

Accounting for the Duration of Analyses in Design Process Decisions

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Georgia Institute of Technology

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ABSTRACT

Although the design phase can account for a sizable amount of the resources consumed during the product realization process, the time and costs associated with the design process are often neglected when making design decisions. To investigate this issue, we define a process-centric decision model in which the design-phase consumption of resources, such as time and money, is explicitly modeled. While it is clear that the utility of a design is almost always directly impacted by the monetary costs of the design process, our decision model also accounts for the fact that the profit earned by a product depends strongly on its launch date. The decision model allows us thus to consider the trade-off between the time necessary for analysis and the improvement in product quality that results from the analysis. The decision model is sufficiently generic that almost any set of beliefs about the alternatives or analyses, as well as any utility-based preference structure can be modeled. To illustrate the usefulness of the model, it was solved quantitatively for two different design scenarios. The results indicate that designers should consider the duration as well as the monetary cost of analyses; depending on the cost-benefit trade-offs, it may be best to perform analyses sequentially, in parallel, or not at all.

INTRODUCTION

Many different frameworks have been proposed to describe the process of design [1,2,3,4,5,6]. These frameworks generally attempt to prescribe a particular method that designers should use to guide themselves through the design process. Decision-Based Design (DBD) is one such framework and is based on the viewpoint that design can be decomposed into a series of decisions [7]. DBD is based upon the mathematical foundation of decision theory provided by axiomatic utility theory [8]. DBD uses this basis to analyze the series of decisions, and prescribes that the Decision

Maker (DM) should select the action that maximizes his or her expected utility. Hazelrigg [1] argues that if the DM is a designer in an industrial context, then the DM should adopt an enterprise viewpoint and define the utility as a function of the net profit. Strictly speaking, this utility should be determined by considering the sum of all effects of the decision, regardless of whether those effects are direct or indirect. Practically speaking however, considering every effect may not be feasible. As such, researchers often limit their scope of concern, and focus primarily on the utility generated by the artifact. They may neglect the costs of marketing, shipping, or even designing. Manufacturing cost is one of the few aspects of generating a product that often is included as a factor of design decisions. Designers generally recognize its impact on net profit and will make tradeoffs between performance and manufacturing cost. Even a modest reduction in manufacturing cost per unit of a high volume product can result in significant savings and more than offset some losses in performance.

In this paper, we argue that the subject of focus in DBD should be expanded to include the design phase as well. Much like tradeoffs arise from the consideration of manufacturing cost, tradeoffs will become available through explicit consideration of the resources used during the design process. The costs incurred during the design process are varied and can be direct monetary costs (wages paid to designers, costs of materials for prototypes) or indirect costs (time loss, scheduling costs). As an example of how expanding the focus of the design decision can impact the product realization process, consider the following scenario:

An OEM parts supplier is preparing a bid for a contract to design hydrogen fuel cells for a major automobile manufacturer. The supplier's researchers have developed two new technologies that are expected to outperform the technology of the automobile manufacturer's current

supplier. The first technology appears to be rather robust, and is projected to bring in a gross profit of \$10M plus or minus \$5M. The second technology has the potential of longer life, but the research department is less certain about its robustness in application. The gross profit for the second technology is estimated at \$15M plus or minus \$10M.

The head designer on the team has six months to choose which new technology to propose before the bid is due. As long as she submits the proposal before the deadline, she is sure that her design will be accepted. However, if she does not submit the proposal on time, the automobile manufacturer will renew its contract with its current supplier and the OEM parts supplier will not get a contract. During the remaining six months, she could have the research department perform further analysis on the technologies. Each analysis would cost \$100K, but would also take 4 months to perform, leaving 2 months for design refinement. From previous experience, the head designer knows that the research tests usually give her enough information to predict the actual gross profit within \$1.5M. The head designer must decide whether to perform testing to gather more information, or to save the testing costs and select a design for refinement now.

If the resources consumed during the design process are not considered, the firm only sees a decision about whether or not to reduce uncertainty about two design alternatives. In this simple situation, the decision is trivial; the firm would perform the tests and reduce the uncertainty. However, if the utility of the entire product realization process were to be considered, the decision becomes more complex. The firm would need to decide whether the tradeoff between performance and resource costs is worthwhile. Even this simple example illustrates why a broader focus is required: a limited focus reduces the ability of the designer to make reasonable comparisons, and therefore reduces his or her ability to make good decisions.

Recent work by Thompson and Paredis [9] made a first step in broadening the focus of design decisions to include the design process. They presented a decision model in which “the decision alternatives are the particular actions available to the design team.” These actions include the analysis of a particular design alternative, or the selection of an alternative for refinement. Their model takes a holistic approach to design, and encourages designers to consider tradeoffs in all of the phases of the product realization process.

A limitation of the preliminary model proposed by Thompson and Paredis is that it only considers the direct monetary costs of performing analyses, and neglects the importance of indirect effects, such as Time to Market (TTM), in the calculation of the expected net profit. TTM is a measure of the length of time required to develop a product so that it can be sold in the marketplace. A short TTM implies that the

product will not sustain large design costs, and as a result reach the break-even point quickly and bring in profits for a longer time. A short TTM also indicates a greater probability of reaching the market before competition, in which case the enterprise is rewarded with a larger market share [10, 11]. If it is the first to enter a market, the enterprise will have 100% of the market share.

In this paper, we present a modified version of the original decision model in which the time required to conduct testing is included as a cost of performing an analysis. We make several assumptions about the form of the uncertain parameters that may not be realistic in practice (i.e. normally distributed). However, it is not our goal to make specific statements about a particular set of design alternatives using the model. Rather, the decision model is leveraged to investigate the impact of continuing to relax the assumption that the cost of the design process is negligible. The remainder of this paper is organized as follows: In the next section, related work is discussed, and then the background for this paper is introduced. Next, a decision model that considers the value of time consumed during analysis is presented and evaluated using two scenarios. Finally, concluding remarks are offered.

RELATED WORK

In this paper, we argue that the focus of DBD should be expanded to include the various costs of the entire product realization process. We focus specifically on the design process as a first step in this work. Thompson and Paredis investigated the value of a process-centric problem formulation [9] and identify a need for consideration of the costs of the design process in decision making. They present a decision model which considers the monetary costs of the design process in design decisions. The model is also compared to current Value of Information work, and is found to provide better information when a sequence of tests is available.

Motte [12] presents a similar decision model in which he examines the utility of three different strategies for handling the uncertainty prevalent in the design phase. In his simple decision model, Motte identifies several direct monetary costs of refining design alternatives as well as costs due to time. However, his model accounts only for discrete outcomes, and is specialized such that it cannot be generalized to model a generic design decision.

In his framework for DBD [1] Hazelrigg argued that in an enterprise context the net profit should be the primary driver of utility, and recognized the breakdown of profit into revenues and costs. He also stated that time has an important value in these decisions and reinforced his argument with an example about interest and discount rates. However, his definition of the value of time focuses primarily on delay in

revenue streams. In the context of business and marketing, time can often be valuable in other ways.

Pawar et al. [11] argue that design process time is valuable in that it directly affected the Time to Market (TTM) of a product. TTM is a measure of how long it takes for a product to reach the marketplace. According to Pawar, gross profit is strongly affected by TTM, as products with shorter total TTM's reap the benefits of extra sales revenue, earlier breakeven on investments, extended sales life, and increased market share.

Urban et al. [10] also stresses the importance of a short TTM and early product launch under competition. They developed a simple model that demonstrates the market advantage granted to pioneering products. From the model, the earliest entrant to a market earned the largest market share, with later entrants being forced to produce superior goods, advertise heavily, or cut prices in order to gain market share themselves.

Reinertsen [13] investigated the effect of a six month launch delay on cumulative profit for a product in which market price decayed each year. He found that the rate of price decay greatly impacts the profitability of the product, quickly reducing the total profit by 100%. Reinertsen also made the dramatic claim that, for a product with a five year lifespan, 'six months delay can be worth 33 percent of life cycle profits' [14].

Charney [15] asserts that 80-90% of the TTM equation is determined in the design phase. Therefore we believe it is proper that engineers should consider the impacts of their decisions on TTM, and make tradeoffs accordingly.

BACKGROUND

Research in DBD uses the foundation of decision theory to examine the design process, and declare a prescriptive method of designing. Thompson and Paredis [9] argue that the decisions should be viewed from a holistic viewpoint and that all effects of the decision should be included when considering the utility. Their decision model showed the merit of such an approach, even for a simple example. However, this preliminary model focuses only upon the direct monetary effects of design decisions, and fails to include indirect effects such as those due to delays in TTM. In this paper, the framework of their preliminary model is expanded to include indirect effects of design decisions. To demonstrate how indirect effects can have a significant impact on the design process utility, we examine the importance of time-related consequences of the design process in two scenarios.

SCENARIO 1

The first scenario is that of the OEM parts supplier as described in the introduction. She must decide between two technologies to include as part of a bid to a major automotive manufacturer, and she can decide to perform tests on the technologies to reduce uncertainty about their performance. The first scenario is a commonly occurring decision in engineering design under time constraints. Quite often, deadlines can arise such that a decision must be made while there is still significant uncertainty about outcomes. In this case, the manager must decide quickly because the automobile manufacturer will not accept bids after the deadline. In practice, these deadlines may be arbitrarily declared, and some flex time may actually exist. However, there are also many situations in which the deadline is firm. For example, NASA space launches must meet their launch windows, or else the mission will not be given clearance to take off.

SCENARIO 2

Many design decisions do not have firm deadlines by which they must be made. In the second scenario, a situation is examined where the DM is forced to decide not by some outside constraints, but by consideration of his own utility. Whereas the first scenario examines the value of the decision model under constrained circumstances, the second scenario illustrates the decision model's value in situations where the DM is not constrained by deadlines.

An enterprise that manufactures consumer electronics is developing its next generation of mobile entertainment devices. The design team has proposed two new product ideas that it feels will be successful in the market. The first product combines the functionality of two older products, while the second product possesses a degree of portability that is currently unrivaled in the marketplace. The VP of New Product Development is relatively confident that the first product will be a success, and the gross profit over its lifetime is projected to be \$20M plus or minus \$7M. The VP is much less confident about the second product, which has a gross profit projected to be \$30M plus or minus \$15M.

The marketing division has offered to analyze the products by performing consumer surveys. The analysis would cost \$80K per test, and takes it 4 months to perform the tests and compile the results. The marketing division tells the VP that their analyses typically predict the actual profitability of a product within \$1M.

In this scenario, there is no deadline for completion that restricts the VP's decisions, but every day the product is still being designed is a day that it is not being sold. The VP must decide whether the analyses are worth performing, or whether it is better to make the decision now and send the product to the market faster. It is assumed that the VP does

not want the two products to compete against each other and as such will only select one product for development.

This scenario is iconic of a general high level design decision. As in the first scenario, there are several key components in the design decision. The DM is faced with a decision of two design alternatives with uncertain outcomes. The DM also has the ability to perform an analysis with known quality, monetary cost, and length of time. The DM also has a set of beliefs that indicate how the value of the artifact changes over time.

In reality, it may be impossible to know the exact quality, monetary cost, or length of time required for an analysis. However, these attributes are assumed to be deterministic in this model in order to reduce the computational complexity of solving the model. The consideration of uncertainty in these variables may lead to a more accurate calculation in the model, but we argue that this additional accuracy is unnecessary to support the claims made in this paper. Particularly, we argue that the direct and indirect effects of the design process should be taken into consideration in DBD.

DEFINING THE MODEL

In the decision model proposed by Thompson and Paredis [9], the design decisions available to the DM are to either 'Analyze' or 'Select' one of two alternatives. The option of 'Analyze' is used to describe any of several methods of gathering additional information about a design alternative. The analysis could refer to marketing analyses, prototype development, or computer simulation. The important aspects of an analysis in the model are that (1) the analysis provides information about the alternative tested which can be used to reduce uncertainty, and (2) the analysis consumes some resources. The option of 'Select' is used to describe the process of refining the focus in the design process. In some contexts, 'Select' could mean that a final design is determined and finalized plans are sent to be manufactured. Another viewpoint is that a 'Select' decision is merely a decision to perform further refinement on that alternative only.

In [Figure 1](#), we present a decision model that is similar to the model proposed by Thompson and Paredis. The decision model is shown in the form of a decision tree, which is a method of visualizing decisions. In the new decision model, the utility function accounts for the duration of analysis by modeling its effect on value. A second difference is that a new decision alternative is introduced, 'Analyze A and B'. The ability to analyze both alternatives immediately is important, because its availability acknowledges the importance of parallel analysis when time is important.

<[figure 1](#) here>

In a decision tree, boxes represent decisions and circles represent chance events. Arcs emanating from decision boxes represent decision alternatives, whereas arcs emanating from chance events represent outcomes. Performing an analysis on one of the products enables the DM to update his prior knowledge about that product based on the outcome of the analysis. In Bayesian terms the prior knowledge is represented as the prior distribution and the updated knowledge is defined as the posterior distribution. In this decision tree, $a(t)$ and $b(t)$ represent the earnings of products A and B if released at time t . The estimated values from analyses on A and B are represented by α and β , respectively. The functions under the chance events represent probability density functions, where

- $f(a(t))$ and $f(b(t))$ are the prior distributions of the earnings of products A and B at time t , respectively.
- $f_A(\alpha)$ and $f_B(\beta)$ are the marginal distributions of the outcomes of the analyses on products A and B.
- $f_{A,B}(\alpha, \beta)$ is the joint marginal distribution of the outcomes of the analyses on both products A and B.
- $f_{a|A=\alpha}(a(t))$ and $f_{b|B=\beta}(b(t))$ are the posterior distributions of the earnings of products A and B given the values from the marketing analysis.
- $u(*)$ is the utility of the argument.
- $c(*)$ is the monetary cost of performing the analysis.
- T_A and T_B are the amount of time required to perform the analyses on A and B.

According to utility theory, the DM should select the alternative with the largest expected utility. For a decision tree, a DM calculates the expected utility by rolling back the branches. At decision nodes, a rational decision maker will always select the best option, and therefore the maximum utility of all alternatives at that node is rolled back. At chance nodes, the branch is rolled back by calculating the expectation over all possible outcomes of the event [16].

The equations generated by evaluating the decision tree are generalized such that any formulation of uncertainty can be represented. Therefore, the first step required to solve the model is to formalize the parameters mathematically. In this paper, normal probability distributions are used to model the uncertainty about performance. The normal distribution was chosen because it simplifies the calculation of the posterior distributions conditional on the outcome of analyses. An example for two products is shown in [Figure 2](#). As shown in the figure, the expected net profit of A is slightly less than that of B, but B is much more variable. This introduces an