

Opportunities for Decision Analysis In Engineering Management

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Abstract

Engineering managers routinely make decisions with incomplete information in the presence of significant uncertainty that may involve multiple conflicting objectives. Decision and Risk Analysis (DRA) represent a collection of analytic tools that can be used to structure, analyze and revisit such technical decisions. However, DRA potential has not yet been widely recognized in engineering management decision-making. In this paper, we draw on our experience in teaching a graduate DRA course to more than 250 engineering managers and a review of the literature to achieve two main objectives. First, we present an overview of the decisions made by engineering managers, along with the associated objectives and surrounding uncertainties. Second, we provide a series of decision analysis templates for these decisions, covering a wide range of engineering management decision problems. These templates can be tailored to fit a specific company and then repeatedly used by managers to make better, faster and more consistent decisions.

Key words: Decision Analysis; Multiple Objectives; Technical Uncertainty; Engineering and Manufacturing Management; Product Development Decisions.

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1. Introduction

Engineering and Manufacturing managers face continuous pressure to reduce product development time, improve quality and value of products, and reduce production costs. They routinely make decisions with incomplete information in the presence of significant uncertainty (Schrader et al. 1993; Courtney et al. 1997). In addition, many of these decisions involve multiple conflicting objectives (Hammond et al. 1998). The decision-making challenge is further complicated by interaction with other parts of the organization bringing different perspectives to the problem (Kusnic and Owen 1992). Decision-makers must, therefore, not only make good decisions, but also be able to justify their choices and where possible, obtain buy-in up front. This paper explores the opportunities of the decision and risk analysis (DRA) paradigm in such decision-making environment.

The DRA paradigm and methodology is well established in many application areas ranging from energy (Keeney and McDaniels 1999), medical (Krischer 1980), to public policy decisions (Keeney 1988). However, its potential has not yet been widely recognized in engineering and manufacturing management decision-making (Chelst 1998a). In this paper, we show that DRA techniques are useful in structuring and analyzing broad classes of engineering management decisions. We do so by first providing an overview of the different kinds of decisions, objectives and uncertainties typically faced by engineering managers. Then, we group these decisions into seven major categories and develop a decision analysis template (i.e. a standard model) for each, providing engineering managers and decision analysts with useful modeling starting points.¹ Finally, we make an important observation regarding the nature of these seven decision categories, as they seem to be highly repetitive and share a basic decision structure and many common elements. This observation motivates the development of automated decision support tools based on reusable DRA templates. The templates are not supposed to be used for the less frequent, high-level strategic decisions, but for repetitive, operational decisions with abundant prior knowledge and experience surrounding them.²

This paper is motivated by our experience in teaching more than 250 engineering managers at a large automotive company and an extensive review of the DRA and engineering management literatures. We draw on these sources to develop the lists of uncertainties, objectives and DRA templates presented in Sections 2, 3, and 4 respectively.

¹ In a similar attempt, Mintzberg et al. (1976) studied 25 different decision processes taken from different industries and proposed a generic decision model that describes the structure of each.

² Mintzberg and Westley (2001) refer to this style of decision making as “thinking first” approach.

The engineering managers that we have interacted with are in a specially designed engineering management masters program and were selected from a broad cross-section of the company's technical management (Chelst et al. 1998b). In aggregate these experienced managers-students have completed more than 50 team projects, drawn directly from their work experiences, for the DRA course. These projects have covered the entire spectrum of product development, engineering, and manufacturing management. The decision level has ranged from one-person decisions to be made that day to strategic technical decisions involving choice of suppliers or global manufacturing flexibility.

In published DRA literature it is possible to find numerous disparate studies that could be labeled as engineering management decision-making.³ A paper by Corner and Kirkwood (1991) reviews the applications reported in the OR/MS literature. A special issue of *Interfaces* (1992) presents important applications of DRA and an update of consulting and management practices around the world. Other papers present a broad view of the corporate support at Du Pont (Krumm and Rolle 1992), Kodak (Clemen and Kwit 1999), Xerox (de Neufville and Pirnar 1999), GM (Kusnic and Owen 1992) and Ford (Gurusami 1998) for the methodology.

Traditionally, DRA models were built to analyze one-time decision situations. However, most engineering management decisions are repetitive. As an example, consider how many make/buy decisions a manufacturing company has to go through every year, how many requests for engineering design changes are submitted during the development of a single product, or how many decisions relating to the acceleration of a development phase are made during project execution. Hundreds, if not thousands, of these decisions are made every year in an average sized manufacturing firm. Launch data at a large automotive firm indicates that requests for late engineering changes averaged around 2600 in the last twelve months prior to launching a new product (Giordano et al. 1999). Another development data shows that managers make several hundred make/buy decisions in a single development project (Fine and Whitney 1996). If organizations were able to build standard decision models for these highly frequent and similar decision situations, which characterize most engineering management decisions, then they will be able to achieve multiple goals ranging from expediting the decision making process, documenting it, communicating it clearly, defending

³ It is also worth noting that Ullman (2002) also proposed the use of DRA techniques in engineering design.

it, teaching it (to inexperienced decision makers), to capturing and preserving organizational best practices (Matheson and Matheson 1998).⁴

The rest of the paper proceeds as follows. In the next two sections, we describe the common uncertainties and fundamental objectives that routinely arise in engineering management decision contexts. In section 4, we explore the different classes of engineering management DRA applications and present a template that frames an illustrative decision within each class. Section 5 summarizes the implementation experience, of one of these proposed templates, at a large automotive firm. Limitations or DRA and barriers to its use in engineering environments are discussed in Section 6. Finally, we present our conclusions and a summary of the paper in Section 7.

2. Uncertainties Surrounding Engineering Decisions

Uncertainty is doubt that threatens to block action (Klein 1998). It is an inherent characteristic of most engineering decisions. There is uncertainty whether or not a launch or delivery date can be met and what resources it will take. There is uncertainty whether or not a new design can meet its targets for performance and cost. There is uncertainty in the performance of a product when new unproven technologies are introduced into the development or production of that product. The list goes on, but what do all of these uncertainties have in common? Our experiences indicate that in almost every instance, the engineering managers challenged with these uncertainties were able to determine a relatively short list of possible outcomes and assign probabilities for each based on either historical data or their past experiences. When faced with this type of uncertainty (i.e. few discrete outcomes or scenarios define the future), Courtney et al. (1997) suggest that decision analysis is the tool of choice for making sound decisions.

Our intent in this section is not to present an exhaustive list of all uncertainties surrounding engineering management decisions. However, it is to emphasize the fact that the key challenge facing engineering managers is not to drive the uncertainty out of a decision situation, but to explicitly account for it in their up front decision making and management plans. Engineering managers need to understand the role of uncertainty in shaping their decisions. Underestimating uncertainty can lead to decisions that neither defend against the threats nor take advantage of the opportunities that higher levels of uncertainty may provide (Reinertsen 1997).

⁴ Plous (1993) reports on an experiment proving the reconstructive nature of memory. Thus, memory cannot be relied upon to explain how a decision was reached or for reusing a decision-making process in the future.

A generic set of key uncertain elements common to a variety of engineering management decisions is as follows:

Time: The element of time is part of every decision. It always confronts managers as a key uncertainty; except in routine processes with a long track record. Time uncertainty could appear at the single-activity level when the decision-maker is considering alternative ways to complete activities and wonders “How long it takes to complete a task?” Or at the project level, when the team questions: “Can the project deadline be met?” In general, the closer the technology utilized is to the cutting edge, the more uncertainty exists with regard to time.

Cost: Uncertainty with regard to cost is similar to time uncertainty. The more experience with similar projects the less uncertainty. Estimates of variable production costs for a totally new product can involve significant uncertainty especially in the early design phase. This uncertainty would be compounded if the technology of the production processes were unproven.

Performance: As a design team is given a complex new design challenge, they are unsure that they can deliver a design that will meet specifications within the given time and budget constraints. Consequently, the performance of the product upon release could be viewed as uncertain. For example, in software products there will be uncertainty with regard to the number of unfixed bugs at release. For a car, the ultimate NVH (noise, vibration and harshness) or ride/handling will be uncertain until physical prototypes are on the test track.

Resources: The uncertainty surrounding the resources required to complete a project is closely linked to the above three variables. If the targeted time of completion and performance are almost inviolable, then the resources required to meet these goals will be uncertain. If resources are fixed, then "time" will be the key uncertain variable. If time and resources are fixed, then performance will be the major uncertainty.

Demand: Demand uncertainty may be broken into long-term (i.e. overall demand over product life) and short-term (i.e. month-to month demand) uncertainties. Long-term demand uncertainty directly influences all production technology and capacity decisions. Short-term demand uncertainty complicates the production planning process. Demand uncertainty can be caused by our inability to predict customer acceptance or needs in a new product. Alternatively, it could be the result of unanticipated competitive actions or economic conditions.

Globalization: Globalization introduces an added level of complexity to all of the above uncertainties. Cost uncertainty increases dramatically when currency fluctuations need to be factored in. Demand for a global product is subject to vagaries of national and regional

politics and economics. Designing a product to meet the needs of diverse global markets increases the performance uncertainty.

3. Fundamental Objectives in Engineering Decision Making

The previous section described various ways in which uncertainty complicates engineering decisions. Another major complication results from multiple fundamental objectives that may need to be traded off. These multiple objectives arise whether the decision is which supplier to choose, which technology to utilize or what design alternative to pursue. Some objectives could have simple scalar measures such as dollars, computation speed, or weight. Other objectives such as “ease-of-use” may require the construction of an arbitrary scale (Keeney 1992). Common fundamental objectives can be grouped into six major categories with many sub-objectives (Keeney 1993; Keeney 1999).

Financial: Almost every decision has a financial component. The objective is either to maximize profit or more often to minimize cost. Two dimensions of cost that are frequently traded off are capital cost and annual operating cost. In theory, it is easy to integrate these two into one single cost function; in practice these are distinct costs to be explicitly traded off because they fall within different corporate budget categories.

Performance: The performance objective covers a broad range of issues that relate to the primary function of the system under consideration and is of special interest to engineering managers. If the decision were the choice of computer, performance would include measures such as speed, storage, and battery technology. If the challenge were engine design, performance would include horsepower, torque, and fuel economy.

User Needs: User needs capture those issues that may be of unique interest or concern to the decision maker and the decision context. These could include objectives such as (a) maximize ease-of-upgrade (b) maximize compatibility, and (c) minimize time of delivery. Other user needs may relate to the speed of delivery of a new piece of equipment or completion of a design change.

Operational Needs: The class of objectives that we call “operational” is meant to cover aspects of the decision that impact day-to-day operations that are not totally captured by the cost of operations. For example, in the purchase of equipment, operational needs would include the number of personnel required to operate and maintain the equipment. Although this variable could also have been included in cost, many companies treat head count as a separate variable with its own corporate controls. Operational needs would also include

power requirements, allowed ambient dust, frequency of maintenance, and training requirements.

Management Issues: The decision alternatives may need to be evaluated in terms of their impact on senior management and other parts of the company. Consequently, this class of objectives may include (a) minimize need for senior management involvement and (b) minimize impact on other parts of the organization.

Environmental Impact: Some decisions have an impact that extends beyond the organizational walls. Almost all major facility location decisions will have an environmental impact. The impact could relate to pollution levels, bio-diversity, traffic congestion, land-use patterns or the local economy. Even narrow decisions with regard to the choice of manufacturing technology would sometimes warrant the inclusion of objectives such as “minimize pollution / hazardous waste” (Wenstop et al. 1988).

4. DRA Applications in Engineering Management

In this section, we utilize the general classes of uncertainties and objectives, discussed earlier, to build fundamental decision models (influence diagrams, decision trees, and objectives trees) that could be used to frame several generic classes of engineering decisions. Table 1 provides a summary of the seven representative classes of engineering management decisions.⁵ Within each class, we define one or more specific illustrative decision and the related alternatives. The final two columns list some of the relevant objectives and uncertainties. In the sections that follow, we present and discuss a template for framing one decision within each of these classes and also refer the reader to one or more real examples reported in the literature.

(Insert Table 1 about here)

4.1 Make / Buy Decisions

All organizations are constrained in terms of their manufacturing capacity and/or capability and consequently must decide on what parts of their business to produce in-house and what others to outsource. In the simplest context, the primary objective of a make/buy decision problem is to minimize the total production cost or to maximize revenue. There is

⁵ These classes of engineering and manufacturing management decisions are mainly based on an exhaustive list of important trade-off decisions described by Skinner (1969). However, we have ignored decisions that dealt with staffing, training and organizational design from his list in order to abide by the operations perspective that this paper considers.

one decision with two alternatives: whether to make a part in-house or to contract it to a supplier.

Typically companies deal with this decision by building a deterministic spreadsheet model that contains production cost data (fixed and variable), purchase price of component (if outsourced) and demand forecasts. Uncertainty is usually not accounted for except through performing some deterministic sensitivity analysis on demand or cost data. Using DRA techniques provide a better approach for dealing with this problem. No spreadsheet or mathematical model would have the framing, presentation, and analysis capability that an influence diagram or a decision tree would offer. Simply framing the decision problem with an influence diagram as shown in Figure 1 provides a superior approach in terms of presenting the problem and communicating its structure and elements to other stakeholders. The influence diagram may then be used as a basis for discussion to include or ignore other decision elements.⁶ The elliptic nodes in the figure convey the existence of two uncertainties: demand and production cost (ignoring the shaded node in the figure for now). This decision influences the cost of production (note the directional arrow connecting the two nodes in the figure). The influence implies that the distribution used to model cost differs depending on the alternative being investigated. The figure also shows that demand is influenced by cost and both uncertainties influence revenue. An influence arrow from the decision to the demand node could be added to the figure if the decision-maker believes that demand for the product will be affected by the make/buy decision.

(Insert Figure 1 about here)

Building influence diagrams is an exercise in brainstorming the main decision elements. Converting the influence diagrams into decision trees represent the progress from the framing phase to the data collection phase. Each node in the influence diagram is represented in the decision tree, but with more explicit information regarding alternative actions, probabilistic distributions for each uncertainty, and precise outcomes for different combinations of alternatives and uncertainties. Figure 2(a) represents the decision tree corresponding to the make/buy influence diagram in Figure 1. The two decision alternatives are shown as two branches emanating from the decision node. The demand is shown to have two possible outcomes; for example, high and low demand. Cost is also shown to have two possible outcomes conditional on the different demand outcomes. In total, there are eight

⁶ Alternatively, framing may be performed with the use of a schematic tree to represent a sequence of decisions interspersed with a collection of random events (Cohan 1984).

different scenarios; each resulting in a different revenue shown as a terminal value at the end of each branch.

(Insert Figure 2 about here)

If the base problem is to be expanded to include the fact that the company and its suppliers may have different capabilities and experiences in making the part, a third uncertainty may be added to the influence diagram: “technical success” (the shaded node in Figure 1). If there is uncertainty in supplier performance (which may result in either a “good” or “bad” part) and this in turn influences the demand for the final product, then Figure 2(b) would replace the buy branch in Figure 2(a).

4.2 Go - No Go decisions:

Engineering managers often face decisions with just two basic alternatives: maintain status quo or change in attempt to improve. Some examples of decisions include whether or not to introduce a new product, incorporate a late design change, shut down a production line, upgrade an existing manufacturing process, or adopt a new technology (Weber 1993; Krishnan and Bhattacharya, 1998).

One common go/no-go decision involves a late design change. This type of decision arises both in hardware design as well as with the launch of a new software product. There could be several reasons for considering last minute design changes that occur way beyond the engineering freeze dates and critically close to the launch date. The motivation for the change might be performance related, to include another feature, enhance a performance measure (e.g. speed, torque, horsepower), or adopt a new technology. The changes might have the benefit of allowing the organization to produce a product closer to customer preferences at the time of launch. Alternatively, the motivation might be the recognition of a design weakness that could generate warranty costs or liability.

The decision to introduce a late design change into the development process is very sensitive. While addressing one concern, it might introduce numerous others. Tackling a warranty problem in one subsystem in a rush could produce problems in another subsystem. In general, companies do not utilize a formal or consistent process to analyze the need or risk of a late design change. The process is usually very subjective requiring that each change request must be accompanied with a description of the change, its need and potential value, and implementation cost and time. The chief engineer reviews this document and makes a decision on a case-by-case basis (Giordano et al. 1999).

This decision process can be improved through the structure and discipline provided by the use of DRA tools. Figure 3 reflects the basic decision and the related uncertainties. There is one decision to make with two alternatives: make or do not make the change. There are five uncertainties included in the model. There is uncertainty as to whether or not the late change will actually achieve its intended goal of improving performance (i.e. “Performance” node). Performance simultaneously influences “Demand” for the product and “Warranty Cost” estimates. The next uncertainty is related to how long it will take (or cost) to implement the change: “Implementation Time” node. A delay in launch could result in lost production and sales as represented by the “Cost of Lost Production” node. Finally, the consequence of each alternative is measured, in this example, by “Revenue”, which is influenced by warranty cost, demand, and lost production uncertainties.

A major advantage of using an influence diagram to model the late design change decision is in its ability to provide consistent and objective analysis. A form to request late design changes can be devised to populate the decision model with the necessary data. Then, the decision maker can simply run the standard model to determine the optimal strategy and to easily conduct sensitivity analysis on important parameters. We will further elaborate on this issue in Section 5.

(Insert Figure 3 about here)

4.3 Project Management Decisions

Engineering projects contain inherent risks and uncertainties. The traditional method of combating these uncertainties is to factor contingency into the time and cost estimates of a project (Rosenau 1993). Unfortunately, even with contingency factors considered most projects miss their target schedule, cost, or scope. The contingency approach to project risk management treats the symptoms of project management problems and does not allow managers to identify and understand the sources of risk involved in the project that are responsible for schedule delays and cost overruns (Browning 1998). This fact alone makes DRA an attractive tool for managers to address the uncertainty in the completion times, cost and performance of project activities (Booker and Bryson 1985; Bhuta 1992).

Developing engineering products require several design iterations before compliance with an imposed set of design specifications. The number and magnitude of these iterations are seldom known with certainty to the project manager at the outset of the development process. Failing to incorporate the impact of iterations into the schedule and budget of the

development process results in a large discrepancy between the baseline plan and the actual duration and cost of the process. Sequencing of project activities is another major issue in engineering project management (Yassine et al. 1999). Sequencing of tasks is concerned with the possibility of executing sequential tasks concurrently or with some degree of overlapping and the associated risk levels involved. Concurrent engineering is a vivid example of this management strategy where it advocates the parallel execution (or overlapping) of development activities as a tool for faster product introduction (Krishnan et al. 1997).

As an example, consider the process of designing a new automotive cylinder block. The process might require several design iterations before compliance with an imposed set of design specifications (Yassine et al. 1999). The influence diagram shown in Figure 4 describes the basic structure and elements of this product development project. In the figure, there are two major decisions to be made: "Task Execution Strategy" and "Overlapping Magnitude". The first decision addresses the sequencing of the project tasks and the second covers the choice of possible overlapping times between project activities. There are four uncertainties. The node "Manufacturing Feasibility" reflects the performance uncertainty, of the engineering design activity, to fulfill the design objectives or to produce a manufacturable design. The node "Infeasibility Magnitude" probabilistically captures the amount of rework (i.e. redesign) that the engineering design activity has to repeat in order to produce a feasible design. The "Number of Design Process Iterations" node represents the uncertainty in the number of iterations involved in the process before an acceptable design is reached. The "Information Change During Overlapping" node reflects the change in design information from the time overlapping starts until the end of the design phase. Changes in design information, if any, during overlapping have to be incorporated into the design process by performing some rework.

(Insert Figure 4 about here)

Considering the fact that PERT is the only tool available to project managers that allows limited incorporation of uncertainty in task durations, DRA project management models become a real asset. These models will allow project managers to plan for iterations upfront, devise a winning overlapping strategy, and accurately predict project costs and lead-times.

4.4 Prototyping Decisions

A fundamental capability of decision analysis is its ability to determine the expected value of collecting information that improves a forecast but which cannot completely resolve

the uncertainty. This information has been termed either sample information or imperfect information. The classic example in business textbooks involves the use of a market test to better estimate demand. In engineering management context this same issue arises when evaluating the potential benefit of building a prototype of a new product or constructing a pilot plant to prove out a new manufacturing technology.

The decision as to whether or not to build a prototype product or process is usually imbedded in a core decision of whether or not to go ahead with current plans for the product or manufacturing process. The greatest value of building a product prototype is in reducing the risk and magnitude of costly design iterations (Klein et al. 1994; Thomke and Bell 2001). For example, building and testing a prototype for a molded part may detect a problem with the mold before the costly development activity of building an injection mold (Ulrich and Eppinger 1995). The performance tests on a prototype of a complex product, such as an automobile, are used to decide whether or not there is a need for a minor or major redesign of a component or entire system.

The three major uncertainties associated with this decision are a) the time (or cost) of design activities prior to the prototype build decision (i.e. upstream), b) the time (or cost) of prototype development, and c) the impact of the prototype on subsequent (i.e. downstream) tasks. The impact can be measured as the reduction in downstream task duration (or cost) when a prototype is utilized versus no prototype. A representative influence diagram is shown in Figure 5. The diagram shows that the product development time or cost is influenced by the three major development activities. The uncertainty in the duration and cost of the downstream tasks is influenced by whether a prototype activity is involved or not. Note that the time and cost of design and development activities prior and subsequent to the prototype build decision are intentionally lumped into one single activity for simplification.

(Insert Figure 5 about here)

4.5 Product Planning

Companies have come to realize the need to evaluate and optimize a portfolio of products rather than designing each product as if it were in isolation (Sanderson and Uzumeri 1997). Du Pont, for example, is a leading user of decision analysis to address this problem (Krumm and Rolle 1992). By planning an entire portfolio as an entity, companies can achieve efficiencies of design and manufacturing through a) minimizing overlap and cannibalization, b) maximizing commonality of components that are invisible to the end-user and c) providing coverage of all segments and global markets.

In Figure 6 we illustrate the basic decision with just two product classes, luxury and standard. The main decisions involve establishing a set of price points for the family of products and defining the characteristics of each product to provide increasing value consistent with higher price points. This class of decisions arises whether the product family is microprocessors, cameras or automobiles. It even arises in the service industry as exemplified by the portfolio of warranties available with an expensive purchase.

(Insert Figure 6 about here)

As in every product-planning problem, the major uncertainty revolves around product demand. That uncertainty is influenced by the pricing and feature decisions. In the portfolio problem there is an intervening random event between demand for the standard and luxury products. That uncertain event is the degree of cannibalization of the luxury product by the standard product. The closer the two products are in features and the farther apart they are in price, the more cannibalization there will be between the two product categories. There are also a number of other relevant random events that influence all product decisions in this case, but were left out of the diagram for simplicity. These include uncertainty regarding competitive actions and the economy.

4.6 Capacity Planning

A fundamental question when introducing a new product or service is "how much capacity to build?" This question arises whether the focus is a power plant, a manufacturing facility or a service facility such as a hospital or sports stadium. Capacity planning decisions generally involve large capital investments, can take years to plan and implement and their affects can linger on for a decade (manufacturing) or decades as in the case of power plants and stadiums.

The length of the planning horizon automatically increases the surrounding uncertainty, as the decision-makers must peer deeper into their crystal ball to predict the future. First and foremost, they face uncertainty surrounding overall demand for the product or service that can be influenced by changes in overall economic conditions, changes in market taste or structure, or technological breakthroughs that dramatically influence the overall demand. The risks are compounded by uncertainty about the company's market share that may be influenced by competitors' actions.

In addition to these externalities, there can be significant uncertainty regarding the actual operating capacity or throughput of the facility (Spetzler and Zamora 1989). The initial yield for a new chip factory can be highly uncertain. A complex assembly system could face

unanticipated bottlenecks. Other uncertain elements could relate to the time to bring the facility on line and to a lesser extent the cost associated with its construction.

Figure 7 presents an influence diagram for the capacity planning problem. There is one decision in this influence diagram: How much capacity to build? Furthermore, there are three major uncertainties: total demand, market share, and actual yield. Total demand is influenced by two main uncertainties: economic conditions and technological developments. The company's market share is influenced by the competition. The actual yield of the plant capacity influences total cost which in turn determine the company's profit. The influence diagram may also include a location decision such as where to build the capacity. Such a decision will influence the actual yield uncertainty and all of the uncertainties influencing the “Total Demand” node.

(Insert Figure 7 about here)

Within the aggregate capacity decision, there is a subsidiary decision of how to divide up this capacity and in particular how much flexibility to build in (Graves and Jordan 1995). Flexibility allows production mix to adjust as product demand shifts, with minimal incremental investment. Demand uncertainty drives the need for and the financial value of flexibility investments. Flexibility mitigates the risk of demand uncertainty at an expense of some extra investment. Additional decision elements could easily be incorporated into the basic influence diagram, above, in order to evaluate the additional flexibility decision.

4.7 Selection Problems

We use the term “selection problems” to cover a wide array of engineering decision making problems that involve the selection of one alternative from amongst a set of distinct alternatives. The decision maker may need to choose from a list of alternative technologies, materials, suppliers, facility locations or projects. If the primary objective was cost and there was significant uncertainty, the decision tree would be the preferred tool of analysis. More often, however, these types of selection problems are difficult because they involve multiple objectives. The first step in modeling this situation is to create a fundamental objectives tree that captures the main issues. If the objectives and their associated measures are quantifiable and there is data or expert opinion for each alternative, multi-attributed utility theory (MAUT) (Keeney and Raiffa 1993) would be the preferred analysis tool. If the objectives and measures are hard to quantify and there is little specific data on the alternatives, then the Analytic Hierarchy Process (AHP) (Zahedi 1986) could be used. Both MAUT and AHP are capable of integrating several different types of data into a single decision model. This is

important in an engineering environment because decisions are usually based not only on quantitative financial data (such as cost or profit) but also on non-financial quantitative data (such as torque or horsepower output of an alternative engines) and on qualitative judgmental /subjective measures (Weber 1993).

The key challenges in constructing a useful fundamental objectives tree is to create a parsimonious list that is complete but not cumbersome and for which measures can be defined. In some instances, an artificial scale may need to be constructed (Keeney 1992) to reflect an important objective. Although every decision warrants a unique objectives tree, in the sections that follow we present representative trees for different classes of selection problems. In almost all cases, there will be at least the following three major groups of objectives: a) cost, b) timing and c) performance. These categories are often at the top of a hierarchical list of objectives. Cost might be further divided between capital and operating. This sub-categorization makes sense as long as these costs come from distinct budget categories that at times are traded off. Performance is the broadest category and can cover a wide range of measures. In the choice of powertrain, this could include hp, torque, fuel economy, and NVH.

4.7.1 Supplier Choice

The days are gone when important supplier decisions simply involve a comparison of costs adjusted for quality (Fine and Whitney 1996; Gurusami 1998). With the increasing awareness of supply chain management, organizations are seeking strategic alliances with global, full-service suppliers that can support the organization in all business aspects including quality, cost, delivery, and global presence. In addition, manufacturers of complex products are passing on more and more of the subsystem design responsibility to their tier 1 suppliers. Thus, suppliers must also be evaluated on measures that capture their design capability.

In Figure 8 we present a scaled down version of an objectives tree that would be used to select a full service supplier (FSS) for a major subsystem such as a seating system for a car. The five major categories of objectives include a) design process, b) manufacturing capability, c) product characteristics, d) supplier management stability, and e) cost. In this day of total supply chain management, manufacturing includes not just quality but also timely delivery and flexible capacity. The quality of the design process is included since at the time the particular choice is being made the details of the design may not have been finalized. In addition, one purchase will often lead to the purchase of future products that are only in the

planning stages. Thus they must also consider the long-term stability of the supplier organization.

(Insert Figure 8 about here)

4.7.2 Technology Choice

Selecting the right product or manufacturing technology is a critical decision that can engage the organization in substantial long-term commitment. At one extreme the decision could involve the choice of the entire process. On a smaller scale it might be limited to a single piece of equipment.

A simple illustrative example of a choice of technology involves selecting amongst alternative bomb detection systems (Clemen 1996). The fundamental objectives tree included four objectives: cost, effectiveness, implementation, and acceptance.⁷ Cost is a high level objective that includes sub-objectives a) purchase cost and b) operating costs. The performance objective is primarily linked to detection capabilities: a) detection of metal weapons and b) detection of explosives. Included in this category might also be a measure of reliability such as percentage downtime. Ease of operation is an important issue that can be reflected through two surrogate measures a) staffing requirements and b) training costs. Since this equipment interferes with the free flow of the public another objective is to maximize “customer acceptance.” This measure could involve a subjective assessment of customer acceptance or use customer-processing time as a surrogate measure. There may or may not be a difference between the time to install and make fully operational different detection systems. This objective would be to minimize implementation challenge. This includes measures such as a) time to deliver and install and b) start-up training costs. Finally, an important measure that often arises in technology choice decisions is “ease of upgrade.” This is of special concern in fast moving areas of technology such as computers and computerized equipment. Usually this measure will require the creation of a subjective scale and a subject matter expert to evaluate “ease of upgrade” for each of the alternatives.

4.7.3 Facility Location

The problem of where to locate a major public facility is almost always a multi-faceted problem whether the facility is a library (Clemen 1996), a power plant (Wenstop and Carlsen 1988; Kirkwood 1982), a hazardous waste site (Merkhofer and Keeney 1987), or a

⁷ This objectives tree is modest when compared to the objectives tree used in a technology choice for the Baltimore Gas and Electric Company (Keeney et al. 1986). Their objectives tree involved 8 major categories with fifteen specific measures.

service terminal (Hegde and Tadikamalla 1990). Besides the issues of cost of construction, land acquisition and transportation there are also environmental impact issues. More recently manufacturing managers have come to realize that the placement of a new manufacturing plant must also consider a variety of non-cost issues. Of particular concern is the availability of a skilled or trainable workforce that can meet the increasingly sophisticated needs of a modern manufacturing facility (MacCormack et al. 1994). Additional issues arise when the alternatives in question involve which country to build the plant. Now a host of other measures related to the national economy, trade laws, infrastructure and political stability must be factored in.

4.7.4 Rank Ordering

In many contexts, engineering managers must consider a list of potential projects or product features to proceed with. If these projects or features are essentially independent of one another, a simple strategy often used is to rank order them and move ahead with the highest ranked ones. The most common context for this type of decision is R&D project selection (Schmidt and Freeland 1992; Hess 1993). In an R&D setting, the most important criteria articulated by Hess (1993) are the probability of technical success of a project, development speed and cost, capital requirements, sales potential, and marketing cost.

Another popular rank ordering application in engineering management is Quality Function Deployment (QFD). In this case, MAUT (or AHP) can be used to prioritize customer requirements before proceeding with the QFD application (Armacost et al. 1994). This pre-QFD analysis step is useful in situations where there are multiple classes of customers, each with different (sometimes conflicting) set of priorities.

5. Implementation Experience

Organizations need not attempt to launch an aggressive effort to build company-wide DRA models in one single step. However, implementation can proceed incrementally by prioritizing and selecting decision situations in greater need of support and automation. One such opportunity identified by a team of our student-managers involved the “late engineering changes” process in their company (refer to Section 4.2). This section will summarize their findings in implementing a structured approach, based on the RDA paradigm, for addressing the late engineering changes decision (Giordano et al. 1999).

The team started the project by conducting a RAPID (Rapid Action for Process Improvement Deployment) on the “late engineering change” process to understand the

current process and address the effects of late engineering changes on the end product.⁸ By conducting the RAPID, the team was able to gather valuable information regarding the current decision making process, problems associated with it, and proposals for improvement.

All participants of the RAPID came to an agreement regarding the following:

- Most late engineering changes are made strictly on judgment.
- The current method for late engineering changes is not adequate.
- In the case where experienced engineers are involved, decisions are made in a short period and are most likely successful.
- It is essential to capture the lessons learned and implement past experiences into the model for inexperienced engineers.
- It is almost impossible, even with experienced engineers, to capture all aspects of the late change decision without a disciplined approach.

The DRA model developed is an expanded version of the one shown in Figure 3. However, the model provides for six categories of change drivers: management directed, customer satisfaction, quality, cost, feasibility, and missed target.⁹ Figure 9 shows the influence diagram used. The “Change Driver” decision node allows users to specify the reason for which the change is requested and accordingly the decision process will differ depending on the condition driving the change. Once the change driver is specified, the main decision becomes whether to “make” the change or not. Another pseudo decision node is “Program Timing”. If the launch date cannot be met due to incorporating the change, then the change request is automatically declined and the decision process is aborted.¹⁰ A third pseudo decision deals with the type of testing required if the change is implemented. The two test types considered are “Design Verification Plan” (DVP), if there exist a test program in place, and “Engineering Judgment”, if no standard test exists.

The “Make Change” decision influences “Customer Satisfaction”. Customers may then react (“Customer Reaction” node) by either purchasing or not purchasing the vehicle (of course only due to that particular feature/part affected by the design change).¹¹ If customers decide to buy the car, then the “Owner’s Action” will either be to “Live with Condition” (i.e. feature/part affected by not making the requested design change) or to “Fix on Warranty”.

⁸ A RAPID for a specific process takes the form of a workshop with the appropriate stakeholders represented.

⁹ In this paper we will only show the decision tree for the first four of these change drivers due to clarity and space limitations.

¹⁰ This decision node could be an uncertainty if management allows for the possibility of not meeting the program timing, given that the “Make Change” alternative may prove to have a better expected value.

¹¹ This node is analogous to an uncertain “Demand” node.

This would ultimately determine the “Warranty Estimate” the company will incur. Furthermore, “Warranty Estimate” is also influenced by the “Test Type” decision. The more complete the testing program is, the lower the number of warranty repairs per 1000 vehicles (R/1000) is likely to be.

The revenue node is influenced by four uncertainties: demand for the car as represented by the “Customer Reaction”, “Warranty Estimate”, variable (i.e. piece) cost (saved or incurred over the base program piece cost, due to making the change), and fixed (i.e. tooling) cost (incurred over the base program). Finally, the decision tree that result from the above influence diagram is shown in Figure 10.

The model was implemented using MS Excel and the add-in DRA software called Precision Tree. An extra layer of Visual Basic Macro programming was added to develop a user friendly input layer and automated generation of reports from the DRA analysis. The model user is a team of design change stakeholders. The team is required to complete a questionnaire, which will take about half an hour.¹² Once the input is gathered, the Excel-based model, automatically process the data and a sequence of reports are generated including the optimal decision and what risks, in terms of cost, are associated with that decision.

The DRA model was proven out via a series of test phases. These phases validated that the model functioned as designed as well as met the user needs. The first phase of testing was conducted using two sets of historical late change data. The second phase consisted of piloting the model, over several weeks period, at an assembly plant. The plant engineering involved in the change process utilized the model successfully over the pilot period and suggested many changes, which were incorporated into the model. Finally, the team developed a roll out plan for a select vehicle program. Once successful, the model can be rolled out to other programs.

6. Alternatives, Limitations and Barriers to the Use of DRA in Engineering

Management

What are the realistic alternatives to using Decision Analysis when faced with significant uncertainty and/or multiple objectives in a wide range of common engineering management decisions? At one end of the spectrum are the non-analytic processes that discuss creating a list of pros and cons and somehow integrating this list to come up with a

¹² The questionnaire is a sequence of MS Excel forms developed as a user-friendly interface to the DRA model.

decision. At the other end of the spectrum are more sophisticated tools that are harder to understand intuitively and require more expertise to implement. Simulation is one alternative to decision trees and would be appropriate for modeling complex stochastic systems. Multi-objective optimization such as goal programming would be appropriate if there were large numbers of decision variables (such as design parameters) with a potential wide range of values. However, for a decision with a limited number of discrete alternatives MAUT or AHP would be far easier to understand and explain.

DRA techniques are not appropriate for every engineering management decision problem. For example, MAUT can be used to rank order a set of distinct alternatives. However, if the challenge were to select a set of two or more alternatives that may interact or overlap, a portfolio model would be more appropriate than MAUT (De Maio et al. 1994). Furthermore, a complex set of sequential decisions such as what would arise in a multi-year capacity expansion problem might better be modeled with dynamic programming techniques. Finally, DRA techniques would be less appropriate if there were a large number of decision alternatives to be evaluated or if the decision variables were continuous. If the problem included more than a few constraints, the analyst would need a procedure that creates feasible solutions before attempting to find the optimal solution. Analogously, decision trees and MAUT would be of limited value in modeling complex systems, whether or not there was uncertainty. Simulation, systems dynamics or theory of constraints might then be the more appropriate analytic approach. However, it should be noted that decision tree software is now capable of interacting with sophisticated spreadsheet models that extend their ability to model complex systems.

In our experience the most significant barrier to the use of this structured decision process is the feeling that it will take too much time and effort. This problem is compounded by the positive reinforcement executives receive as they rise through the ranks making the “right” decisions all along the way. This is coupled with a growing sense that decisions have to be made faster and faster and that all that is needed for a good decision is the right group of experienced managers to get together in a large meeting and hammer out a preferred strategy. However, such an approach is riddled with well-documented biases, is heavily influenced by personalities and is not reproducible. If the decision may need to be revisited because the situation or decision makers have changed, there is no foundation to build upon. In essence one executive’s lament best summarizes the situation: “We never have enough time to make the right decision the first time but we always have enough time to revisit the decision over and over again.”

A second barrier is that engineers are trained to be analytical with honed quantitative skills, but not steeped in probabilistic thinking (Hammond and Keeney 1999). They tend to avoid converting opinions and subjective judgments into basis for decision-making (Luman 1998), instead they prefer to use quantitative decision models (Cabral-Cardoso and Payne 1996). Additionally, addressing and admitting uncertainty among a group of technical experts might be perceived as a sign of weakness or ignorance: “if you are the expert, then you should know all the right answers without any ifs or buts”. This is related to what decision analysts refer to as the “Expert Bias”. In some other situations management penalizes their experts for reflecting uncertainty in their answers or estimates. Management expects a single certain answer instead of a range of possible outcomes/answers regardless of the decision situation and the uncertainties that might surround it.

Lastly, formal and expert MAUT analysis faces a different challenge. With spreadsheets, managers have found it easy to create a list of objectives and assign weights. The ease of the task undermines the need to really understand the fundamental principles of MAUT. Errors can include a) poorly defined objectives that may overlap resulting in double counting, b) use of linear scales when the value function is non-linear, c) lack of care in obtaining expert assessments and d) assignment of weights without understanding how the weights interact with the scale used to measure performance on each objective. Thus although MAUT (or AHP) is likely to find a more receptive ear than decision trees, engineering managers may not appreciate the difficulty in applying the concepts correctly and believe that expertise or training is not required to use MAUT.

7. Conclusion

The paper demonstrated the opportunities of decision analysis in modeling a wide range of engineering management decisions. To establish the connection between the DRA paradigm and engineering management decision-making, we explored the various uncertainties and multiple objectives that complicate engineering management decisions. Furthermore, the paper offers decision analysts and engineering managers a series of decision analysis templates, covering a wide range of engineering management decisions. Although these templates are not fully built-up, they provide value as modeling starting points.

Contrary to the traditional use of classical DRA models, where a specialized decision model is built for a specific decision problem, this paper advocates the use of standard decision analysis templates. These templates are useful in situations where similar decision problems are frequently encountered. For these decisions, it is worth building standard

decision analysis templates to help decision makers in making better decisions faster and with greater consistency. We have shared one successful implementation experience with the “late engineering changes” decision template. The implementation provides encouraging support for the potential of developing company wide engineering management decision support systems based on decision analysis templates.

We believe that with such decision analysis templates, companies will not only facilitate decision making for inexperienced decision makers, but also allow for the development of best practice repositories that help in preserving the company’s decision-making expertise over time. Moreover, the development of these templates add value indirectly through:

1. Providing a “common language” and “shared vision” for a group to discuss all elements of a decision problem and explore areas of specific disagreement. In turn it helps build consensus which speeds decision implementation.
2. Documenting a decision experience that enables future justification and reuse. As Ullman (2002) noted, most engineering decisions are either totally unrecorded, or at best only the conclusion is captured in a memo. However, the logic behind the decision, the alternatives considered, and the criteria used are lost.¹³
3. Providing a system to track “critical” uncertainties during both the decision making and implementation phases.

¹³ In engineering design research, the flow of decision making is often called design rationale capture and is still the topic of much research (Ullman 1994).

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Table 1

DRA Engineering Management Applications

Problem Type	Alternatives	Objectives	Uncertainties
Make / Buy	Make in-house or Outsource	Reduce Cost Improve quality	Production costs Outsourcing cost Quality Delivery
Go / No Go Launch new product Late design change Process upgrade	Yes or no	Reduce production cost Reduce warranty cost Improve customer satisfaction	Implementation time Performance of new design New problems with new design
Project Management Task execution Task crashing	Parallel vs. sequential Normal vs. accelerated	Min. completion time Min. Project cost Improve probability of completion	Time Cost Performance
Prototyping Product Process	Comprehensiveness Timing	Reduce development time/cost Test market demand	How much prototype represents reality Learning and improvement
Product Planning Product mix Product features Cannibalization	Products to offer Features to include Price points	Increase customer satisfaction Improve sales Reduce production cost	Demand Customer acceptance Market penetration
Capacity Planning Size Location Flexibility	Expand an existing facility Move to another facility Design-in flexibility	Meet future demand at lowest cost Maximize profit	Future demand Production costs Yield or throughput Downtime Productivity
Selection Problems Suppliers Technology Locations Projects Design alternatives Customer attributes	Select amongst alternatives Rank order Alternatives	Best in terms of: Cost Performance Quality Service etc...	Quality Cost Delivery speed Performance

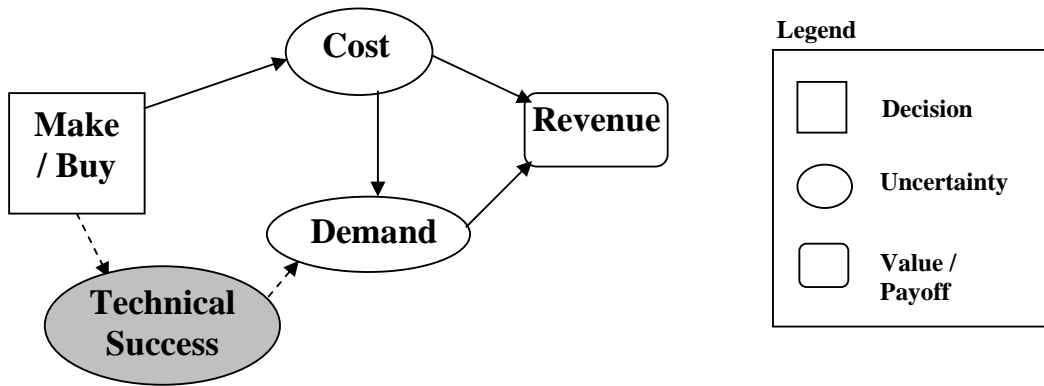


Figure 1: Make/Buy Decision Influence Diagram
 (Shaded node represents an expansion of problem scope)

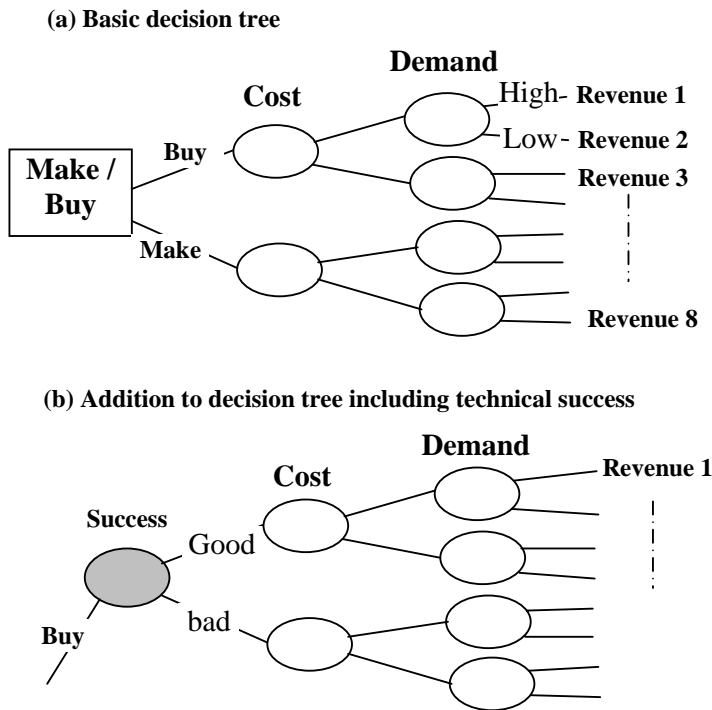


Figure 2: Make/Buy Decision Tree

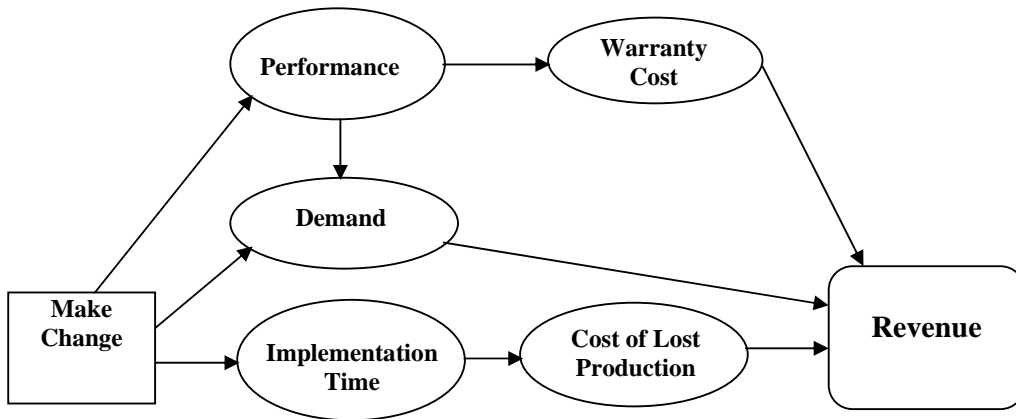


Figure 3: Late Design Change Influence Diagram

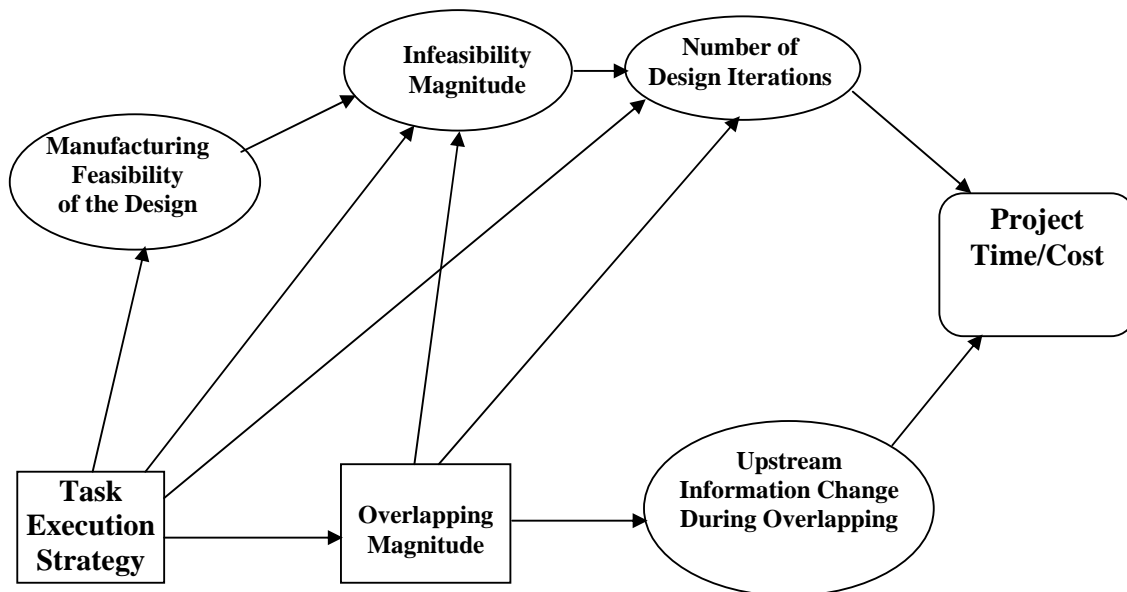


Figure 4: Project Management Influence Diagram

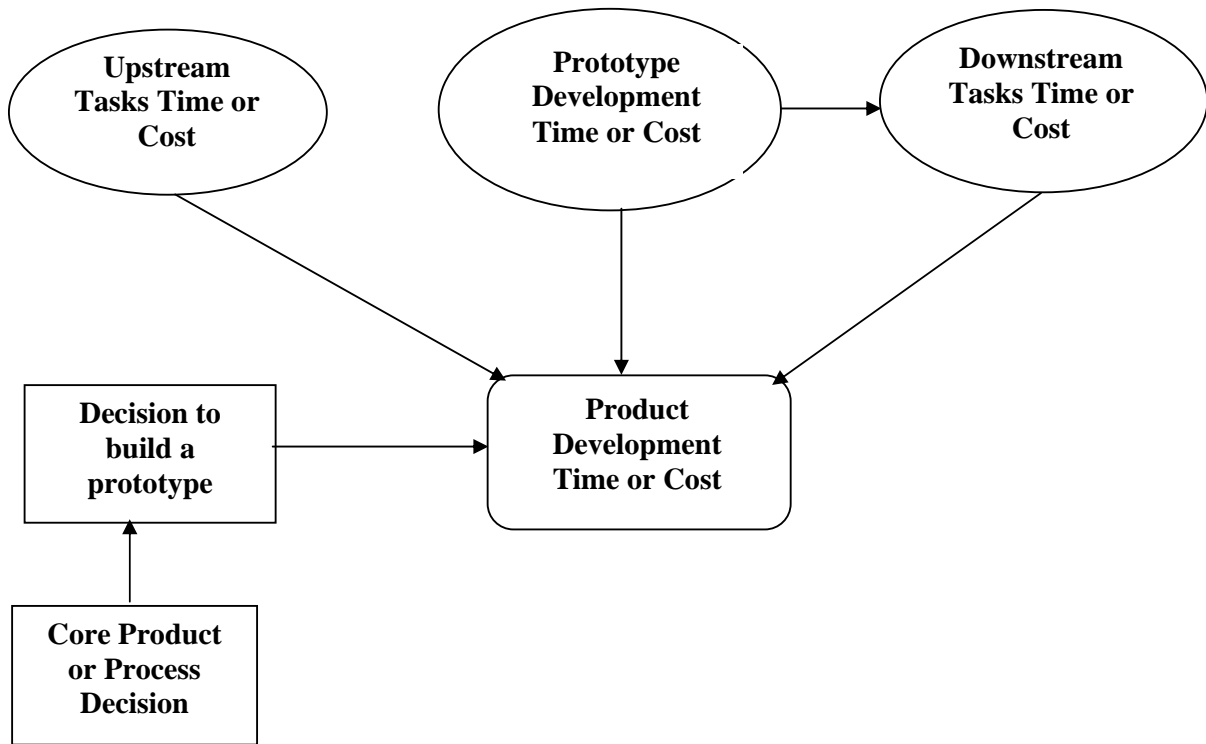


Figure 5: Prototyping Decision Influence Diagram

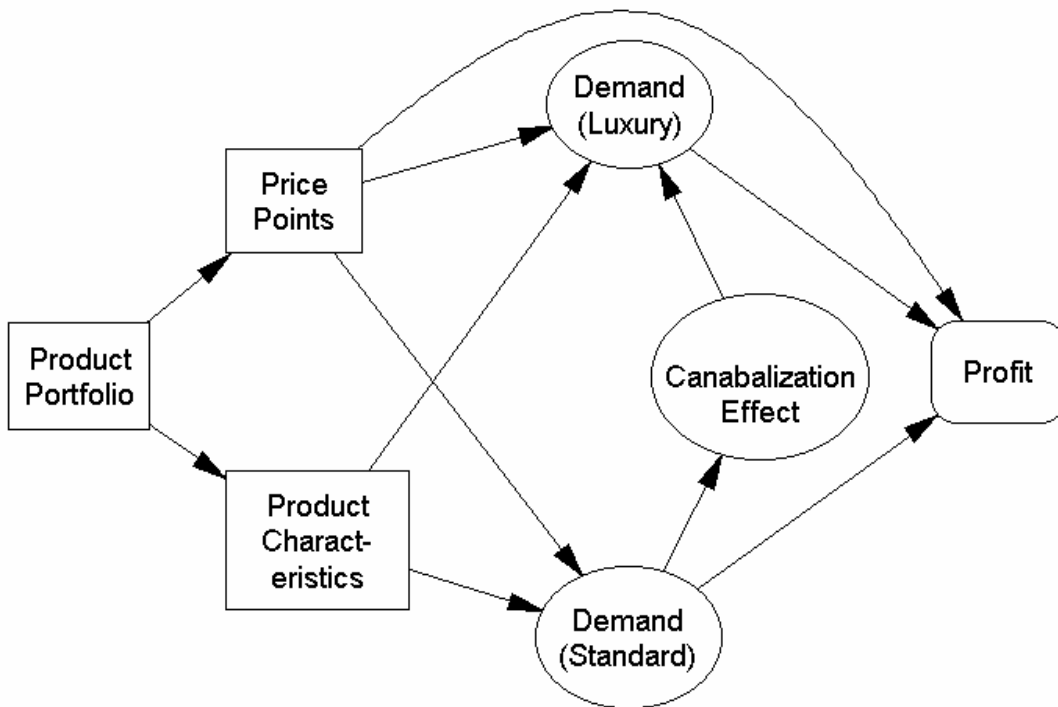


Figure 6: Product Planning Influence Diagram

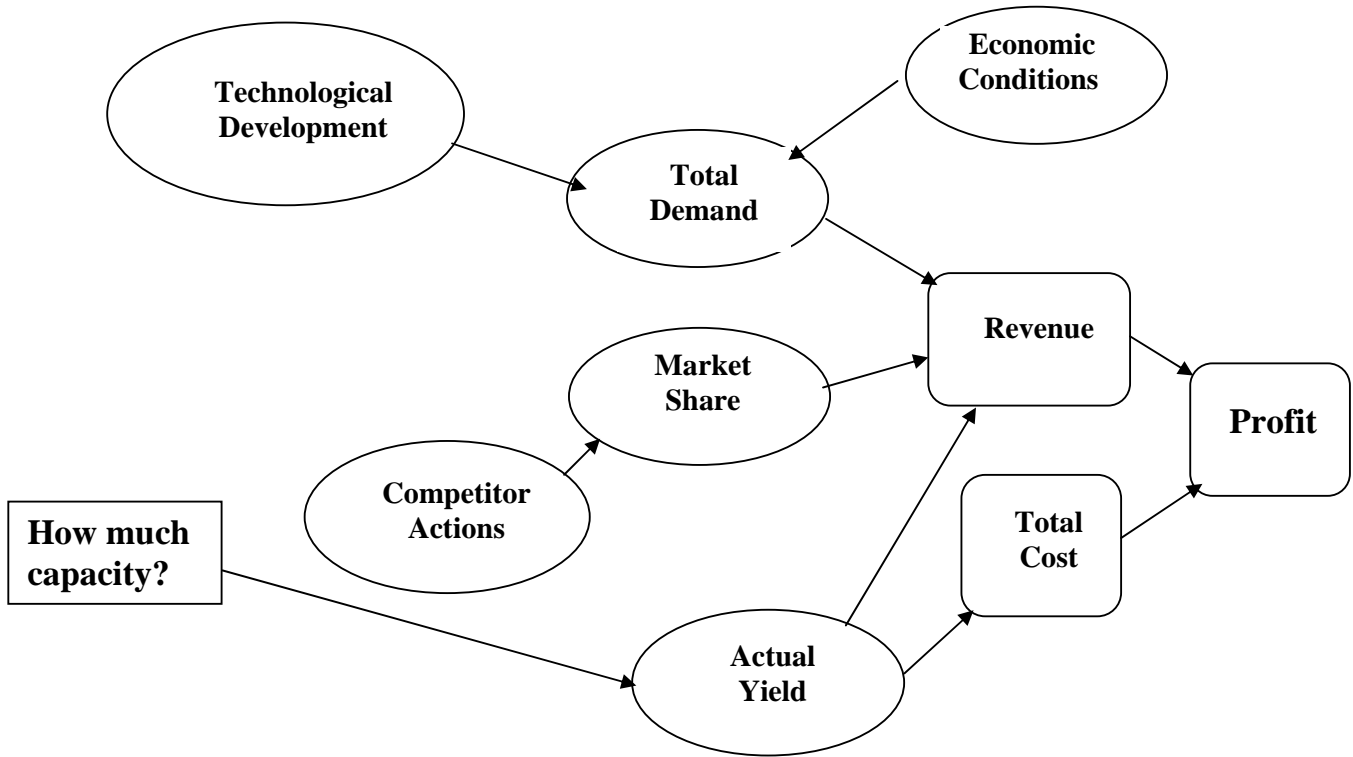


Figure 7: Capacity Planning Influence Diagram

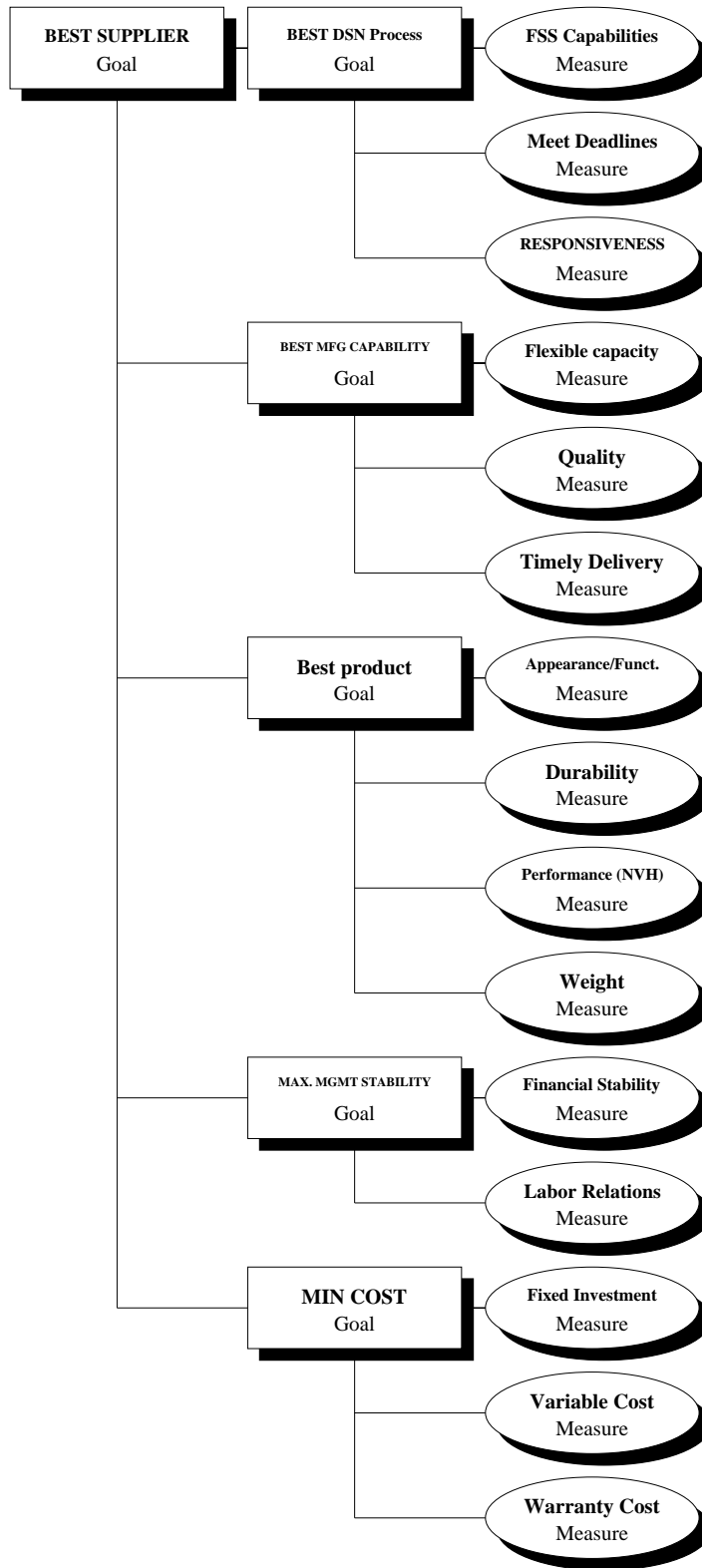


Figure 8: Supplier Selection Objectives Tree

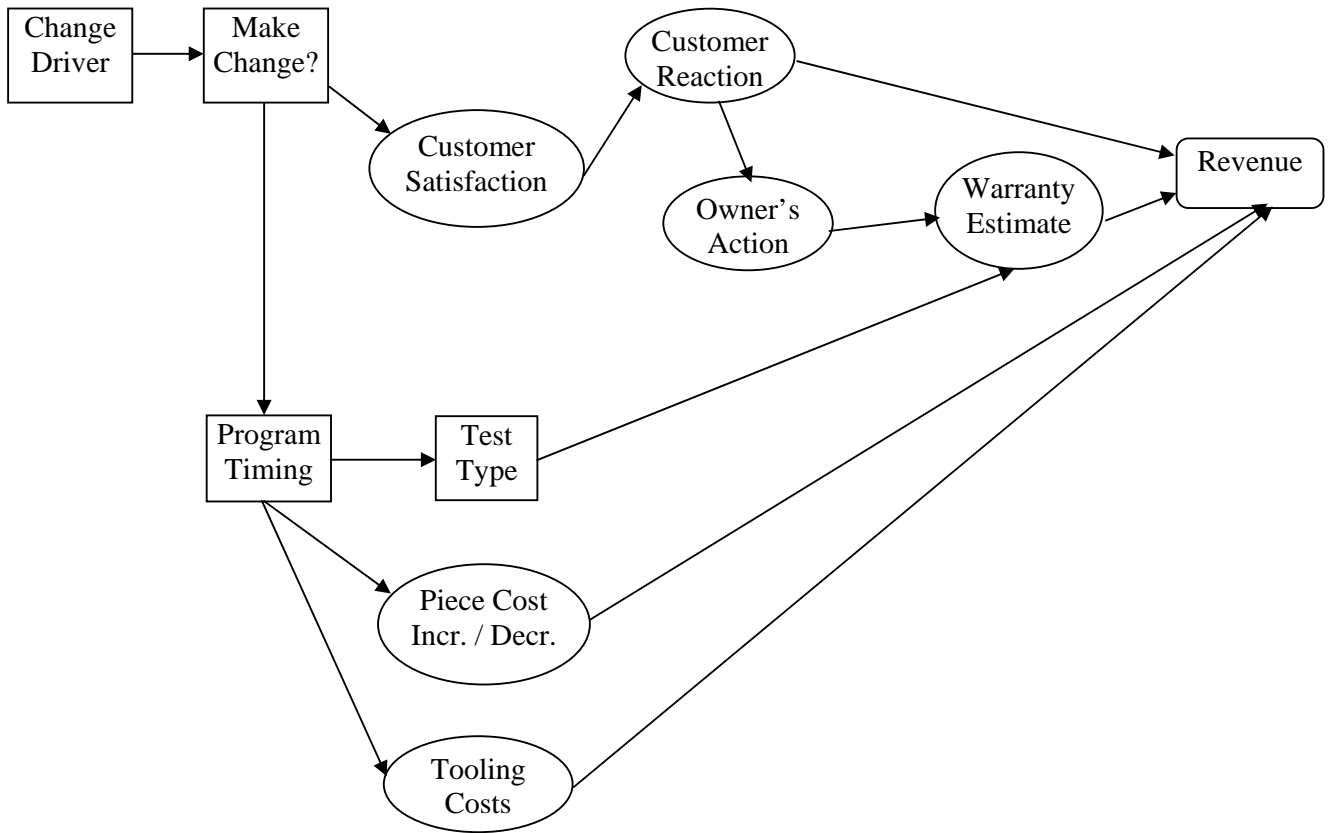


Figure 9: Expanded “Late Design Change” Influence Diagram

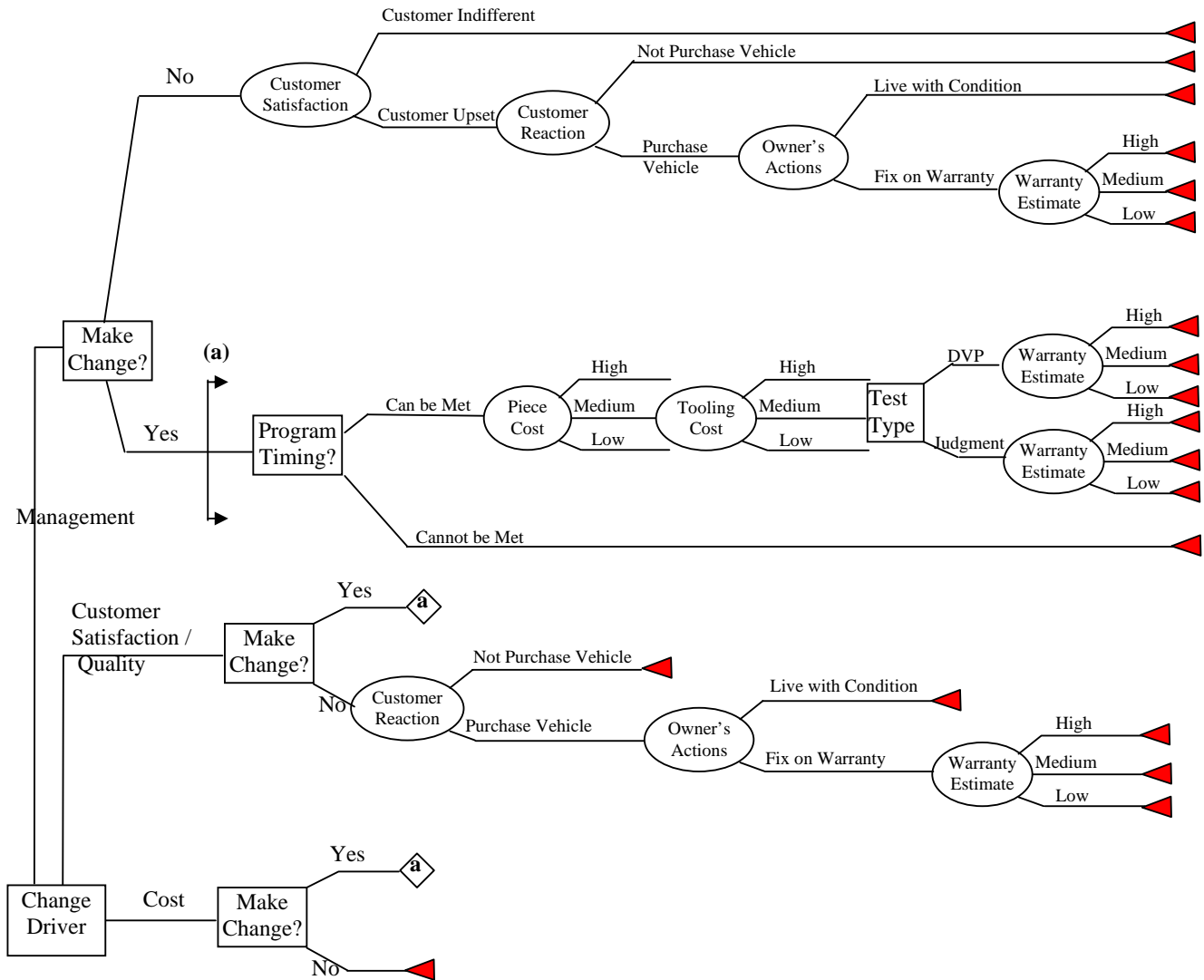


Figure 10: Expanded "Late Design Change" Decision Tree