ON THE INTEGRATION OF PROCESS AND PRODUCT DESIGN WITH MICROECONOMICS AND FINANCES

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Abstract. In this paper the on-going process of integration of tools from process and product design with concepts of microeconomics and finances is discussed. The paper focuses in two such integrations. It is first shown that financial risk considerations can alter the decisions made in a project or in process operations. Then it is shown that some parameters that used to be considered data by PSE models, such as price, should be considered as variables, in some cases, first stage ("here and now") variables and that they have an influence in the technical and operational decisions. Finally, a multi-scale/multi-model for new product design is presented, claiming that consumer behavior should be modeled.

Keywords: Process Design, Product Design. Microeconomics, Financial Risk. .

1. Introduction

In an upcoming book chapter (Bagajewicz, 2005a), it is claimed that the integration of process engineering with business and economics is speeding up. In this chapter, a long list of shortcomings of the methods used in classical engineering projects was given. The list includes lack of proper treatment of financial risk management, impact on liquidity ratios, company cash position, relationship of the projects to short, medium and long term shareholder values or dividends, capitalization, contracts and option contracts that the company may sign, among others. It is also argued that what was used to be an exogenous parameter, like the selling price of a commodity or a product are in fact endogenous decisions, and that in the case of products especially, advertisement and other actions can alter a decision plan. While all those activities take place nowadays, it was pointed out that they are produced *after* the technical decisions are made, when the claim is they should be part of an integrated model.

It was also pointed out that the response to the need for such integration has already started, the latest 8th International Symposium on Process Systems Engineering held in China, (Chen and Westerberg, 2003) being a paramount example where many papers touched on the issue, and pointed to earlier work by Robertson et al. (1995) who pointed out the lack of proper communication in the corporate flow loop (Figure **Error! Reference source not found.**). Indeed, they argue that the four major components of this loop (Manufacturing, Procuring, Managing and Marketing) operate almost as separate entities with minimal data sharing.

In the aforementioned chapter, it was stated that the proper way of conducting decision making under uncertainty is through the use of two (multi) stage stochastic programming. In addition, some comparison between the view of engineers and the view of financiers was offered. It was also argued that while engineers have stuck to concepts like net present value or internal rate of return to value projects, financiers use the firm's weighted average cost of capital, the market value added and the contributions to shareholder value. This is a sizable gap in the approach to project valuation that should be closed. The book chapter then concludes that "*It is therefore imperative that we the engineers incorporate these measures and objectives in project evaluation, when and if, of course, decisions at the technical level have an impact on the outcome*".

Decision making in projects has been around for a while as a discipline (Riggs, 1968; Gregory, 1988; Bellman 1957) especially in resource allocation (Assignment, Transportation,), Scheduling (Man-Machine Charts, Gantt Charts, Critical Path scheduling, etc), Dynamic Programming, Risk (reviewed in more detail in the next section) through the use of decision trees, regret tables and utility theory. The new emerging procedures rely heavily on two-stage stochastic programming and some revival of dynamic programming. Several techniques, like decision trees and utility theory are special cases of two-stage stochastic programming (Aseeri and Bagajewicz, 2004; Bagajewicz, 2005a). Others claim the same when advocating the dynamic programming approach (Cheng et al, 2003).

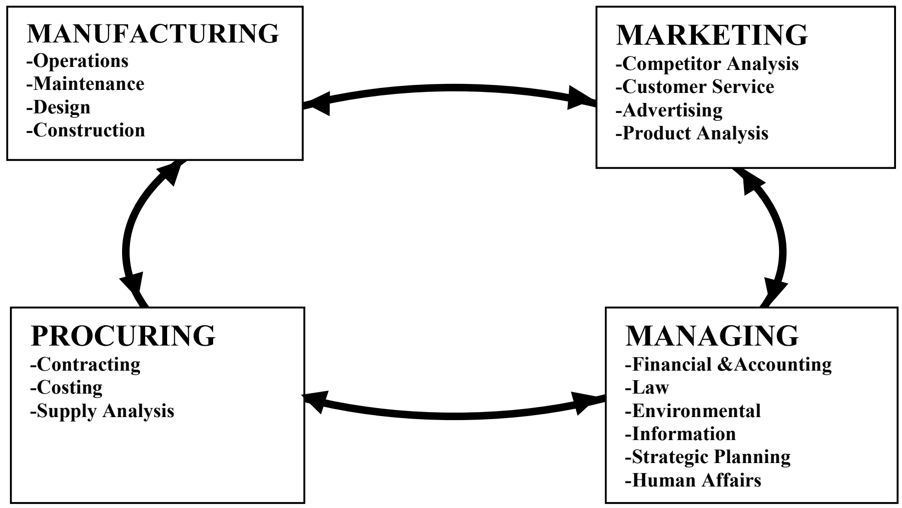

Figure 1. Corporate Information Loop (Following Robertson et al., 1995)

Some pioneering books on scheduling have been published by Puigjaner et al. (1999, 2000), which contain full chapters on financial management in batch plants. They discuss the notion of Enterprise Wide Resource Management Systems (*ERM*), one step above enterprise resource planning (*ERP*) and they outline the cycle of operations involving cash flow and working capital, the management of liquidity, the relationships to business planning, etc. as it relates mostly to batch plants. They even raise the attention to the role of pricing theory and discuss the intertwining of these concepts with existing batch plant scheduling models. Extensive work was also performed by many other authors in a variety of journal articles. Bagajewicz (2005a) lists several articles in Investment Planning, Operations Planning, Refinery Operations, Batch plant design and operation under uncertainty that include cash management, pricing, etc., supply chain design and operations, and financial risk, among many others.

In the rest of this paper we discuss only three aspects of this integration: a) the role of financial risk in decision making, b) the role of pricing in these models, and c) the use of multi-scale multi-model product design paradigms.

2. Financial Risk Management

There are various definitions of risk in the engineering literature, some of them rooted in the finance field, of course. It has been advocated that, contrary to what financiers do, risk is a curve and not a measure that reduces to a number and that risk management is achieved by comparing these curves. We then start with a definition (Barbaro and Bagajewicz, 2004a), which is rescued from older work:

"Consider a certain project, where all the first stage ("here and now") decision represented by ***x*** have been made, that is ***x*** is fixed. Assume also that a sampling is made of the uncertainty space and scenarios are constructed. As a result, a histogram of profit can be constructed (Figure 2). Of this histogram, the left side is usually the focus of attention. Indeed, this side is the one depicting the frequency of pessimistic outcomes, hence the natural tendency to avoid it. In Figure 3 we show several continuous versions of the cumulative probability, called risk curve. The claim is that when one compares one project to another, one would like to see what is what one looses in upper portions of the spectrum of profit as compared to what one avoids by limiting the losses on the downside. One can compare projects featuring the maximum expected profit with others that exhibit smaller risks at low profit values. In Figure 3, for example, the project whose outcome is represented by curve 2 is a result of only putting emphasis in reducing risk at low expectations, whereas curve 3 corresponds to a project crafted to maximize high profit expectations. Finally, curve 4 corresponds to a project that achieves some balance between both.

Bagajewicz (2005a) discusses in detail other risk measures and risk management procedures: Variability or variance (Mulvey et al., 1995) a symmetric measure that does not work well in projects, Downside Risk (Eppen et al, 1989), which Barbaro and Bagajewicz (2004a) proved are the integral of the risk curve, the upper partial mean (Ahmed and Sahinidis, 1998), which has proven to provide non-optimal second stage decisions (Takriti and Sahinidis, 2003), Value at Risk (Guldimann, 2000; Jorion, 2000), a point measure used by financiers, Downside Expected Profit for a confidence level p_{Ω} (Barbaro and Bagajewicz, 2004a), use of chance constraints (Charnes and Cooper, 1959), which Aseeri and Bagajewicz (2004) proved to be a special case of two stage stochastic programming, risk premium, used by financiers, risk adjusted net present value (Keown et al., 2002).

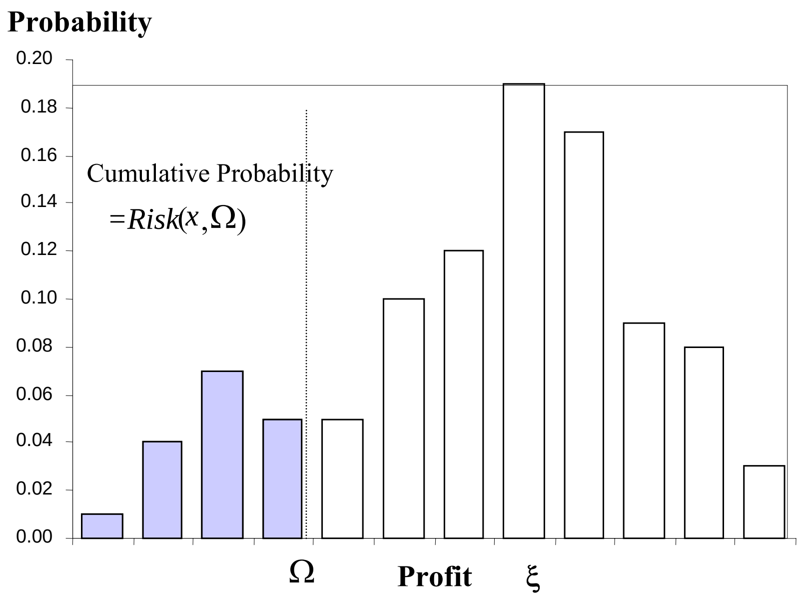

Figure 2. Definition of Risk. Discrete Case.

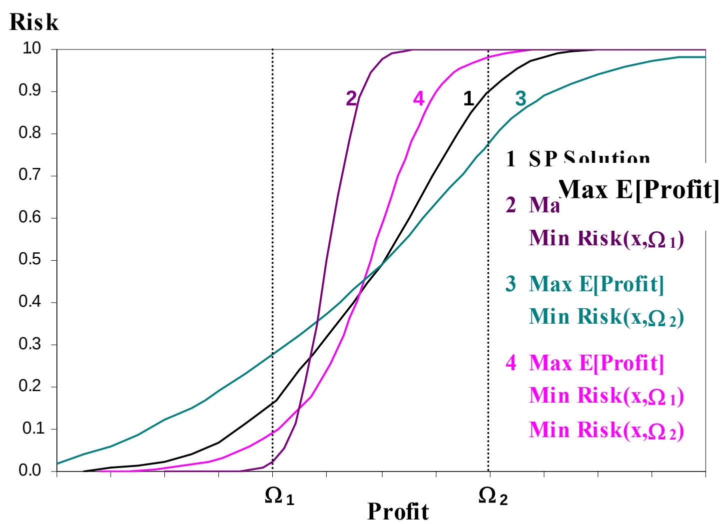

Figure 3. Spectrum of solutions obtainable using a multi-objective approach.

Aseeri and Bagajewicz (2004) introduced some measures to generate a large number of solutions and their corresponding curves through the use of the average sampling algorithm (Verweij et al., 2001) and provided means to make the choice of the more balanced curve in an automatic manner. In addition, they also showed how an upper bound curve can be obtained. The technique was applied to a variety of case studies:

- Offshore Oil Infrastructure and Production Planning (Aseeri et al., 2004)
- Investment planning for gas commercialization in Asia (Aseeri and Bagajewicz, 2004)
- Short term scheduling (Romero et al, 2003; Bonfill et al., 2004; Guillén et al., 2005a).
- Supply chain design under uncertainty (Mele et al, 2003; Guillén et al., 2003, 2005b)

- Inventory Management in Investment Planning (Barbaro and Bagajewicz, 2004b)
- Contracts and Option Contracts in Investment Planning (Barbaro and Bagajewicz, 2004b)
- Refinery Operations Planning (Pongsakdi et al, 2005).
- New definition of Environmental Risk (Janjira et al., 2005).
- Planning of Cleaning in heat exchanger networks (Lavaja and Bagajewicz, 2004a,b)
- Energy Recovery in the total Site (Bagajewicz and Barbaro, 2003).
- Water/Wastewater Management Systems (Koppol and Bagajewicz, 2003).

Romero et al. (2003b) also touch on budgeting issues, that is cash management, which started with the pioneering ideas put forth by Badell et al (1998), Badell and Puigjaner (2001a,b), and Badell et al. (2004). This technique offers, for the first time a reasonable decomposition of the full two-stage stochastic model. In addition, the technique allows the calculation of a (sometimes) tight upper bound, which is very useful to know when to stop.

3. Pricing

Guillén et al (2005a) proposed that prices be correlated with demands in the well-known relationship price×demand =constant in the context of planning the production and scheduling batch plants. Thus, prices became a first stage decision variable instead of en exogenous parameter. Thus, altering the production schedule should and indeed does, have an effect on the fixed costs per unit used in existing classical pricing models (Dorward, 1987; Mas-Collel et al. 1995), and proved that iterative models that solve scheduling and pricing separately not always converge, and when they do, they may not be optimal. They also showed the advantage of integrated model.

We now review the concepts used by microeconomics and how they can be integrated into investment and operations planning. We assume first that there is an established market for the product (be it new or not) and that the total demand is assumed constant. The question is what price will be the right one to attract the optimal number of customers and the new demand one will create associated to it. This will have an effect on the size of the production planned or the capacity of the process chosen in the case of investment planning. We begin with the following equation that relates price and demand. Let p_1 be the targeted new product selling price, d_1 its demand, p_2 the average competitor's product price, and d_2 is the corresponding competitor demand. We start assuming the following relation:

$$p_1 d_1 = c\ p_2 d_2 \tag{1}$$

where c is a constant. This relation can be derived using the concept of indifference curves (Hirshleifer and Hirshleifer, 1998), which expresses how much equal utility (happiness) a combination of product 1 and 2 will provide to a customer. Such an expression, compatible with (1) is $d_1^{r_1} d_2^{r_2} = U$, where U is the utility and $c= r_1/ r_2$. This form of the utility function is known as the Cobb-Douglas utility. The standard form of the Cobb-Douglas utility requires $r_1 + r_2 = 1$, a condition that makes the utility double when both d_1 and d_2 double. Conversely, when $r_1 + r_2 > 1$, utility increases by a factor larger than two, when both d_1 and d_2 double, called increasing returns to scale, which is non-standard. Thus, (1) is obtained by maximizing U subject to a budget constraint $p_1 d_1 + p_2 d_2 \le Y$, where Y is the total consumer budget. For a fixed total market demand D, we have $d_2 = (D - d_1)$. In general, we expect the overall demand to be a function of time and also susceptible to increase. There are other utility functions one can use. For example, one can use one that assumes constant elasticity of substitution, like follows: $U = (d_1^{\rho} + d_2^{\rho})^{1/\rho}$, which renders an expression that is similar to (1): $p_1 d_1^{1-\rho} = p_2 d_2^{1-\rho}$. Elasticity of substitution is defined as the change of demand of one product with respect to the other for unit change in the relative prices.

Equation (1) does not express the dynamics of the competition process, but rather the state of equilibrium achieved among competitors at some point in time. When c=1, equation (1) reveals that equal prices of the new product and that of the competitors' product, results in an evenly shared market. Such outcome would be realistic if the following conditions are met: a) Both the new product and that of the competitors have been in the market for a long time, b)The quality of each product is the same, c) Advertising campaigns are equally effective, and d) Production capacities of all competitors can satisfy the demands

4. Modified Pricing model for New Products

We now depart from classical microeconomics theory and analyze pricing of new products. The above listed conditions are hardly met for a new product. At first, the competitors will have a clear advantage over the new product because they will have been established in the market for a number of years. They will have earned loyal customers and will have successful advertising campaigns in place. On the other hand, the new product will have the advantage of being a superior product, which will either increase convenience of use or save money and time to the customer. In economics, the substitutability between goods is measured by the elasticity of substitution (see above). The standard utility function which considers substitutability is called Constant Elasticity of Substitution (CES) utility function. We will first assume a simpler approach to illustrate the ideas. To account for influences from advertising, two correcting functions are introduced into the model as follows:

$$\beta(t,a) \cdot p_1 d_1 = c\, p_2 (D - d_1) \cdot \alpha(t,a) \tag{2}$$

This still corresponds to an indifference curve of the form $d_1^{r_1} d_1^{r_2} = U$, where now r_1 and r_2 are functions of $\alpha(t,a)$ and $\beta(t,a)$. The function $\alpha(t,a)$ is a function of time and the advertisement campaign efforts for the new product (a), or word of mouth in some cases. This function ranges between zero and one. At the beginning (t=0), $\alpha(0,a)$=0 (or a very small number) indicating that the demand of the new product d_1 is zero (or very small) no matter what the price is. As time goes by, the function approaches one, reflecting equal opportunities for all competitors in terms of advertisement. Thus, before the value of $\alpha(t,a)$ reaches one, the competitors have a competitive advantage by virtue of their longer standing in the market, with an established customer base. Thus, we can call $\alpha(t,a)$ the Inferiority Function for the new product. In turn, $\beta(t,a)$ is also a function of time and the advertisement campaign of the new product (a). At the beginning (t = 0), $\beta(0,a) = 1$ indicating that there is no initial advantage for the new product. As time increases, β approaches zero asymptotically, and becomes zero only if the competition disappears. The function represents the superiority of the new product and ultimately, its competitive edge. Therefore, we call it the Superiority function. We envision these two functions to have concave and convex forms as shown in figure 4.

One gets some estimated values for $\alpha(t,a)$ and $\beta(t,a)$ using data from the performance of similar novel products in the past. We note that this is a simplified model that does not contain a change in advertisement efforts that the competitors may carry in response to the introduction of the new product.

Even if one has good knowledge of the inferiority and superiority functions, the model contains at least two unknowns: p_1 and d_1 (assuming that the competitors' average price does not change). We make such assumption for simplicity of analysis. To be able to determine the values of p_1 and d_1, which is related to a decision on capacity of installations that needs to be made ahead of time, we need to add some other relations. Although this will be later part of an integrated model, we illustrate one simple way of doing it here. A general rule of thumb states that a company should try to recover their investment within a certain small number of years, especially in the case of risky investments. This is usually two or three for high risk/high investment ventures. In other words, the expectation is that in exchange for the high risk involved that return of investment should be anywhere between 30 to 50% or higher. In the context of uncertainty, one can consider that this recovery time is a first stage variable, which when varied will lead to different projects. The model will render the corresponding price, which is usually a first stage decision for the first few periods of time and can turn into a second stage one for latter periods.

In reality, prices do not stay constant and the above model assumes so. Introducing variable prices requires the introduction of new equations. Aside from speculations about the rate of return desired, one has very little new conditions to impose. Such conditions could be related to the cash position of the company, the share holder value strategy, liquidity ratios, etc. A recent paper discusses some of the connections between project decisions and corporate strategies (Umeda, 2004). Other underlying assumptions are that advertisement costs are on a per unit basis, while they could be considered a lump sum. In reality, one needs to assume that advertisement efforts can be made a decision variable, and therefore formulate the superiority and inferiority functions in terms of advertisement efforts.

Finally, in microeconomics, pricing includes the demand side analysis, the firm costs function, the firm's optimal behavior, all of which we somehow cover, and the market structure, which we have not mentioned. Such market structure could be perfect competitive, monopoly, or oligopoly. One structure one can start assuming is monopolistic competition, (Dixit and Stiglitz, 1977) which is based on two assumptions: a) the firm maximize it's own profit by choosing an optimal price for given prices by other firms, and b) each demand is small relative to entire market. Usually, this model is solved using backward induction, that is, solving first for the equilibrium prices and later for other decision variables, like quality or number of brands.

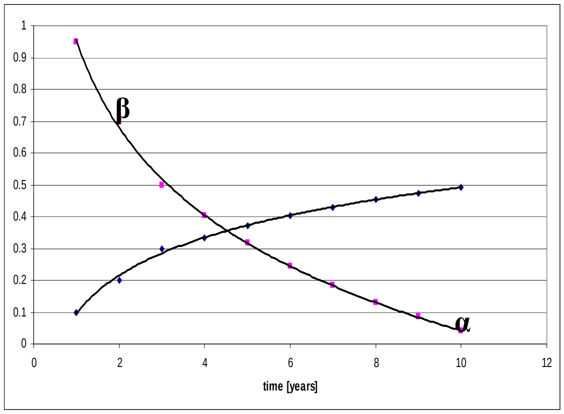

Figure 4. Inferiority and superiority functions.

5. Advertising

In order to effectively advertise a product, service or good, the following concerns must be addressed and determined. These concerns include 1) The size of the total advertising budget, 2) The allocation of this budget to marketing areas, 3) The allocation of the individual market area budgets among media, 4) The timing of advertising, 5) The theme of the campaign, and 6) The effort to be invested in a campaign. Figure 5 depicts the basic advertising trend for a generic product, service or good. During the beginning of advertising, there is a linear trend between the advertising rate and sales of the product. Once the product begins to gain popularity, the sales reach a threshold, and the trend between sales and advertising rate is no longer linear. Soon, the product will begin to saturate the market and the product reaches its height in popularity. At this point, with an increased advertising rate, the product begins to oversaturate the market. As a result, sales begin to decline. (Rao, 1970).

Thus, in a very simple model (the one we want to start with), one could consider a linear relation between demand d_1 and advertisement costs, which will directly conflict with our model above because what we need to build is the inferiority and superiority functions. First, one needs to realize that this advertising model mostly considers that there is no effect of the competition advertising and is independent of pricing. We can nonetheless, use the conceptual framework, to say that our inferiority and superiority functions are somewhat linear with advertisement efforts. For example, one can start with the simplest case: $\beta(t,a) = 1$, that is the existing product is as good as the new one in the consumer minds for a long time.

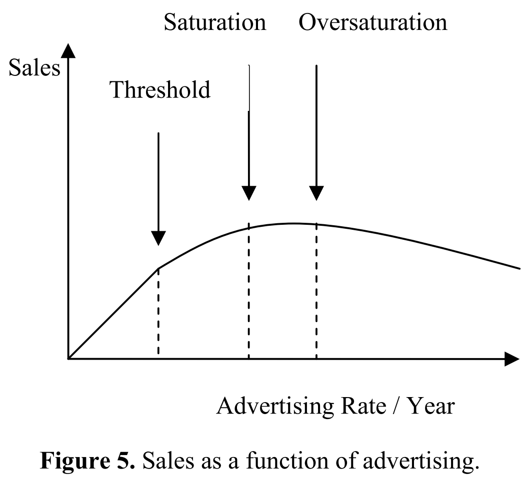

Figure 5. Sales as a function of advertising.

There are other ways of modeling advertising, which are somehow consistent with the above pricing scheme. If for example one consider the advertisement effort a, which makes one unit of the new product worth A units of the existing products. Then one can substitute d_1 by d_1/A in the utility function that assumes constant elasticity of substitution as follows: $U = [(d_1 \ / A)^{\rho} + d_2^{\rho}]^{1/\rho}$ and continue from there assuming certain cost function for A.

Pricing and advertisement in the context of an investment planning model was discussed in a recent paper (Bagajewicz, 2005b). The model illustrated through an example of investments in microbreweries, that modeling advertisement efforts has an impact on first stage decisions regarding capacity, location of the manufacturing facility, choice of markets, pricing and advertisement expenses.

6. Dynamics of New Products Development

In recent years, several authors advocated that process system engineers should pay increased attention to a new paradigm, that of Product Design, (Westerberg and Subramanian 2000; Cussler and Moggridge, 2001). There are in general two types of "products". One group are pure components or mixtures, in various forms (sometimes structured, i.e. multiphase), like creams, pastes, lotions, food, flame retardants, insect repellents, pesticides, etc, which are either directly consumed by end-users or sold as raw materials for other end-user products. Their characteristic is that they are "used" once. The other group of products is devices, which serve certain functionality and are characterized by the fact that can be used repeatedly. They are in general, mechanical or electronic devices. The boundary between these two groups is not well defined sometimes.

The engineering of new products has been understood so far as

- ❖ Optimizing an a-priori defined product, be it the components of mixtures or devices, or
- ❖ Discovery of components, in addition to the optimization of the parameters.

so that certain properties of the product are achieved are achieved. Examples of the above can be found in several articles and books (Achenie et al ,2002; Seider et al, 2004). For example, the 'discovery" of new refrigerants can be made where what is targeted is high heat of vaporization and low heat capacity, Cussler and Moggridge (2001) do the same for de-icing products. In the case of devices, Seider et al (2004) discuss the hemodialysis machine or the automotive fuel cell. When "market driven" new products are considered, the target performance is usually set by Marketing. We omit discussing "technology driven" new products, where properties are first set by discovery on the engineering side.

Targeting properties like viscosities, heat capacities, vapor pressures, etc, as well as device functionalities like efficiencies of hemodialysis machines, etc, are part of more complex activity that involves identifying other properties that make customers "happy". Thus, for example, soaps and lotions have properties like "creaminess, thickness and smoothness" (Cussler and Moggridge, 2001; Wibowo and Ng, 2001) , which is related to viscosity and surface tension and if the lotion/soaps/cream is multiphase to the proportion of phases, etc. Foods have all types of "tastes" that can be related to the concentration of substances (sugar, pepper, species, additives in general), and "textures". Let us call them "consumer properties" (***y***), with the understanding that sometimes we do not have means to quantify them properly.

Thus what marketing provides is one and only one instance of properties that corresponds one state of "happiness" and it also figures out (simultaneously or later) what price the consumer would be willing to pay for it. But marketing (or others) identify these properties using purely commercialization criteria. Engineers, when target the desired properties provide the costs, but they do so by targeting a set of well-known physico-chemical properties (***x***). Somewhere in this process there is a function ***x***=*g*(***y***), that translates consumer properties into desired physicochemical properties. In return engineering and R&D, provide the product structure ***z*** and the cost through a function *C*(•), that is ***Cost*** =*C*(***z***), as illustrated in figure 6.

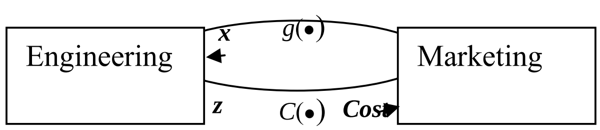

Figure 6. Sales as a function of advertising.

This could give rise to an iterative cycle where marketing adjusts its desired consumer properties ***y*** until the profitability is maximized. We do not know how many iterations are performed in industry (if any), but even if they are performed to convergence, one has to wonder how these iterations are performed. In other words, given z_i and therefore $Cost(z_i)$ **,** how is y_{i+1} obtained? While this is hard to know and may be an ad-hoc procedure in each case, what we know is that usually, what Marketing wants is to maximize profit, so that is the starting point to build a strategy.

Thus, profit being the objective, one has to enter in the dynamics above described that connects in one single model, prices, demands, costs, market share, advertisement efforts, etc. We have apparently been able to asses all these pieces, except the relationship between demand and price, through the only big unknown we still have: the form of the superiority function $\beta(t,a)$, which would in essence say how many more customers would buy the new product vs. the existing one given a certain difference in prices, or in more simpler term, given equal prices how much more of the product would he/she buy.

The answer then is given by looking at Hedonic theory (Feeenstra, 1995). Such theory should tell us how to construct this superiority function. Thus, if product discovery and design is to be done right, what one needs is to identify is a multivariable function G(●) that would give us "Consumer happiness" = G(y). This is a utility function in a similar sense as described in macroeconomics, but not quite. Indeed, it is a step further. The utility function in microeconomics is written in terms of quantity of product, whereas G(●) describes how much "happiness" one gets from a unit of product, and allows us to calculate such happiness as a function of y, which we now intend to manipulate.

7. Multi-scale Product Design Model

Based on all the above outlined concepts we are now in a position to propose a multi-scale composite model that can allow us obtain the right product. This is obtained as follows. Let w_1 be a variable lumping first stage variables, such as manufacturing capacity, plant locations, warehouses, transportation means, customer zones, etc. Let w_2 be the set of second stage variables and let p be the price (assumed a first stage variable for simplicity). Then we want to maximize the Expected Profit

$$\max_{z,p} \sum_s NPV(z, w_1, w_{2s})$$

$$\begin{aligned}
s.t.\quad & Sales_s = Sales\,(z, p, a, w_1, w_{2s}) \\
& Fixed\ Capital\ Investment = Fixed\ Capital\ Investment\ (z, w_1) \\
& Manufacturing\ Costs_s = Manufacturing\ Costs\ (z, w_1, w_{2s}) \\
& Supply\ Chain\ Costs_s = Supply\ Chain\ Costs\ (z, w_1, w_{2s}) \\
& Marketing\ Costs_s = Marketing\ Costs\ (z, a, w_1, w_{2s})
\end{aligned}$$

Thus, the model "discovers" a new molecule/mixture by adequately varying z, which contains structural molecular parameters (groups, or other information like connectivity indices), concentrations of compounds in mixtures, phases, structure, etc., or it optimizes continuous parameters of a known mixture or a known device. Everything, first stage and second stage costs, as well as second stage sales are thus dependant on the molecular, microscopic design. This is the smallest scale. Then there is the manufacturing scale, where the appropriate technology to produce the chemicals/devices is selected, the investment level is determined, etc. In the next scale, one has the supply chain costs (plant location, transportation issues, etc.). Finally, the Marketing scale includes Sales and Marketing costs.

All the above elements of this model are fairly known to Process Systems and Logistics researchers and practitioners, except the Sales and Marketing models, which have not been hitherto considered in detail. We start discussing briefly the architecture of these models. In addition, supply chain and marketing costs can be considered "weak" functions of z, that is, functions that vary very little with the choice of z. The sales function $Sales_s = p\ d_s$, where d_s is the demand, which is determined by the market model (2) which in turn contains the superiority function $\beta(z;t,a)$, which in turn is a function of consumer happiness function G (notice we have now made the superiority function dependant on z). This requires the use of molecular descriptions to tie molecular structure to properties x. Finally, the fixed capital investment model requires the

8. Conclusions

In this paper, we highlighted two elements of the integration between process systems engineering with finances and microeconomics, specifically financial risk and pricing theory. It is argued that product design cannot be performed properly without using pricing theory and without modeling consumer and behavior. A multi-scale model structure is proposed to handle this. Modeling the competition is, for space reasons, left out from the discussion.

Acknowledgements

Financial aid by Enpromer and NSF-PASI funds are gratefully acknowledge.

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