design for market systems

Integrating social, economic, and physical sciences to engineer product success. By Jeremy J. Michalek

Product success depends on successful planning of both the big picture and the details. Mechanical engineers tend to focus on the details—making products work as intended physically—and they leave it to managers and government to interpret trends and set targets. But obtaining desired mechanical properties is not the end goal. The net impact of design choices on the end user, the firm, and society depends on how these choices play out in the market.

In part due to our detailed focus, engineers today play a relatively small role in big-picture decision-making in the firm and in government. Yet decisions that fail to adequately consider the implications of engineering tradeoffs on big-picture outcomes result in unintended consequences—and big-picture decisions affect engineering design work directly.

We need to better understand the implications of engineering design in the big picture, and we need to train more engineers for strategic decision-making to achieve broad social, economic, and environmental objectives. We need a science that can support decisions at the interface of engineering and market systems.

SCIENCE IN DESIGN

Mechanical engineers learn to apply principles of the physical sciences so they can predict product behavior and design products that behave as intended physically. But when it comes to understanding what design choices will mean in the marketplace, suddenly science vanishes: Designers are taught to weigh the relative importance of customer needs and benchmark the product's performance—hoping a design that performs on these criteria will perform in the market.

But we need not abandon science where engineering

Marketing says, "Let's figure out what consumers want" (and get engineers to build it). Engineering says, "Let's make a high-performance product" (and get marketers to sell it).

systems meet market systems: Using social and economic sciences to predict market behavior can enable us to design products that behave as intended—not just physically, but also in the market.

Despite the ubiquitous customer focus of today's design processes, there remains a "throw it over the wall" mentality in analysis. Engineering designers employ complex models for engineering analysis, but they typically do not model the role that market forces play in driving engineering goals or determining outcomes.

The fields of marketing and management science have worked for some time to construct tools for measuring and predicting market behavior to guide business decisions. However, most studies in these fields examine products like yogurt or ketchup—products where there are few relevant engineering tradeoffs and there exist large data sets of purchase histories from customers identified by their scanned supermarket rewards cards (e.g., they know if you usually buy Coke but decided to buy Pepsi when it was on sale).

Products like these can often be launched and managed with scant knowledge of engineering details. But when more complex products are involved, engineering analysis is critical to making good business decisions. It is here that design should be supported by market analysis and market planning should be informed by design tradeoffs.

MARKET SYSTEMS

The market is a system, and like engineering systems we can use analysis to break it down and study it scientifically—so long as we maintain an appropriate scope and account for uncertainty.

Mechanical engineering researchers such as Shapour Azarm at the University of Maryland, Wei Chen at Northwestern University, Kemper Lewis of the State University of New York at Buffalo, Panos Papalambros at the University of Michigan, Michael J. Scott at the University of Illinois at Chicago, and I, as well as collaborators outside of mechanical engineering, are working to study engineering design in the context of market systems. By integrating quantitative engineering and economic models, the ability to understand, predict, and account for the market implications of design decisions is beginning to come into focus—a new set of design for X tools focused on market systems.

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Some of these efforts grew out of the Decision-Based Design thrust supported by the National Science Foundation in the 1990s: Researchers working to establish a decision-theoretic basis for design discovered that many of their problems could not be solved without invoking a model to predict expected market responses to design decisions. If we wish to make design choices that are good for the firm or for society, then we must be able to predict the impact of our decisions on these larger systems.

Our primary approach to making these predictions is to build mathematical models based on fundamental economic principles and fit the models to data—from past consumer choices, controlled experiments, or operational accounting. Leveraging established tools and models from econometrics and marketing like utility theory, game theory, discrete choice models, and conjoint analysis, we can measure and make predictions such as how much of one desirable attribute a consumer would be willing to trade in order to gain more of another—or what the likely competitor and retailer reactions would be if we introduced a new feature in a product line.

A typical model of consumer choice behavior, for example, will state that each consumer i gains some utility u_{ij} from each product j in a particular class of products in the market. A rational consumer will always select the product that provides the greatest utility, but the modeler cannot measure with certainty which product that will be. We take utility to be partly observable v and partly unobservable ε so that $u=v+\varepsilon$. The unobservable component ε is treated as a random variable, so that we can calculate only the probability of an individual i choosing a particular product j out of a set of alternatives J as $P_j = \Pr[u_{ij} > u_{ik} \, \forall k \in J]$. The observable component v is taken to be a function of the product's attributes and price. A functional relationship is specified, for example $v_{ij} = \boldsymbol{\beta}_i^{\mathrm{T}} \mathbf{z}_j$, where $\boldsymbol{\beta}_i$ is a vector of unknown preference parameters for consumer i, and $\mathbf{z}_j$ is a vector of product j's attributes and price. The function's parameters $\boldsymbol{\beta}$ are found through maximum likelihood or Bayesian estimation so that the model's predictions best match the choices observed in the marketplace or in controlled choice experiments.

Finally, the resulting choice model can be used to predict the probability of the consumer selecting a particular product out of a set of alternatives, given the attributes and prices of the products.

Of course, we cannot predict any particular individual's choice with certainty, but on average these models make good predictions. Armed with these predictions, we can optimize products not just for technical performance, but also for performance in the marketplace.

For example, Shapour Azarm at Maryland, Nathan Williams of Washington State University, and I have been working with marketing researchers and companies like Ford and Black & Decker to identify the effect that retail distribution structure has on design. (Think of the negotiation leverage of dominant big-box retailers like Wal-Mart.)

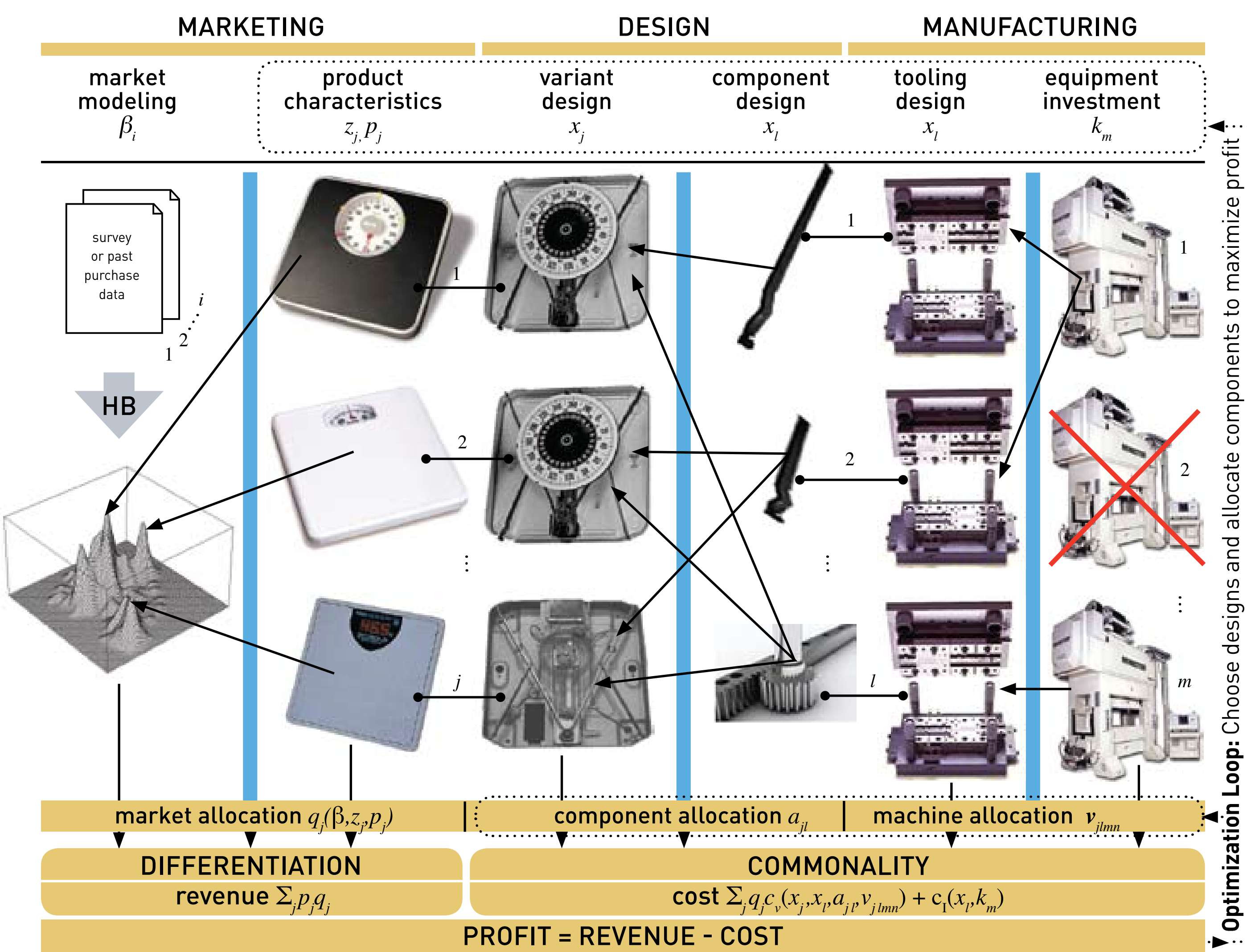
We have found that the behavior of profit-seeking retailers has a significant effect not only on prices, but also on which designs make it to the shelves. This puts pressure on designers to create products that will be profitable to retailers as well as to manufacturers. Otherwise they may not be carried in stores.

We've also found that failing to account for retailer and competitor reactions to a new product entry can lead to poor design choices.

Our case studies examining products from pain relievers to bathroom scales and angle grinders find that ignoring competitor pricing responses to a new entry leads to overestimating expected profits by as much as 80 percent. Profit-seeking competitors will react to new product entries by adjusting prices in the short run and redesigning their product line in the long run to stay competitive. Anticipating these adjustments may mean designing a different product altogether—a product that would perform well in today's market may perform poorly in the market that the new product will create.

Meanwhile, Wei Chen of Northwestern and I have been examining how firms can design product families with the best balance of commonality and differentiation for cutting costs while attracting customers across a distribution of diverse consumer preferences. Cost reduction goals

BALANCING MARKETING AND MANUFACTURING OBJECTIVES IN PRODUCT FAMILY DESIGN



▲ Building mathematical models to predict the implications of marketing, design, and manufacturing decisions supports integrated decision-making to achieve company-level objectives.

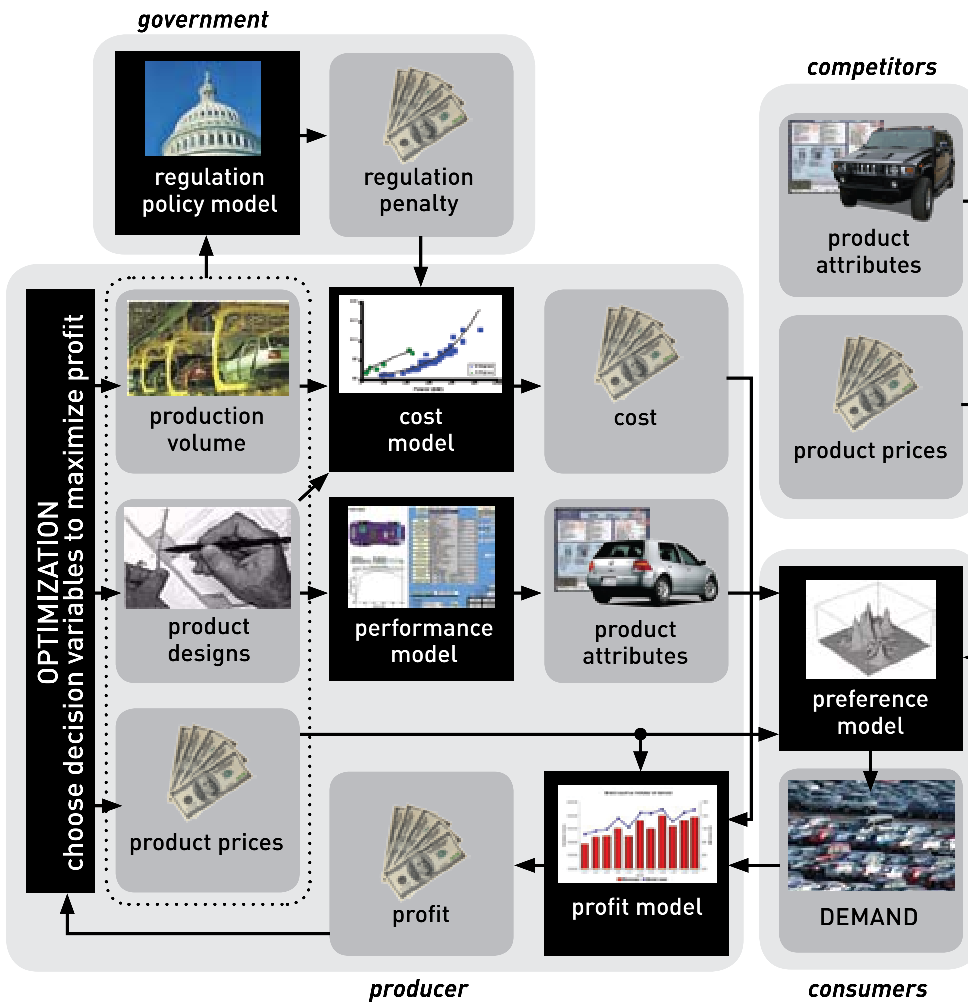
call for greater commonality to increase economies of scale and scope, while marketing goals call for greater diversity to attract niche market segments. By quantifying both revenue and cost implications we aim to identify the right strategic balance for the firm.

TRAINING THE NEXT GENERATION

To disseminate these models and principles to young practicing engineers and ready them to bring a rigorous big-picture perspective with them into the workforce, Professor Erica Fuchs at Carnegie Mellon and I developed a new course called "Decision Tools for Engineering Design and Entrepreneurship."

Students learn methods for developing process-based manufacturing cost plans that assess the impact of design choices on yield rates, labor, capital costs, and ultimately the expected net present value of future cash flows. They also learn to build consumer choice models for predicting market performance as a function of a product's attributes and price relative to competitors, and they account for uncertainty and determine the sensitivity of their conclusions to assumptions.

MARKETS, REGULATIONS, AND COMPETITION IN DESIGN



▲ Understanding the implications of public policy by predicting choices in the marketplace.

This past semester students worked in teams applying these methods to study several new technologies—from LED stage lighting, a new surfboard design, and lithium-ion polymer laptop batteries, to electrical power transmission components and an electronic dosimeter invention patented by the father of one of our students and studied in the course to determine economic competitiveness in the medical field.

One team even traveled to China to study manufacturing operations at the sponsor's facility. We aim to train these students with rigorous interdisciplinary systems thinking that will prepare them to drive the next generation of innovation and economic growth.

ENGINEERING IN POLICY-MAKING

But design for market systems does not just mean helping firms design for profit. It also has application to public policy decisions.

For example, with the support of the National Science Foundation's Faculty Early Career Development Program I am working to understand and predict the implications that environmental policies, such as the new fuel economy standards passed by Congress last December, will have on automotive design outcomes and the adoption of technologies such as hybrid, plug-in, and alternative fuel vehicles.

Design choices are made in the context of rising gas prices, changing consumer preferences, international competitive pressures, and engineering tradeoffs. Engineering analysis plays a critical role in determining outcomes.

Economists tend to assume that the product itself is a fixed commodity, but engineers know full well that different choices and tradeoffs are made under different economic and regulatory conditions. With all of the tradeoffs involved in designing automobiles and investing in new technologies, well-intended policies can easily have unintended consequences, unless policymakers have a good understanding of what is technically possible and where market forces will drive strategic design decisions under proposed regulatory scenarios.

Integrated modeling has the power to enable informed decision-making at the firm and in public policy-making. Technology and engineering tradeoffs play a critical role in determining societal outcomes from economic growth to safety and environmental impact.

So why aren't more engineers involved at the highest levels of policy-making? We aim to help change this by preparing more engineers with skills for rigorous big-picture thinking and systems analysis as well as detailed technical skills, priming them to take leadership roles for policy-making in firms and in government.

In today's competitive globalized economy, engineers need more than strong technical skills. Today's engineers need to be trained to apply technical skills with systems thinking to predict the implications of their decisions in a broader context and make strategic choices with desirable implications for economic, social, and environmental sustainability. ■

For Further Reading

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