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OPTIMAL DESIGN DECISIONS IN PRODUCT PORTFOLIO VALUATION

Panayotis Georgiopoulos*
panayio@umich.edu

Program in Manufacturing
University of Michigan
Ann Arbor, Michigan 48109

Ryan Fellini†, Michael Sasena†, Panos Y. Papalambros‡
{rfellini,msasena,pyp}@umich.edu

Department of Mechanical Engineering
University of Michigan
Ann Arbor, Michigan 48109

ABSTRACT

Product portfolio valuation is a core business milestone in a firm's product development process: Determine what will be the final value to the firm derived from allocating assets into an appropriate product mix. Optimal engineering design typically deals with determining the best product based on technological (and, occasionally, cost) requirements. Linking technological with business decisions allows the firm to follow a product valuation process that directly considers not only what assets to invest but also what are the appropriate physical properties of these assets. Thus, optimal designs are determined within a business context that maximizes the firm's value. The article demonstrates how this integration can be accomplished analytically using a simple example in automotive product development.

NOMENCLATURE

C units of capacity currently installed
CAFE corporate average fuel economy
$\mathbb{E}$ expected value
fe fuel economy
$\mathbf{g}(\mathbf{x})$ engineering constraint set
i vehicle index
K capital investment
L vehicle's segment CAFE limit
M vehicle's profit margin
NPV net present value
P vehicle's price
PV present value of future cash flows
PC premium compact vehicle
r_a weighted average cost of capital
SUV sport utility vehicle
t_{0-60} 0 to 60 acceleration time
T end of life-cycle
$\mathbf{w}$ product portfolio weights
$\mathbf{x}$ engineering design variables
x_0 engineering performance attribute baseline point
x_C engineering performance attribute critical point
x_I engineering performance attribute ideal point
X product demand
Y firm's market share
α speed of reversion
Δt monthly period
μ expected growth rate of product demand
v customer perceived value
σ volatility of product demand

INTRODUCTION

This article addresses modeling and solution of resource allocation decisions in product development. In operations re-

*D.Eng. Candidate
†Ph.D. Candidate
‡Professor

search and investment science the resource allocation decision-making process is defined as the process of determining the percentage of assets to invest in different products. We broaden this definition by adding the simultaneous determination of the physical properties of the products corresponding to these assets. Such properties are considered within the domain of engineering design decisions. Although it is well understood that financial and engineering decisions are interdependent in product development, quantification of this relationship is a major challenge, in part due to the different cultures and modeling approaches prevailing within the financial planning and engineering communities. Using a simple but effective financial model and an engineering performance simulation model we show how some of these differences can be bridged, leading to improved product portfolio decisions.

Engineering considerations in investment science are mainly associated with cost. The term technical uncertainty is used to describe the physical difficulty of completing a project (Dixit and Pindyck, 1994). Similarly, technological uncertainty relates to the uncertain outcome of R&D research. Depending on the assessment of technical uncertainty, cost estimates are assumed to be either fixed capital investments (Onno and Pennings, 1998; McDonald and Siegel, 1986) or stochastic elements in the investment problem (Pindyck, 1991). Hazelrigg (1998) proposed an approach that links product design properties to the firm's objectives using utility theory. Researchers from the engineering design community have demonstrated (Marston and Mistree, 1998; Gu et al., 2000), enhanced (Li and Azarm, 2000; 2001), and modified (Wassenaar and Chen, 2001) Hazelrigg's initial ideas.

In the present work we formulate an "enterprize-wide" decision problem for the firm, with the net present value resulting from the decisions as the objective function. This objective depends on both asset allocation variables and product design variables, thus linking product design properties with the firm's business goals. Constraints are imposed from the business perspective of costs and expected sales, and from the technical perspective of product performance. The analysis models used to compute the outcomes of those decisions are computationally intensive simulations based on both investment and engineering science.

The specific decision problem explored here is a simple product portfolio valuation: Given a production capacity and cost structure, historical data on sales, and two possible products that can be built in the existing production facility, what percent of production capacity should be allocated to each product and what should be the design specifications for these products? The interesting new element here is that asset allocation and asset properties determination are treated in a concurrent fashion. The product valuation process is a core decision-making process within a firm. Yet, engineering information produced from time-consuming and capital-intensive technical studies tends to have a largely passive role in the planning department of the firm. Occasionally, depending on the business cycle and the mood of the management, we may see the other extreme, where product performance considerations drive portfolio decisions too strongly. In either case the quality of the enterprize decisions suffers. A balanced, concurrent decision process is desirable.

To approach this challenge quantitatively one must maintain credibility within both communities, a quest that can be presumably achieved by using modeling practices acceptable and accessible to both the financial and the engineering communities. In this spirit the design methodology proposed here is based on the standard capital budgeting practice. The goal is to aid the decision-maker in understanding (at least some of) the trade-offs between the engineering and the business aspects of a design decision. In the standard finance literature (see Brealey and Myers, 2000) an investment opportunity should be consistent with the criterion of maximizing the market value of the firm's stock, hence enable the firm's stock owners to maximize their wealth and, subsequently, their utility of consumption over time (Trigeorgis, 1998). This is a different approach of valuing investment opportunities from the expected utility maximization, which has had limited acceptance in capital budgeting practice (Carr et al., 2001).

In the following sections we present the general formulation of product valuation as an optimal design problem, and then proceed to show how this model can be built in a particular portfolio problem involving two automotive products that must operate under government regulations and associated penalties for violation. Computational results are included that show the quantitative interdependence of investment and engineering decisions. A great number of simplifying assumptions are made to make the study relatively simple. These assumptions are noted as the models are developed. The general approach will hold if assumptions can be relaxed but computation will become more demanding.

OPTIMAL DESIGN AND PRODUCT VALUATION

A typical engineering design problem is posed as

$$\begin{aligned} \text{maximize} \quad & \textit{(engineering performance)} \\ \text{with respect to} \quad & \textit{(design variables)} \\ \text{subject to} \quad & \textit{(engineering constraints)} \end{aligned} \tag{1}$$

the implication being that all the relevant decisions are engineering ones. The typical investment decision model is

$$\begin{aligned} \text{maximize} \quad & \textit{(expected net present value)} \\ \text{with respect to} \quad & \textit{(what to produce,} \\ & \textit{production quantity,} \\ & \textit{production location)} \\ \text{subject to} \quad & \textit{(uncertainty, investment cost,} \\ & \textit{cost of capital, decision time,} \\ & \textit{capacity constraints),} \end{aligned} \tag{2}$$

where the relevant investment decisions relate to revenues and expenditures. The engineering decision model is assumed usually to be deterministic; even though this can be a questionable assumption, in most situations the costs of dealing with uncertainty are so high that they overshadow the need for a more robust solution. On the contrary, the investment model is really meaningful only under uncertainty, and so in order to pose Eq. (2) the sources of uncertainty must be defined analytically to the extent possible. The time horizon for the investment opportunity must be also defined.

To link revenues and expenditures associated with asset allocation with the engineering performance of those assets, the two problems above are combined in an enterprize-wide decision model

$$\begin{aligned} \text{maximize } & \textit{(expected net present value)} \\ \text{with respect to } & \textit{(investment variables,} \\ & \textit{engineering variables)} \\ \text{subject to } & \textit{(investment constraints,} \\ & \textit{engineering constraints).} \end{aligned} \tag{3}$$

This problem represents one product strategy and is solved with an appropriate optimization method. The model can be resolved for alternative product strategies, and comparisons can be made. The term "appropriate" is used above because the nature of the optimization problem may require some judicious choices; for example, use of surrogate models instead of full simulations or use of global methods instead of gradient-based ones. This is not a central point here, but one needs to keep in mind that the resulting problem postulated in the general terms of Eq. (3) may present its own solution challenges, in addition to its formulation challenges.

There is an underlying argument in the approach presented here: The sense that there are no design and non-design decisions when considering a product. All product decisions are design decisions; they can be partitioned into engineering and business ones and treated with the relevant mathematical models.

In the next section we will present the specific implementation of the general approach above to a simple product portfolio decision.

PRODUCT PORTFOLIO VALUATION MODEL

We consider decisions to be made by an automotive manufacturing firm that markets premium-compact (PC) and full-size sport utility (SUV) vehicles. This market segmentation adopted in the study follows the J.D. Power classification for vehicles in the United States. The firm is assumed to operate in a mature industry where complementary assets (Teece, 1986), such as access to distribution channels, service networks, etc., are given. It is further assumed that the firm's output decision does not affect the product's price. Finally, the decision-maker is assumed to be playing a game against nature, namely, strategy is affected by an exogenously-generated random state not by competitive interaction.

The firm wishes to design new engines and transmissions for both PC and SUV segments. The PC and SUV segments are low and high profit margin segments, respectively. There are C units of monthly capacity currently in place for each product (engine and transmission), and so C is fixed representing a capacity constraint. It is assumed that this capacity is not expandable. The decision-maker faces the following decisions: How should the units of capacity be allocated between the two segments in order to maximize the firm's value? What should the performance specifications for engines and transmissions be and how do these specifications affect the resource allocation decision? Figure (1) presents an overview of the decisions that the firm is facing.

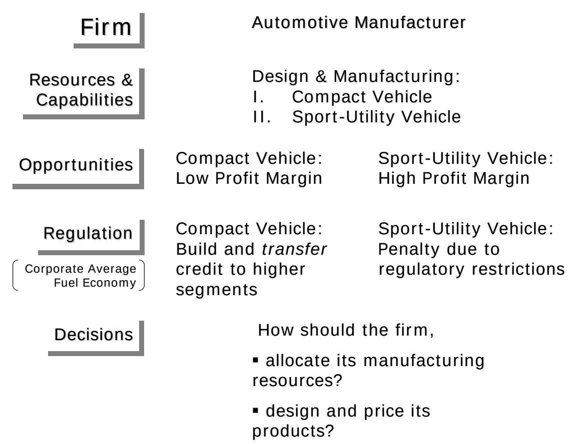

Figure 1. Decisions modeled

Enterprize-wide decision model

Consistent with capital budgeting practice we assume that the firm under consideration evaluates investment opportunities with a single dominant objective: Maximize the market value of the firm's stock. This implies investments with positive net present value (NPV) defined as

$$NPV = \mathbb{E}[PV] - K, \tag{4}$$

where $\mathbb{E}[PV]$ is the expected present value of future cash flows and K is a constant representing the capital investment needed to develop all designs. Other investment costs are ignored; for example, the cost of building the production facility plant is considered a sunk cost because we assume the plant has already been built.

The enterprize-wide decision model is then formulated as follows.

$$\begin{aligned} \text{maximize} \quad & NPV \\ \text{with respect to} \quad & \{\mathbf{w},\mathbf{x}\} \\ \text{subject to} \quad & w_i \cdot C \le \mathbb{E}[\text{Sales}_i], \quad i=\{1,2\} \\ & \textstyle\sum_{i=1}^{2} \text{Cost}_{\text{CAFE}_\text{i}} \le 0 \\ & \textstyle\sum_{i=1}^{2} w_i = 1 \\ & \mathbf{g}(\mathbf{x})_{\text{PC}} \le 0 \\ & \mathbf{g}(\mathbf{x})_{\text{SUV}} \le 0. \end{aligned} \tag{5}$$

This statement is a special case of the model in Eq. (3), where $\mathbf{w}$ is the vector of investment variables, $\mathbf{x}$ is the vector of engineering variables, the first two inequalities and the equality are the investment constraints, and the last two vector inequalities are the engineering constraints. Definitions of the symbols used are given in the nomenclature. In the following subsections we will explain in detail the variables, objective and constraint definitions used in this model.

Definition of the decision vector

The decisions for each vehicle segment are engine size, final drive ratio, and monthly production capacity. Engine size and final drive ratio represent the vector of engineering design variables $\mathbf{x}$. As the engine size and final drive ratio are increased, vehicle acceleration increases and fuel economy decrease. The final drive ratio essentially scales the vehicle's gearbox. As noted above, the firm's fixed monthly production capacity of engines and transmissions must be allocated between the two segments so that

$$\sum_{i=1}^{2} \frac{\text{Production}_i}{\text{Capacity}} = 1. \tag{6}$$

Using the "weighting" vector $\mathbf{w} = \{w_i : i = 1,2$ for PC, SUV, respectively$\}$ we define the portfolio decisions as the portion of the total monthly capacity to be allocated to each segment, and so

$$w_{PC} + w_{SUV} = 1. \tag{7}$$

This equation is included as an investment constraint in the model of Eq. (5). In summary, the vector of decision variables is

$$\begin{bmatrix} x_{PC1} \\ x_{PC2} \\ w_{PC} \\ x_{SUV1} \\ x_{SUV2} \\ w_{SUV} \end{bmatrix} = \begin{bmatrix} \text{engine size of PC} \\ \text{final drive ratio of PC} \\ \text{capacity allocated to PC} \\ \text{engine size of SUV} \\ \text{final drive ratio of SUV} \\ \text{capacity allocated to SUV} \end{bmatrix}, \tag{8}$$

which includes engineering and investment variables.

Estimation of future sales

Calculation of expected sales is a challenging task. We assume that future cash flows generated by a vehicle's future sales are only imperfectly predictable from current observation. The probability distribution is determined by the present, but the actual path remains uncertain (Dixit, 1992). We consider product demand and the firm's market share as the two main sources of uncertainty.

To describe future product demand we assume that the automotive product demand X is a Brownian motion, following Eq. (9). Seasonality (Tseng and Barz, 1999) and life-cycle considerations (Bollen, 1999) can be also taken into account but are not included in the current calculation.

$$\begin{aligned} \Delta X_t &= \mu X_t \Delta t + \sigma X_t \Delta z \\ \Delta z &= \varepsilon\sqrt{\Delta t} \\ \varepsilon &\sim N(0,1) \end{aligned} \tag{9}$$

Here $\mu\Delta t$ and $\sigma\sqrt{\Delta t}$ are the expected value and the standard deviation, respectively, of $\frac{\Delta X_t}{X_t}$ in Δt. We divided the life of the source of uncertainty into 73 monthly intervals from January 1995 until January 2001. Data provided by J.D. Power & Associates for this period have been employed for the estimation of the expected growth rate μ and volatility σ. The value of X at time Δt (i.e., February 2001) is calculated from the initial value of X (i.e., January 2001), the value at time $2\Delta t$ is calculated from the value at time Δt, and so on (Hull 2000). One simulation trial involves constructing a complete path for X using 84 random samples from a normal distribution. The 84 points represent, in months, two years of product development and production start-up time, and five years of product sales.

The mean-reverting process will be used to model market share uncertainty Y (Dixit and Pindyck, 1994)

$$\begin{aligned} \Delta Y_t &= \alpha(\overline{Y_t} - Y_t)\Delta t + \sigma' \Delta z \\ \Delta z &= \varepsilon\sqrt{\Delta t} \\ \varepsilon &\sim N(0,1). \end{aligned} \tag{10}$$

Here α is the speed of reversion, $\overline{Y}$ is the "normal" level of Y, i.e., the level to which $\overline{Y}$ tends to revert. By running the nonlinear regression

$$\Delta Y = p + qY_{t-1} + \varepsilon_t, \qquad (11)$$

from data provided for the stated period (January 1995 to January 2001) we estimate

$$\begin{aligned} \overline{Y} &= \hat{p}/\hat{q}, \\ \hat{\alpha} &= -log(1+\hat{q}), \\ \hat{\sigma}' &= \hat{\sigma}'_{\varepsilon}\sqrt{\frac{log(1+\hat{q})}{(1+\hat{q})^2-1}}, \end{aligned} \qquad (12)$$

where $\hat{\sigma}'_{\varepsilon}$ is the standard error of the regression, and $\hat{p}$, $\hat{q}$ are the estimated regression coefficients of Eq. (11).

Sales are expressed as a product of the two sources of uncertainty defined above, namely, product demand and market share:

$$\text{Sales}_i = \begin{cases} 0 & \text{the first two years} \\ X_i \cdot Y_i & \text{otherwise.} \end{cases} \qquad (13)$$

Sales_i is a 1×84 vector and represents a random walk in the future (see Fig. 2). During the first 24 months of product development and production start-up time we have null sales.

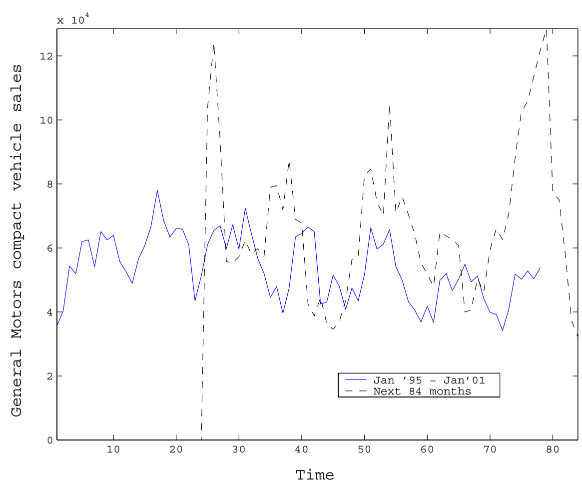

Figure 2. A random walk in the future

Present value model

The profit Π_i in the next eighty four months for each segment i is expressed as follows

$$\Pi_i = (\text{Price}_i \times \text{Profit Margin}_i \times \text{Sales}_i) - \text{Cost}_{\text{CAFE}_i}. \qquad (14)$$

We assume that the profit margin M represents the variable cost structure. The profit margin is set at 1% and 35% for the PC and SUV segments, respectively. The product of price and profit margin is the firm's profit per unit. The $\text{Cost}_{\text{CAFE}_i}$ included here is regulatory penalty for failing to meet the Corporate Average Fuel Economy (CAFE) standard. Each term of Eq. (14) will be discussed in the subsections immediately below. As noted, Π_i is a 1×84 vector and represents a random walk of future profits. During the first 24 months we have null profits.

The decision to develop the new engines and transmissions has been taken a priori. The decision that the firm is facing now is one of resource allocation. Upon determining the optimal production ratio, the decision will be implemented immediately. Hence, no embedded real option exists in the decision (Trigeorgis, 1998). The product development, production start-up, and sales period T for both products is estimated to be seven years or eighty four months. The PV is the expected present value of discounted future payoffs Π_i. It is formally represented as an integral over the space of sample paths of the underlying stochastic processes X and Y

$$PV = \int_0^T \left(\sum_{i=1}^{2} \Pi_i\right) e^{-r_a t}\, dt, \qquad (15)$$

where r_a is the weighted average cost of capital, as estimated by the Capital Asset Pricing Model (CAPM), see, e.g., Brealey and Myers (2000). The CAPM is based on the assumption that decisions are being made from risk-averse investors. Using the CAPM we estimated the weighted average cost of capital of a publicly traded US automotive manufacturer to be 9.39%.

To estimate the expected PV we generated ten thousand random walks that is, a 10000×84 matrix. Discounting all the future payoffs Π_i across the probability space, we get a 10000×1 matrix. The expected present value will be the average of those 10000 numbers (see also Fig 3)

$$\mathbb{E}[PV] = \mathbb{E}\left[\int_0^T \left(\sum_{i=1}^{2} \Pi_i\right) e^{-r_a t}\, dt\right]. \qquad (16)$$

Subtracting the capital investment needed ($3B) we calculate the NPV in Eq. (4). We now turn our attention to the evaluation of each term of Eq. (14).

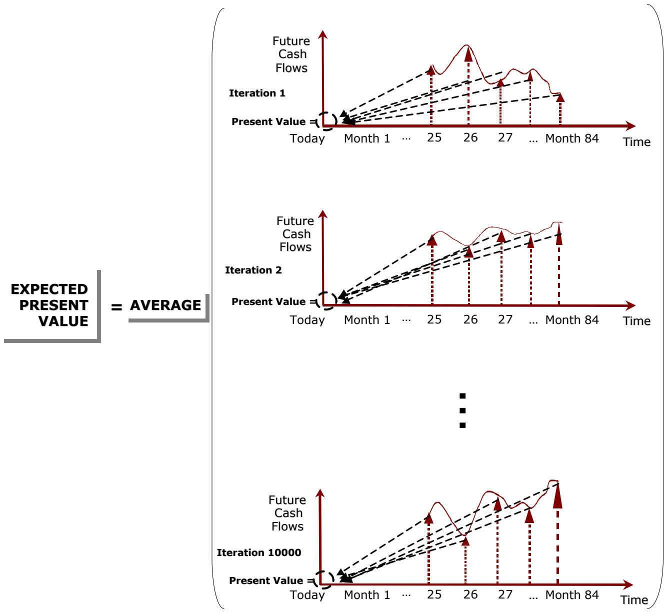

Figure 3. Expected present value

Vehicle pricing

We link engineering performance with the left side of Eq. (14) by assuming that the price of the product can be expressed as a functional relationship of the vehicle attributes aggregated, i.e., customer-perceived, value. Detailed modeling of this relationship is beyond the scope of the present work. We will proceed assuming that the only vehicle attribute that influences the customer's purchasing decision is vehicle acceleration.

To assess the customer-perceived value of vehicle acceleration the value curve method for attribute value assessment is used. This method is based upon the premise that the value of a performance attribute can be represented by continuous value curves if the performance is itself continuous (Donndelinger and Cook, 1997). Each performance attribute x is assumed to have three specification points (see Fig. 4), the ideal point x_I where value for the attribute is at its highest level, the baseline point x_0 where value is nominal (that is 1), and the critical point x_C where the product becomes valueless independent of the level of other attributes. A heuristic expression can be used to approximate the interpolating value between the critical and ideal point (Cook, 1997):

$$\begin{aligned} v(y) &= \left[\frac{(y_C-y_I)^2-(y-y_I)^2}{(y_C-y_I)^2-(y_0-y_I)^2}\right]^{\gamma} \\ y &= \log(x), \end{aligned} \tag{17}$$

where γ should be approximately equal to the time that the attribute x is important to the customer. McConville and Cook (1996) validated the above expression for the value of t_{0-60} for a midsize vehicle customer.

Here we assume this value curve method holds for t_{0-60} for both vehicles. The parameter values for Eq. (17) are given in Table 1.

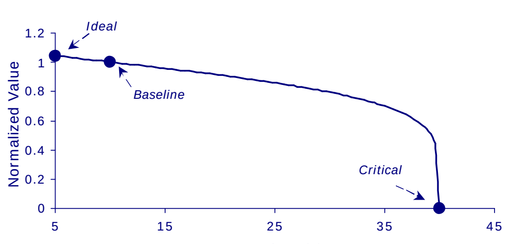

Figure 4. Parabolic approximation for acceleration performance (Cook, 1997)

Table 1. Parameters values in Eq. (17)

Parameter	PC	SUV
γ	0.17	0.17
x_0	10.16 (s)	8.24 (s)
x_I	2 (s)	2 (s)
x_C	40 (s)	40 (s)

We assume that the vehicle price is proportional to the t_{0-60} value. This means that if a design achieves 1.1 value the firm will price the vehicle 10% higher:

$$\text{Price} = (\text{Base Price}) \times (\text{Attribute Value}), \tag{18}$$

where base price for the PC and SUV segments is the listed invoice price for the Chevrolet Cavalier ($14,034) and Tahoe ($28,428) vehicles, respectively. Finally, we assume that the prices of both products will remain unchanged throughout the sales period.

At this point, we recall that the focus of the present work is the link between engineering and financial analysis. The development of customer valence models is critical to the success of our approach and without them it would be difficult to demonstrate any trade-offs. Further development and validation of the proposed design methodology will help define the desired nature of customer valence models and quantify further their role in the decision model.

CAFE cost evaluation

The design variables **x** are engineering decisions associated with physical properties of the products. They also represent business decisions; for example, the size of the engine determines the fuel economy ratings of each segment. These ratings are used in the CAFE evaluation, the environmental legislation that has had a profound influence on the decision making of US manufacturers.

The Energy Policy and Conservation Act of 1975 required passenger car and light truck manufacturers to meet CAFE standards applied on a fleet-wide basis. The fuel economy ratings for a manufacturer's entire line of passenger cars must average at least 27.5 miles per gallon (mpg). For light trucks (including vans and sport utility vehicles) the 1993 CAFE standard was 20.3 mpg. Failure to comply with the limit, L_i, results in a civil penalty of $5 for each 0.1 mpg the manufacturer's fleet falls below the standard, multiplied by the number of vehicles it produces. For example, if a manufacturer produces 2 million cars in a particular model year, and its CAFE falls 0.5 mpg below the standard, it would be liable for a civil penalty of $50 million.

Hence, the fuel economy of each vehicle — which is an outcome of the firm's design decisions — affects the firm's wealth. Specifically, for each vehicle i, the penalty (or credit) due to CAFE is

$$\text{Cost}_{\text{CAFE}_i} = \left[5 \times \frac{L_i - fe_i}{0.1}\right] \times w_i \cdot C, \tag{19}$$

where $w_i \cdot C$ is the production level for product i. Note that the CAFE regulations can only hurt the firm's profits, not contribute to them. For demonstration purposes, we will focus solely on this business aspect of the firm's design decisions.

Monthly profit model summary

Inserting all of the above expressions for revenue and cost into Eq. (14) we get

$$\begin{aligned} \Pi_i &= \text{P}_i \cdot \text{M}_i \cdot \min\{w_i \cdot C,\ X_i \cdot Y_i\} \\ &\quad - \left[5 \tfrac{L_i - fe_i}{0.1}\right] \min\{w_i \cdot C,\ X_i \cdot Y_i\}. \end{aligned} \tag{20}$$

The term $\min\{w_i \cdot C,\ X_i \cdot Y_i\}$ implies the following

$$\text{Sales}_i = \begin{cases} w_i \cdot C \text{ if demand equals or exceeds capacity} \\ X_i \cdot Y_i \text{ otherwise.} \end{cases} \tag{21}$$

That is, if the actual demand exceeds the capacity of the plant the firm can sell only at capacity. If the actual demand is less then the capacity of the plant then the firm can sell only as much as the demand permits. Again, the assumption is that the firm does not possess a flexible plant where it can adjust the capacity. If that were not the case then a different theory of capital budgeting would have been needed to model the resource allocation decision. Eq. (20) will be used in the integrant of the present value calculation of Eq. (16).

Engineering constraints

Bounds on vehicle performance attributes define the constraint set for each segment. The constraints are expressed in terms of the design variables using computer-aided engineering simulation models. The particular model used here is the Advanced Vehicle Simulator (ADVISOR) program (Wipke and Cuddy, 1996), a powertrain simulation tool. From the ADVISOR model library, the automatic transmission versions of the Chevrolet Cavalier LS Sedan and the rear-wheel drive Tahoe are selected as representative of the PC and SUV products considered here.

For each segment the engineering constraint set is

$$\begin{aligned} &\text{fuel economy} \geq b_1 \\ &t_{0-60} \leq b_2 \\ &t_{0-80} \leq b_3 \\ &t_{40-60} \leq b_4 \\ &\text{5-sec distance} \geq b_5 \\ &\text{max acceleration} \geq b_6 \\ &\text{max speed} \geq b_7 \\ &\text{max grade at 55mph} \geq b_8 \end{aligned} \tag{22}$$

where the b's are upper or lower bound parameters. The constraint bounds are set at values that are 20% beyond the current vehicle nominal performance values to allow for new design possibilities. The parameter values used for computation are shown in the summary model Eq. (5) further below.

Investment constraints

The production for each vehicle shall not exceed the total amount that the firm can expect to sell:

$$\text{Production}_i \leq \mathbb{E}[\text{Sales}_i]. \tag{23}$$

To estimate $\mathbb{E}[\text{Sales}_i]$ first we average across the probability space, which is represented by the 10000×84 $\mathbf{X}_i \cdot \mathbf{Y}_i$ matrix. This results in a 1×84 $\mathbf{X}_i \cdot \mathbf{Y}_i$ vector. The average across time would be $\mathbb{E}[\text{Sales}_i]$. For this example, we calculated $\mathbb{E}[\text{Sales}_{PC}]$ and $\mathbb{E}[\text{Sales}_{SUV}]$ to be 59,000 and 57,300 vehicles per month, respectively.

Designs that result in civil penalties will damage the firm's corporate image. Revenues will be affected indirectly by intangible losses. Hence, the CAFE penalty should be non-positive:

$$\sum_{i=1}^{2} \text{Cost}_{\text{CAFE}_i} \leq 0 \tag{24}$$

Equations (23) and (24) are the two inequality constraints on the investment decisions.

Summary of the enterprise model

The model in Eq. (5) involves six variables (four design, two portfolio variables) and nineteen constraints (three from the investment model, and eight each for the PC and SUV segments of the engineering design model). The complete model of Eq. (5) is now assembled using the expressions derived in the preceding sections.

$$\begin{aligned}
\text{maximize} \quad & \mathbb{E}\left[\int_0^T \left(\textstyle\sum_{i=1}^{2} \Pi_i\right) e^{-r_a t}\, dt\right] - \$3\text{B}. \\
\text{with respect to} \quad & \{\mathbf{w}, \mathbf{x}\} \\
\text{subject to} \quad & w_{PC} \cdot C \leq 59000 \\
& w_{SUV} \cdot C \leq 57300 \\
& \textstyle\sum_{i=1}^{2} \text{Cost}_{\text{CAFE}_\text{i}} \leq 0 \\
& \textstyle\sum_{i=1}^{2} w_i = 1 \\
& (\text{final drive})_{PC} \geq 2.5 \\
& (\text{final drive})_{PC} \leq 4.5 \\
& (\text{final drive})_{SUV} \geq 2.5 \\
& (\text{final drive})_{SUV} \leq 4.5 \\
& (\text{engine size})_{PC} \geq 50(\text{kW}) \\
& (\text{engine size})_{PC} \leq 150(\text{kW}) \\
& (\text{engine size})_{SUV} \geq 150(\text{kW}) \\
& (\text{engine size})_{SUV} \leq 250(\text{kW}) \\
& (\text{fuel economy})_{PC} \geq 27.3(\text{mpg}) \\
& (\text{acceleration 0 to 60})_{PC} \leq 12.5(\text{s}) \\
& (\text{acceleration 0 to 80})_{PC} \leq 26.3(\text{s}) \\
& (\text{acceleration 40 to 60})_{PC} \leq 5.9(\text{s}) \\
& (\text{5-sec distance})_{PC} \geq 123.5(\text{ft}) \\
& (\text{max acceleration})_{PC} \geq 13(\text{ft/s}^2) \\
& (\text{max speed})_{PC} \geq 97.3(\text{mph}) \\
& (\text{max grade at 55mph})_{PC} \geq 18.1(\%) \\
& (\text{fuel economy})_{SUV} \geq 12.8(\text{mpg}) \\
& (\text{acceleration 0 to 60})_{SUV} \leq 9.8(\text{s}) \\
& (\text{acceleration 0 to 80})_{SUV} \leq 22.8(\text{s}) \\
& (\text{acceleration 40 to 60})_{SUV} \leq 5.0(\text{s}) \\
& (\text{5-sec distance})_{SUV} \geq 154.5(\text{ft}) \\
& (\text{max acceleration})_{SUV} \geq 15.4(\text{ft/s}^2) \\
& (\text{max speed})_{SUV} \geq 100.4(\text{mph}) \\
& (\text{max grade at 55mph})_{SUV} \geq 18.6(\%)
\end{aligned} \tag{25}$$

We proceed with solution of Eq. (25) in the next section.

PORTFOLIO VALUATION RESULTS

We now present the results obtained by solving the valuation problem posed in Eq. (25). The divided rectangles (DIRECT) optimization algorithm (Jones, 2001) was used. DIRECT can locate global minima efficiently without derivative information, when the number of variables is small, as in this case. It is often inefficient at refining local minima, and so a sequential quadratic programming (SQP) algorithm was combined with DIRECT to find solutions in a more efficient manner.

Optimization problems were solved for two different production capacities: One for a large capacity of 100,000 and another for a capacity of 57,300, which happens to be the maximum expected monthly sales of SUVs. The best feasible solutions found are shown in Table 2.

In terms of constraint activity, for C = 100,000 the acceleration 0 to 80mph and for C = 57,300 the max grade at 55mph are the limiting engineering performance constraints, both for the *PC* segment. In addition, in the large capacity problem the market limit constraint is active for the SUV, while for both capacity problems the CAFE requirement is active, as usually the case is for US automotive manufacturing firms (Wall Street Journal, January 2002).

For C = 100,000 we see that the computed solution matches our intuition. The portfolio aims at producing as many high profit SUVs as the market will bear (57,300). However, when the capacity of the firm equals the market limit, the solution is no longer intuitive. One may conceivably see a choice to produce only SUVs, making them meet the CAFE standard so as not to violate Eq. (24). Yet, forcing the SUVs to meet the CAFE standard reduces their price in Eq. (18) because they would suffer performance loss. We see that a compromise between a smaller SUV engine (better fuel economy) and a small percentage of PC vehicle production yields a more profitable portfolio. It is exactly at such points, where intuition may fail, that the proposed approach brings value to the decision-maker (and the firm).

CONCLUSION

We have demonstrated a model-based methodology that can successfully quantify the impact of engineering design on investment decision-making. More importantly, the methodology allows the decision-maker to evaluate several scenarios quickly and to understand their consequences better. For example, the effect of the production line's capacity on the firm's profit was explored.

The methodology presented here is quite general. While the study presented dealt with a portfolio valuation of products in only two segments, larger, fleet-wide studies can be stated quite easily. The cost of solving these larger enterprize problems would increase substantially, but several steps could be taken to make the process more efficient. A hierarchical structure could be applied to reduce the large problem to several smaller ones

Table 2. Solutions of the enterprise model for different capacities

Variable	Solution for $C = 100,000$	Solution for $C = 57,300$
w_{PC}	0.42	0.17
engine_{PC}	73.1 (kW)	75.2 (kW)
$(\text{final drive})_{PC}$	3.5	3.4
$(\text{fuel economy})_{PC}$	37.61 (mpg)	37.25 (mpg)
$(\text{acceleration 0 to 60})_{PC}$	12.44 (s)	12.29 (s)
$(\text{acceleration 0 to 80})_{PC}$	26.26 (s)	25.89 (s)
$(\text{acceleration 40 to 60})_{PC}$	5.74 (s)	5.76 (s)
$(\text{5-sec distance})_{PC}$	130.34 (ft)	132.24 (ft)
$(\text{max acceleration})_{PC}$	16.04 (ft/s^2)	16.20 (ft/s^2)
$(\text{max speed})_{PC}$	110.31 (mph)	109.85 (mph)
$(\text{max grade at 55mph})_{PC}$	18.25 (%)	18.12 (%)
price_{PC}	98.02 (%)	98.15 (%)
w_{SUV}	0.58	0.83
engine_{SUV}	200.5 (kW)	168.7 (kW)
$(\text{final drive})_{SUV}$	3.7	3.7
$(\text{fuel economy})_{SUV}$	16.46 (mpg)	18.38 (mpg)
$(\text{acceleration 0 to 60})_{SUV}$	8.03 (s)	9.33 (s)
$(\text{acceleration 0 to 80})_{SUV}$	19.05 (s)	22.55 (s)
$(\text{acceleration 40 to 60})_{SUV}$	3.95 (s)	4.63 (s)
$(\text{5-sec distance})_{SUV}$	194.04 (ft)	178.60 (ft)
$(\text{max acceleration})_{SUV}$	19.24 (ft/s^2)	19.24 (ft/s^2)
$(\text{max speed})_{SUV}$	130.88 (mph)	118.03 (mph)
$(\text{max grade at 55mph})_{SUV}$	25.23 (%)	21.42 (%)
price_{SUV}	100.00 (%)	99.08 (%)
NPV(7 year period)	$15.3B	$13B

(Wagner, 1993). Also, surrogate modeling techniques, such as those discussed in Sasena (2002), may be able to reduce the time required to solve the optimization problem. Finally, other valuation processes, such as those employing real options, can be brought to bear. Doing so would allow decision-makers to take full advantage of the proposed methodology. Understanding the role of the engineering design decisions in their business context makes the investment decisions be both better informed and more effective.

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