are met. Two values ($\boldsymbol{m}, \boldsymbol{s}$) are passed onto the cost model, where the unit cost of the floor pan ($\boldsymbol{c}$) and the total investment cost ($\boldsymbol{K}$) are calculated, given the expected future demand ($\boldsymbol{E}[\mathbf{D}_t]$). The total expected net present value (***NPV***) is calculated using $\boldsymbol{c}$ and $\boldsymbol{K}$, through simulation of future demand ($\boldsymbol{D}_t$) using Monte Carlo simulation. The optimization process continues until the NPV converges to the maximum value. Each flexible design alternative is optimized and the final NPV for each alternative will be compared, leading to the selection of a best "flexible design" alternative.

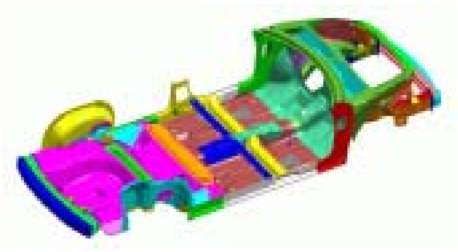

Figure 2: CAD Representation of a Vehicle Underbody and Floor Pan

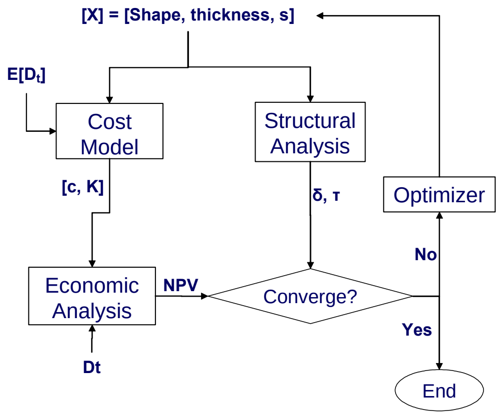

Figure 3: Single Flexible Component Optimization Process

B. Step I: Identify Critical Future Uncertainties

The first step is to identify critical future uncertainties. Possible uncertainties are component specification change (e.g. geometric dimensions), an emerging need for a new component variant, and variation of production quantities for available components. In this case study, future demands and the production volume ratio for two available floor pan sizes are identified as critical future uncertainties.

C. Step II: Generate Multiple Flexible Component Designs

The next step is to generate multiple flexible design alternatives for embedding dimensional flexibility into the floor pan. After considering architectural constraints and other design criteria, four flexible design alternatives are proposed (see Fig. 4).

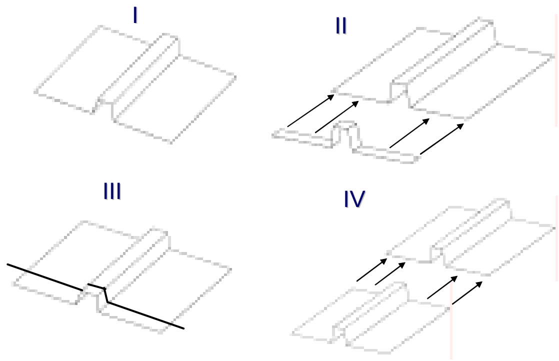

Figure 4: Proposed Flexible Floor Pan Design Alternatives

The first design is the customized design, where two entirely different floor pans are designed for short wheelbase vehicles and long wheelbase vehicles. Short and long floor pans are fabricated using separate stamping dies and tools, requiring separate investment costs for different floor pan sizes. No flexibility is embedded into the floor pan.

For the second design, the main floor pan is designed to fit the short wheelbase vehicles. To accommodate long wheelbase vehicles, a small extension piece (shown) is spot welded to the original floor pan. This design allows addition of different wheelbase vehicles through development of different extension pieces with dimensional restriction $\boldsymbol{WB} \geq \boldsymbol{WB_{min}}$, where $\boldsymbol{WB_{min}}$ is the minimum wheelbase achievable by this design, which is dictated by the length of the original floor pan. Separate stamping dies are required for the original floor pan and the extension piece. Moreover, additional investment cost is required for spot welding facilities.

The third design incorporates flexibility in the floor pan in a different way. The main floor pan is designed for long wheelbase vehicles. To use the floor pan for short wheelbase vehicles, the end of the original floor pan is simply trimmed to meet the short wheelbase specification. This design requires a stamping die and tools for the fabrication of the long floor pan, plus additional investment and labor for trimming to manufacture the short floor pan. Because of additional tools, labor, and time required, the cost of the short floor pan is higher than the larger floor pan. Also, if designed properly, the floor pan can be used for vehicles with various wheelbase dimensions, with constraint that $\boldsymbol{WB \leq WB_{max}}$, where $\boldsymbol{WB_{max}}$ is the maximum wheelbase achievable by this design, dictated by the length of the original floor pan.

For the fourth and the final design alternative, two pieces of equal length are designed as sub components of the floor pan. Depending on the specified length of the floor pan, two sub components are placed in a fixture that is set to the desired floor pan length, and spot welded together. This design offers variability for the floor pan length dimension within a finite bandwidth. This is the design with the highest degree of flexibility. Overall, four different flexible design alternatives are presented, each with their own advantages and disadvantages. In the next section, structural optimization procedures for the four proposed designs are presented.

D. Step III-A: Structural Simulation

Once multiple flexible designs are generated, each design alternative should be optimized in terms of structural topology, shape and welding configuration to reduce component complexity and cost, while satisfying structural criteria. Minimizing complexity of the floor pan reduces the initial investment cost for stamping dies. Minimizing spot welding reduces the variable cost of the floor pan. Such optimizations can be accomplished by constructing and optimizing parametric finite element models of the proposed design.

While various flexible floor pan designs are optimized for shape, welding configuration, unit cost and total investment cost, basic performance (in this case, structural) constraints must also be satisfied. The mathematical formulation of the optimization problem is stated below, with design criteria referenced from other publications.[18, 19]

$$
\begin{aligned}
\min_{x_i^v} \quad & \{m_i^v\};\ i \in q,\ v \in V \\
\text{with respect to} \quad & \{\text{shape, thickness, } s_i^v\};\ i \in q,\ v \in V \\
\text{subject to} \quad & \delta_{\min} \leq \delta_i^v \leq \delta_{\max} \\
& \tau_{\min} \leq \tau_i^v \leq \tau_{\max} \\
& width = constant
\end{aligned}
\tag{6}
$$

By optimizing the shape of the floor pan, its thickness and the number of spot welding connections, an optimum floor pan shape that minimizes mass and spot welding connections is found, while satisfying the structural criteria. Using ANSYS® FEM analysis software, a simplified finite element model of vehicle underbody (shown in Fig. 5) is created. The finite element model is linked to the MATLAB® optimizer program. Using design variables and constraints declared in Eq. (6), the floor pan configuration with minimum mass for each design alternative can be found.

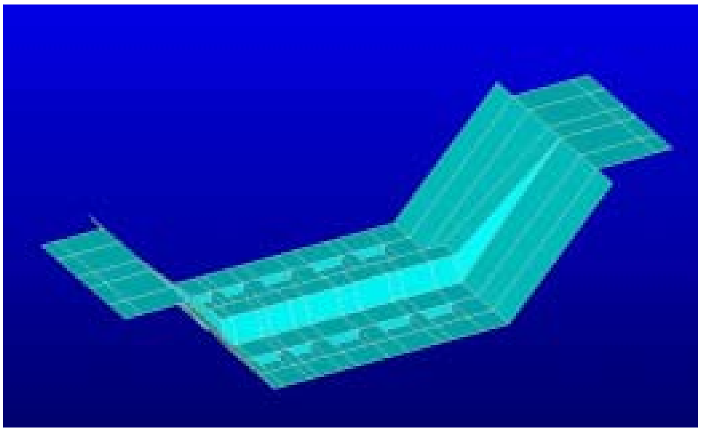

Figure 5: Finite Element Model of Vehicle Underbody

For each design alternative, the optimum shape of the floor pan was found using the MATLAB® optimizer linked with ANSYS® FEM analysis software. Table I lists, for each design alternative, the optimized mass of the small and large floor pan and the number of spot welding connections required.

Design Alternatives	Design I		Design II		Design III		Design IV	
Floor Pan Sizes	**Small**	**Large**	**Small**	**Large**	**Small**	**Large**	**Small**	**Large**
Mass (kg)	17.01	18.22	16.65	18.21	16.64	18.21	18.21	18.21
Welding Spot(s)	0	0	0	10	0	0	4	6

Table I. Optimized Mass of Floor Pan for Each Design Alternative

While the floor pan is optimized for minimum mass, the same set of design variables is used to maximize the expected net present value through economic optimization. The next section describes the process for creating and implementing the economic model to calculate the future expected net present value.

E. Step III-B: Economic Optimization

Economic analysis of different floor pan design alternatives during the lifetime of the platform is critical for estimating the overall benefit realized from the flexibility embedded in each design. A particular design alternative can be implemented throughout the life of the platform, or the manufacturer may decide to switch to another design alternative if it is advantageous to do so. The analysis becomes complicated when future uncertainties exist. In this study, it is assumed that if a flexible design is chosen at the beginning, the design will be implemented throughout the life of the platform. The following assumptions are made for the economic analysis.

- The investment cost consists of stamping die cost, stamping tool cost, assembly station cost and assembly tool cost. The equipment cost (e.g. stamping presses) is not included in the investment cost.

- Stamping dies are refurbished every four years. Cost of refurbishing is assumed to be 25% of a new stamping die cost, with no engineering design changes.

- The total life cycle of the vehicle platform is set to 12 years. This assumes that there will be three generations of vehicle variants with four years of production life cycle each.

- Threshold costs of small and large floor pans are decided by the management using top-down cost decomposition approach. The objective is to choose the flexible design alternative with most cost savings with respect to the threshold cost, given future uncertainty in demand.

- Geometric Brownian Motion (GBM) is used to model uncertain future demand.

The most popular method for evaluating future financial benefit is the Net Present Value (NPV) analysis. NPV is the total present value of future cash flow over a fixed time period for an investment. In this study, the total expected (average) NPV for each design is calculated, given uncertainties in future demand. NPV can be obtained using Eq. (7).

$$NPV = \sum_{i=0}^{T} \frac{CF_i}{(1+r)^i} \tag{7}$$

where $\boldsymbol{T}$ is the number of time periods and $\boldsymbol{CF_i}$ is the cash flow at time period $\boldsymbol{i}$. The discount rate $\boldsymbol{r}$ captures the time value of money, comprised of the risk free interest rate plus a risk premium. Discount rates typically used in industry are approximately 15 ~ 20% per year.[20] In this case study, an annual discount rate of 6% (risk free interest rate) is used, since the risk premium is captured by the Monte Carlo simulation.

Period cash flow is the total sum of cash inflow and outflow during time period $\boldsymbol{i}$. The equation for calculating the cash flow at time period $\boldsymbol{i}$ is

$$CF_i = R_i - C_i - K_i^v;\ v \in V \tag{8}$$

where $\boldsymbol{R_i}$ is the total revenue, $\boldsymbol{C_i}$ is the total variable cost and K_i^v is the total capital investment at time period $\boldsymbol{i}$ when the flexible design alternative $\boldsymbol{v}$ is implemented.. The total revenue $\boldsymbol{R_i}$ can be obtained by

$$R_i = \sum_{j=1}^{q}\left[P_j D_j\right] \tag{9}$$

where q is the number of different component variants, which in this case study, is the number of different floor pan variants. P_j is the management-set threshold cost (=internal price) of the j^{th} component variant, and D_j is the demand of j^{th} component variant. The total variable cost C_i for the time period i is

$$C_i = \sum_{j=1}^{q}\left[c_j^v D_j\right];\ v \in V \tag{10}$$

where c_j^v is the unit cost of j^{th} component variant when the flexible design alternative v is implemented at time i. The component variant unit cost c_j^v is

$$c_j^v = c_{f,j}^v + c_{a,j}^v \tag{11}$$

$c_{f,j}^v$ is the fabrication cost of the j^{th} variant and $c_{a,j}^v$ is the assembly cost of the j^{th} variant when the flexible design alternative v is implemented. In this case study, the assembly cost is only applicable for the floor pan if any subcomponents need to be welded together. The fabrication cost and the assembly cost for the specific floor pan are calculated using a proprietary cost model. Finally, K_i^v, the total capital investment cost at time period i, is

$$K_i^v = \sum_{j=1}^{q}\left[k_{st,j}^v + k_{sa,j}^v + k_{at,j}^v\right];\ v \in V \tag{12}$$

where $k_{st,j}^v$ is the stamping tool investment cost, $k_{sa,j}^v$ is the auxiliary stamping equipment investment cost, and $k_{at,j}^v$ is the assembly tool investment for the j^{th} component when the flexible design alternative v is implemented. Manufacturing costs for each design alternative are calculated. We are primarily interested in a relative cost saving comparisons between proposed design alternatives.

Figure 6 shows expected cost savings in terms of NPV for each design alternative when a constant production ratio of long and short floor pans is maintained throughout the life of the production. The total annual production volume remained constant at 400,000 units, and the ratio between long and short floor pans was changed from 0:4 to 4:0, with an assumption that the annual production is constant with no production volume volatility. It is interesting to see that depending on the production volume ratio, the total NPV for each design alternative varies.

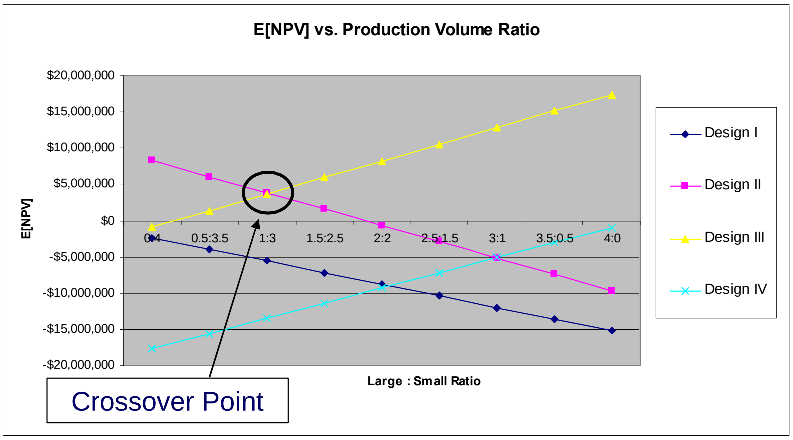

Figure 6: E[NPV] vs. Different Production Volume Ratio (Deterministic)

Two designs of interest are II and III. Depending on the production volume ratio, there is a clear advantage to favor one design over the other. For a ratio below 1:3 (three times more small than large cars are made), it might be more beneficial to choose design II, while in most cases design III is clearly the winning design. This is very useful information for making the final design choice when the general demand trend is known. If future demands for floor pan variants are constant, this would be a very simple analysis, but unfortunately, it is not the case. Since future demands are uncertain, a demand forecast model needs to be constructed.

Annual demand for different floor pans varies from year to year with increasing uncertainty as the future forecast horizon increases. One convenient way to simulate the uncertain future demand over a finite time period is to use Geometric Brownian Motion (GBM) model. Demand at time ***t+1*** can be modeled using GBM [21] by

$$D_{t+1} = D_t e^{[(\alpha - \frac{\sigma^2}{2})\Delta t + \sigma\varepsilon\sqrt{\Delta t}]} \tag{13}$$

where $\boldsymbol{D_t}$ is the demand at time $\boldsymbol{t}$, $\boldsymbol{\alpha}$ is the drift coefficient, $\boldsymbol{\sigma}$ is the volatility coefficient, $\boldsymbol{\Delta t}$ is the unit change in time (a year for this case study), and $\boldsymbol{\varepsilon}$ is a normally distributed random number with zero mean and variance of one. Additionally, $\boldsymbol{E[D_t]}$, the expected demand at time $\boldsymbol{t}$, can be obtained as:

$$E[D_t] = D_o e^{(\alpha t)} \tag{14}$$

$\boldsymbol{D_o}$ is the initial demand. The drift coefficient ($\boldsymbol{\alpha}$) and the volatility coefficient ($\boldsymbol{\sigma}$) are obtained from historical demand data for a particular product. The following equations are used to calculate $\boldsymbol{\alpha}$ and $\boldsymbol{\sigma}$.

$$(\alpha - \frac{1}{2}\sigma^2) = \frac{\sum_{t=1}^{n}(\ln D_{h,t} - \ln D_{h,t-1})}{n} \tag{15}$$

$$\sigma = \text{stdev}\left[\ln\left(D_{h,t}\right) - \ln(D_{h,t-1})\right]_{t=1}^{t=T} \tag{16}$$

$\boldsymbol{n}$ is the total number of time periods observed and $\boldsymbol{D_{h,t}}$ is the historical demand at time $\boldsymbol{t}$. Figure 7 shows an example plot of the expected future demand and one possible outcome of the actual demand.

Table II lists expected annual demands of large and small floor pans with required parameters for future demand forecasting. To determine the best flexible design, mean NPVs for all design alternatives are estimated through Monte Carlo simulation. Since the future demand for different floor pans are uncertain, it is necessary to calculate the mean NPV using the Monte Carlo simulation. It was assumed that there is no switching to another design alternative, and no additional investment cost will be added, other than pre-planned investments at each investment point (years 0, 4 and 8 – stamping die refurbishing cost and assembly investment cost). Results of analyses and discussion are presented in the next section.

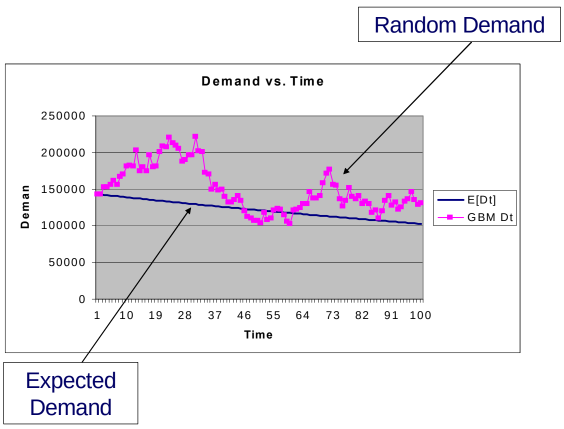

Figure 7: An Example of Future Demand Expressed as Geometric Brownian Motion

Floor Pan Specification	Large	Small
D_o (Annual Demand)	100,000	300,000
α (Trend Coefficient)	-5.52 %	2.09 %
σ (Volatility Coefficient)	13.27 %	7.35 %

Table II. Demand Forecast Parameters for Large and Small Floor Pan

IV. Results and Discussion

A. Results

Using data in Table II, Monte Carlo simulation is performed, each simulation running 25,000 times. Figure 8 show results from the simulation for each design alternative.

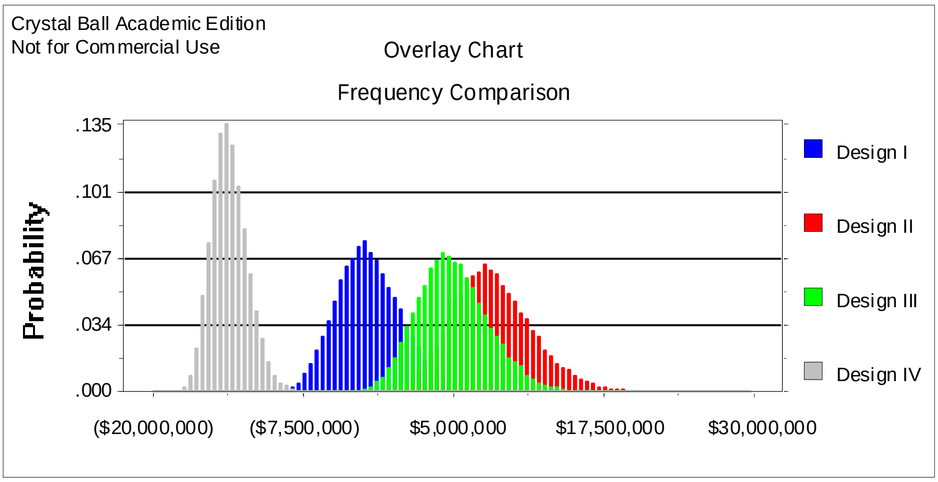

Figure 8: Distribution of NPVs for Proposed Flexible Design Alternatives

B. Discussions

The result from the Monte Carlo simulation indicates that design II is the most profitable flexible design. This is the result of a production volume ratio shift over time, which fell to the region where the design alternative III is no longer favorable (see Fig. 6). The initial expected production ratio was 1:3 (Large:Small), which is very close to the crossover point where the benefit from design alternatives II and III are approximately equal. The negative demand shift for large floor pans and positive demand shift for small floor pans drove the production volume ratio to the left of the crossover point for design II and III, making design alternative II the best choice. It can be stated that, to correctly estimate the net benefit of embedded flexibility over its lifetime, the expected trend of the production volume ratio over the platform lifetime is just as important as the current production volume ratio, which is just a static picture of the current state.

Another interesting result is that the inflexible design I performed better than the flexible design alternative IV. It may be argued that there is an "excessive" amount of flexibility built into design IV for the assumed uncertainty. Results may be different if the floor pan length itself were treated as an uncertain variable. In other words, if an uncertain demand for non-standard floor pan size arises, the flexibility built in the design alternative IV will be more valuable.

How can these flexible designs be utilized to yield maximum benefit? One possible solution is to switch between different designs at each decision point to achieve greater economic benefit. At each decision point, the decision maker can switch to another design, depending on future demand projections and floor pan specification changes. However, one must consider the cost/benefit tradeoff of switching to a new design vs. staying with current design. The following condition must be met in order to justify the switch – additional benefit from the switch has to exceed the additional cost arising from the switch (e.g. new stamping die cost, assembling tool cost) minus the cost for staying with the current design (e.g. stamping die refurbishing cost).

Finally, the proposed design process can be further developed to embed flexibility into a multi-component system, for example, an entire automotive platform. By properly identifying and embedding flexibility into a subset of system elements, the system itself can achieve a greater degree of flexibility to adapt to changing market needs and regulation changes with a minimum increase in investment and system complexity.

V. Conclusions

In this study, a multidisciplinary optimization design process for embedding flexibility in a product platform component is introduced. Embedding flexibility allows manufacturers to respond to changing market needs while minimizing the increase in cost and complexity. Once important component criteria and future uncertainties are identified, several flexible design alternatives are generated. Each design is optimized for cost while meeting functional requirement criteria, and then evaluated economically, accounting for future uncertainties. The design process is demonstrated through a detailed case study, where four flexible design alternatives for a vehicle floor pan are optimized and evaluated for the lifetime economic benefit under uncertain demand.

Results revealed that current production volume ratios as well as future production volume trends are important considerations for embedding flexibility in the component. It was also observed that "excessive" flexibility resulted in poor economic performance, giving way to the question "What is the optimum degree of flexibility?" Enhancement of the design process using a design switch strategy and further implementation of the process to a multi-component system are mentioned as promising future research topics.

References

[1]Pine, B. J., *Mass Customization: The New Frontier in Business Competition*, Harvard Business School Press, Boston, MA, 1993.

[2]Meyer, M. H., and Lehnerd, A. P., *The Power of Product Platforms: Building Value and Cost Leadership*, The Free Press, New York, NY, 1997

[3]Robertson, D., and Ulrich, K., "Planning Product Platforms," *Sloan Management Review*, Vol. 39, No. 4, 1998, pp. 19-31.

[4]Sanderson, S. W., and Uzumeri, M., *Managing Product Families*, Irwin, Chicago, IL, 1997

[5]Bremmer, R., "Cutting Edge Platforms," *Financial Times Automotive World*, September 1999, pp. 30-38.

[6]Simpson, T. W., Maier, J. R. A., and Mistree, F., "Product Platform Design: Method and Application," *Research in Engineering Design*, Vol. 13, No. 1, 2001, pp. 2-22.

[7]Fellini, R., Kokkolaras, M., Michelena, N., Papalambros, P., Saitou, K., Perez-Duarte, A., and Fenyes, P. A., "A Sensitivity-Based Commonality Strategy for Family Products of Mild Variation, with Application to Automotive Body Structures," *Proceedings of the 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, September 4-6, Atlanta, GA, 2002, AIAA2002-5610.

[8]Nelson, S. A., II, Parkinson, M. B., and Papalambros, P. Y., "Multicriteria Optimization in Product Platform Design," *ASME Journal of Mechanical Design*, Vol. 123, No. 2, 2001, pp. 199-204.

[9]Martin, M. V., and Ishii, K., "Design for Variety: Developing Standardized and Modularized Product Platform Architectures," *Research in Engineering Design*, Vol. 13, No. 4, 2002, pp. 213-235.

[10]de Weck, O., Suh, E. S., and Chang, D., **"**Product Family and Platform Portfolio Optimization,**"** *ASME Design Engineering Technical Conference*, September 2-6, Chicago, IL, 2003, DETC2003/DAC-48721.

[11]Kidd, S. L., "A Systematic Method for Valuing a Product Platform Strategy," Masters Thesis, Leaders for Manufacturing, MIT, Cambridge, MA, 1998.

[12]Cook, H. E., *Product Management: Value, Quality, Cost, Price, Profit and Organization*, Chapman & Hall, New York, NY, 1997, pp. 73.

[13]ESD Symposium Committee, "Engineering Systems Research and Practice," *ESD Internal Symposium*, MIT, Cambridge, MA, May 29-30, 2002.

[14]Sethi, A. K., and Sethi, S. P., “Flexibility in Manufacturing: A Survey,” *The International Journal of Flexible Manufacturing Systems*, Vol. 2, 1990, pp. 289-328.

[15]Trigeorgis, L., *Real Options: Managerial Flexibility and Strategy in Resource Allocation*, MIT Press, Cambridge, MA, 1996.

[16]Black, F. and Scholes, M., “The Pricing of Option and Corporate Liabilities,” *Journal of Political Economy*, Vol. 81, 1973, pp. 637-654.

[17]Georgiopoulos, P., Fellini, R., Sasena, M., and Papalambros, P. Y., “Optimal Design Decisions in Product Portfolio Valuation,” *ASME Design Engineering Technical Conference*, September 29 - October 2, Montreal, Canada, 2002, DETC2002/DAC-34097.

[18]Fenton, J., *Handbook of Automotive Body Construction and Design Analysis*, Professional Engineering Publishing Limited, London, UK, 1998.

[19]”The New Audi A8: A New Sporting Dimension in the Luxury Segment,” *Audiworld.com*, September 8, 2002.

[20]de Neufville, *Applied Systems Analysis: Engineering Planning and Technology Management*, McGraw-Hill Publishing Company, New York, NY, 1990, pp. 230.

[21]Guimarães Dias, M. A., “Overview of Real Options in Petroleum,” *Real Options in Real Life Seminar*, MIT/Sloan School of Management, Cambridge, MA, May 2, 2002.