Chapter 7

FORMALISMS FOR NEGOTIATION IN ENGINEERING DESIGN

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Abstract Engineering projects often undergo several design iterations before being completed. Information received from other groups working on a project (analysis, manufacturing, marketing, sales) will often necessitate changes in a design. The interaction between different groups associated with a design project often takes the form of informal "negotiation." This form of interaction commonly arises when engineering information is imprecise. The Method of Imprecision (M_oI) is a formal method for the representation and manipulation of preliminary and imprecise design information. It provides a mechanism for the formalization of these informal negotiations. The nature and scope of informal negotiation in engineering is explored and discussed, and application of the M_oI is illustrated with an example.

Introduction

Engineering design projects in industry commonly involve many different work groups or individuals. In addition to a division of labor by subsystems, there is a division of labor by engineering task. For example, the solid modeling and finite element analysis of an artifact may be handled by different engineers. Production engineers form a group with its own set of concerns, reflected in the considerable literature on the importance of design for manufacture (see [5] for a good bibliography). Finally, design engineers are ultimately responsible to their customers. The customers' concerns are typically represented by management or marketing, who form yet another group with an interest in the design process. The groups within an organization that participate in a project, who are not necessarily all engineers, will be referred to here as *working groups*.

Interest in the issues that arise when so many different groups share the design task has led other researchers to explore concurrent engineering. [16], in particular, have pointed out the importance of the communication of set-based information between downstream and upstream processes. In this paper, we deal with situations of *negotiation* between working groups that arise in the course of a shared design task. Negotiation occurs whenever one working group desires a change in work done by another working group. Often, a defining feature of a negotiation situation is that the two groups have different views of the design object or process. It is possible, however, for situations that are appropriately modeled as negotiation to arise where there is a single, agreed-upon view of the design. In general, this negotiation is highly informal.

Other researchers, particularly in the artificial intelligence community, have seen conflict and negotiation between agents as a crucial part of the design process. Several systems have been developed that attempt to model, incorporate, or handle conflict in design [2, 3, 6, 9, 13]. These projects will be discussed below.

This paper was motivated by work done by the authors in collaboration with a US auto manufacturer and a material manufacturing research center. We found that the informal negotiations described above are common, so common that informal negotiation appears nearly an automatic part of any design process. In most cases, it is not even recognized as negotiation, yet in some instances the culture of negotiation is so highly developed that parties “come to the bargaining table” with exaggerated estimates because they expect to be “bargained down.”

Why is this sort of negotiation so prevalent? One reason is the fundamental imprecision inherent in engineering design. Final designs are exact (including manufacturing tolerances), yet such precision is present only at the end of the design process. Engineers (and managers) routinely conduct analyses and make decisions with imprecise quantities. As a design progresses, information becomes more precise, and it may become necessary to revise earlier estimates. Yet the preliminary decisions account for an overwhelming fraction of the total cost of a design, with some studies citing figures up to 70% [17].

Despite the ubiquity of imprecision in engineering design, there are few tools for dealing with imprecise information. One such tool is the *Method of Imprecision* ($\mathrm{M_oI}$) [18], a formal method for representing and manipulating uncertainty in engineering design employing the mathematics of fuzzy sets. It has been shown that the $\mathrm{M_oI}$ can be used to combine design information using a variety of different trade-off strategies [11, 15]. Other references have developed the $\mathrm{M_oI}$ for industrial application [8].

Current work undertakes to use the structure of the M$_o$I to formalize the presently informal negotiation process. The mechanisms employed by the M$_o$I for the representation of uncertain or imprecise information are particularly well-suited to the formal representation of the negotiation process. By formalizing the negotiation process, design teams can promote a more complete exchange of information and have a mechanism to trace the history of a design through its iterations. The existence of a formal negotiation tool may facilitate the inclusion of important performance goal and market information, thus allowing the incorporation of more relevant information into the early design stages.

This paper discusses the context and importance of design negotiation in industry, and demonstrates the application of the M$_o$I to place negotiations on a formal basis.

Examples of Negotiation in Design

The following examples are not exhaustive, but they indicate the wide range of design negotiation situations:

Unreachable target performance values

One example of design negotiation occurs when an engineer or engineering group is given the task of designing a product to a target performance specification. When the product is a newer model of an existing product, the target is often an incremental improvement over last year's model. As an example, consider an automobile chassis, where an existing model has a torsional stiffness of 12,000 ft.-lbs./degree and this year's requirement is to exceed that by 10%. If the engineers are unable to reach the fixed target easily, they will return to the manager who set the task and begin a negotiation process (indeed, this meeting may be scheduled long before any potential problems are known). The engineers may ask for more resources, for a relaxation of other targets, or for a compromise on the original target. Targets are almost never immovable, and managers are commonly willing to negotiate.

Here, negotiation serves to address an inadequacy in the original description of the problem: the ostensibly exact (or *crisp*) requirement is in fact fuzzy, and through negotiation the two groups (in this case, chassis designers and their managers) explore the nature of the "constraints." To formalize this negotiation and reduce pre-distorted bargaining positions, it is important to be able to represent the inherent fuzziness in the constraint. The M$_o$I uses fuzzy sets to represent such imprecision, as will be shown further below.

Trade-offs between facets of performance

An additional layer of complication is added when several target performances are considered at once; here, negotiation can occur even when all specifications are met. In fact, there are usually at least two specifications, since cost of engineering and production resources is almost always a factor. In the example of the chassis design, the designers' position may be to offer the manager a choice between a 6% improvement at a production cost slightly lower than the present model's, or an 11% improvement at a substantially higher cost. To this, the managers may well counter that the new target is 8% improvement, as cheaply as possible.

The trade-off between cost and performance is one of many conflicts that are resolved through negotiation. A typical project will have an array of performance targets. The chassis example mentioned above will also have bending stiffness, weight, noise, and vibrational targets in addition to the torsional stiffness. The overall performance of the design depends on the individual performances, but the exact nature of the dependence varies greatly with the particular problem. The negotiation process is a means by which the true measure (and compromise) of overall performance is uncovered. A method to formalize negotiation may provide quicker and more complete information about the overall performance relationship.

Conflicts between design and manufacturing

The problem of design for manufacturability has been addressed by others [5], but it has not previously been noted that conflicts between design and manufacturing are often resolved through a negotiation process. Sometimes the issue is the rejection of an unmanufacturable design by the production engineer. In many cases, a production engineer suggests changes that will make manufacture simpler, and negotiates with the design engineer for a compromise that will give the most satisfactory overall performance when production cost and reliability are taken into account. In the most optimistic case, a manufacturing group may suggest changes that improve the overall design performance. In a worst-case scenario, poor or no negotiation can lead to spectacular failures. The infamous 1981 collapse of the Hyatt Regency walkway in Kansas City, Missouri, the deadliest engineering disaster in U.S. history, has been attributed to miscommunication between designers and fabricators [14]. A formalism for negotiation can help to facilitate the resolution of these conflicts, and can at the same time provide an unambiguous record of decisions that are made at each step of the design process.

Conflicts between engineering groups

When different working groups have responsibility for different subsystems, or for different aspects, of a design, the requirements of one group may conflict with the requirements of another. Stiffeners added to improve the structural rigidity of a frame might eliminate space that the fuel system group was counting on for the fuel tank. While in mature designs a structural part may well be described by a volume envelope and a few immutable points of contact, there are many situations in which the interaction between parts is not so rigidly described. Even when constraints are imposed in an attempt to avoid conflict between working groups, points of intersection between subsystems are often negotiated.

The incorporation of unquantifiable performances

Many design problems include performance criteria that are difficult, if not impossible, to measure, yet these criteria can be so important as to drive a design. Aesthetic and emotional concerns are certainly of great importance in the auto industry [4], and they also play a surprisingly significant role in other fields, from heavy machinery to military aircraft.

Style, beauty, appearance of solidity, color, image, are all examples of immeasurable attributes that can play a substantial role in the desirability of an engineered object. The fact that they are not easily quantified can lead to either underestimation or overestimation of their role in a design. An engineer designing for more concrete performance specifications may ignore them altogether, yet that same engineer may be working within strict geometrical constraints dictated by a stylist's vision.

Immeasurable performances present the greatest challenge in the formalization of design negotiation as presented in this paper. Still, steps can be taken to formalize this part of the design process, and this formalization can lead to a clearer picture of true overall design requirements.

These examples are meant to convey the nature of the problem of informal negotiation in engineering design. The following section describes a formal system to conduct negotiation more rigorously.

Prior Research on Negotiation

Other researchers have also recognized the importance of negotiation in design. Some take the point of view that any contradiction that arises in the design process is a conflict to be resolved by negotiation. This paper takes a less inclusive view of negotiation, but points out that the formal representation of any trade-off is realized in the same way as a negotiation between two parties.

Researchers in artificial intelligence have noted that conflict is an integral part of the design process. A few are mentioned here: [9] present a more comprehensive bibliography of current research and a thoughtful list of potential sources of conflict in addition to their own work on a design support environment called Schemebuilder. [2] have approached conflict from a utility theory point of view; their work is perhaps the most comparable to the research direction outlined in this paper, but they have focused on a computer implementation of the decision and have limited themselves to a linear weighted sum model and fairly restrictive representations for goals. The work accomplished previously with the $\mathrm{M_oI}$, and the applications proposed in this paper, offer more possibilities for the modeling of the design but less automation of the decisions. Some interesting work has been done on a design support system using Pareto optimality by [13]. The system does not calculate optimal solutions, but rather tracks a history of design decisions and automatically notifies agents when it seems that a better design might be overlooked.

These approaches to managing conflict in design, and others from the artificial intelligence community [3, 6], have concentrated on environments that model the design process itself, with the idea that such a model will be applicable in any design situation, thus approaching the design problem from above. The act of negotiation is seen as an entity to be modeled. The research discussed here approaches the design problem from below, where the crucial problem is to model the imprecision inherent in design information, and to use that model of design imprecision to guide negotiation.

Imprecision in the Design Process

The following is a brief review of the Method of Imprecision and some necessary definitions. The reader is referred to [1, 10, 12], and [18] for more details.

The $\mathrm{M_oI}$ formalizes design decision making in the presence of uncertainty by the specification of *preferences* on *design* and *performance variables*. Variables are sometimes referred to as *parameters*. Design variables are denoted d_i, where i ranges from 1 to n. The set of design variable values under consideration for d_i is denoted $\mathcal{X}_i$. The preference that a designer has for values of d_i, the ith design variable, is represented by a preference function on $\mathcal{X}_i$, termed the *design preference*:

$$\mu_{d_i}(d_i) : \mathcal{X}_i \rightarrow [0,1]$$

A preference of 1 denotes a completely satisfactory value of the variable, a preference of 0 denotes an unacceptable value, and values in between represent intermediate levels of satisfaction. By treating the preferences μ as a membership function, the $\mathrm{M_oI}$ can employ the mathematics of fuzzy sets [7, 19] to perform calculations on the uncertain variables.

Performance variables are denoted p_j, with j ranging from 1 to q, and the set of possible values of p_j is denoted $\mathcal{Y}_j$. The customer's[1] preference for values of p_j, the jth performance variable, is called a *functional requirement* and is represented by a preference function on $\mathcal{Y}_j$:

$$\mu_{p_j}(p_j) : \mathcal{Y}_j \rightarrow [0, 1]$$

The set of all performance variables can be represented as a vector $\vec{p} \in \mathcal{Y}$, and the set of all design variables as $\vec{d} \in \mathcal{X}$. Each performance variable p_j is defined by a mapping f_j such that $p_j = f_j(\vec{d})$. The mappings f_j can be any calculation or procedure to measure the performance of a design, including closed-form equations, iterative and heuristic methods, "black box" functions, experiments, and consumer evaluations. When performance and design variables are not all of equal importance, each can be assigned a *weight*, ω_{p_j} or ω_{d_i}.

The individual preferences on variables are combined into an overall preference μ_o by the use of an *aggregation function* $\mathcal{P}$:

$$\mu_o = \mathcal{P}\left(\mu_{d_1}, \omega_{d_1}, ..., \mu_{d_n}, \omega_{d_n}, \mu_{p_1}, \omega_{p_1}, ..., \mu_{p_q}, \omega_{p_q}\right).$$

This overall preference is a measure of the overall performance of the design when all criteria are considered. The design problem is thus to identify design configurations that maximize μ_o, i.e., designs $\vec{d}^*$ such that:

$$\mu_o(\vec{d}^*) = \mu_o^* = \sup\{\mu_o(\vec{d}) \mid \vec{d} \in \mathcal{X}\}.$$

The aggregation function $\mathcal{P}$ reflects the design or trade-off strategy, which indicates to what degree competing attributes of the design should be traded-off against each other [11, 15]. The appropriate design strategy is dictated by the design problem. A design problem will in general require a hierarchy of different trade-off strategies which successively aggregate design attributes.

Formalizing Negotiation

The M$_\text{o}$I has been applied previously as a decision support tool for self-contained design problems. Its extension to facilitate negotiation between working groups in engineering design entails a broader perspective on the design problem.

The first step in any application of the M$_\text{o}$I is the identification of design and performance variables. Variables may be continuous or discrete, numerical or represented by linguistic terms. The model used by the M$_\text{o}$I will employ

[1]The functional requirement μ_{p_j} is called the customer's preference for values of p_j, even if it is the designer who estimates μ_{p_j}.

the most important variables. An advantage of formalizing decisions is that it allows the timely incorporation of information that hitherto was not considered until after the end of a design iteration (when redesign is often the only option).

The second step is the specification of preferences over the values of the variables. By treating the specified preferences on these variables as membership functions, the M_oI can use the mathematics of fuzzy sets to make calculations on these imprecise variables. The imprecision that arises here is *uncertainty* as to the (best) final value—this imprecision will be lessened as the design progresses until the final design is precisely described. The specification of preference on performance variables logically precedes preferences on design variables. Preferences on performance variables represent targets, and are, at least at the outset, independent requirements. Preferences on design variables are likely to change if there is a change in the functional requirements.

The performance variables embody the design task: a designer must create plans for a device that will satisfy given values of a number of performance measures. Some performance variables arise because of a particular choice of design solution. For example, in the course of performing its specified task (providing rotational power), an internal combustion engine generates heat, so heat dissipation becomes a performance parameter, although it is incidental to the primary function of the automobile, which is to carry a load from one point to another. Responsibility for providing preferences on the performance variables will depend on the structure of the company. Ultimately, it is the customer who has preferences for performance, though the customer is often not polled directly. (This paper suggests, but does not explore, the possibilities offered by the M_oI in market research.) Typically, market analysts and management teams are responsible for providing detailed information as to customers' desires. Simply formalizing the preferences can resolve many confusions. The fuzzy preferences contain much more information than a simple list of target values. They show a full range of acceptable values, and the relative desirability of values over that range. Together with weighting and trade-off strategy information, they can tell how much a change in one performance variable is worth in terms of another variable. Details of the specification of preference have been presented previously [10].

Design engineers then specify preferences on the design variables. These design preferences embody everything that is not explicitly represented in the calculation of the performances. The design preferences may thus contain the engineers' intuition about such concerns as manufacturability; in the example detailed below, style is taken into account as a design preference.

Preferences alone provide only a portion of the relevant information. Variables are assigned weights that reflect their relative importance. Trade-off combination strategies [11, 15] must be determined, indicating to what extent superior performance in one aspect is to compensate for lower performance elsewhere. There can be more than one trade-off strategy in a design with many variables: for example, one might allow significant trade-off between cost and weight, but insist on considering safety independently. Even in cases where two variables can trade-off strongly, an unacceptable preference ($\mu = 0$) in one variable can never be overcome. The preferences, weights, and trade-off strategy are used to calculate overall preference for the designs in the design space [11, 15].

A complete specification of preferences on all performance variables would eliminate the need for negotiation whose sole purpose is to clarify the functional requirements. Design engineers are generally qualified to calculate the values of the performance variables p_j; what they lack is complete information as to which performance vectors $\vec{p}$ are to be preferred if one performance variable comes in above or below target. It is not just in situations where targets are unreachable that negotiation ensues; negotiation can also be required because an engineering group finds one target particularly easy to meet and wants to know where to spread around the extra slack that variable provides. If all design variables were simply quantifiable, as are cost, weight, stiffness, and so forth, the task of formalization would be more straightforward. The incorporation of unquantifiable performances presents a particular difficulty. Managers or customers may find it difficult to describe their global preferences for these unquantifiable variables, and a design may have to be seen for a level of satisfaction to be determined. This difficulty can be partially surmounted by the use of linguistic variables, which fuzzy mathematics handles naturally [20].

In situations in which it is unreasonable to expect one group to be expert in another's field, such as the cases mentioned earlier of conflicts between design and manufacturing, or between different design groups, the M_OI can provide a common language for the resolution of contradictions. Two working groups with radically different concerns can use the formalism of preference as a starting point, so that the issues that one group addresses can be taken into account by another group. More detailed formalisms, such as those to represent particular manufacturing issues, will need to be developed in knowledge-specific contexts. The formalism of preference by the M_OI provides a common language for discourse.

At each stage or iteration of the design process, the formalization of decision-making documents the process. In many cases, the decision will include a redesign, with perhaps a modification of preferences on performance variables. In the redesign, with greater information and more analysis, preferences on design variables are likely to change as well. As working groups familiarize themselves with the method, the results of the informal negotiation can be compared to the formal answer produced by the analysis of the M_OI. With greater familiarity, the calculations of the M_OI serve as decision support. One of the

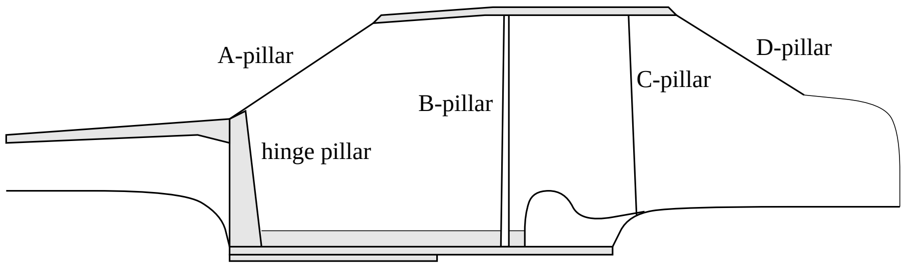

Figure 7.1 Schematic of the car body

many advantages of using the MoI is the clear record of decisions and rationales that it provides.

Example

A simple example of an automotive design problem will help to illustrate the method. Vehicle body design is concerned with tens of design variables and many performance parameters from noise and vibrational response to stiffness to manufacturing cost to style. For this illustrative example, we will assume that there are only three relevant design variables: pillar gauge, roof and floor plate thickness, and fore-aft location of the B-pillar (Figure 7.1). There are three relevant performance parameters: weight (assumed linear with material cost), bending stiffness, and style.

In the example under discussion, as is often the case in the automobile industry, style drives the design. Suppose that the car being designed is not a new design, but an incremental change from, and, it is is hoped, improvement on, a two-door model produced the year before. Here the directive from the stylist is that the new look is lower and sleeker: the roof should be lowered, the clearance between the frame and the ground reduced, and the window opening between the A-pillar and B-pillar should be lengthened. In addition to this small but crucial styling change, the designers are asked to make a 10% improvement over the bending stiffness K_B^{old} of last year's model, with the weight W to stay the same, so that the increase in material cost reflects only inflation. The designers thus have in hand a set of functional requirements consisting of a sketch with some vague explanation, and two targets:

$$K_B^{\mathrm{new}} \geq 1.10 K_B^{\mathrm{old}} \qquad \text{and} \qquad W^{\mathrm{new}} \leq W^{\mathrm{old}}$$

Finite element analysis is used to evaluate candidate designs for performance with respect to the two hard targets, and the attendant solid model will provide sketches for managers or stylists to evaluate the aesthetic impact.

Even in this quite simplified problem, there are already several issues that can be modeled as negotiation. Weight and stiffness will tend to increase together, and the trade-off between these facets of performance is an example of a case where, although there may be only one designer, there is a conflict between aspects of the design that can be formally modeled as a negotiation. If the target of a 10% improvement over the bending stiffness of last year's model turns out to be difficult to achieve, a negotiation between engineers and managers will ensue. The incorporation of the styling requirements is probably the most clear-cut example of the need for negotiation, since the engineers who effect the design will need to consult with the stylists as to the suitability of a completed design. In this illustrative example, we ignore many complications, notably the consideration of manufacturing concerns at the design stage. These additional complications would be addressed formally in a similar manner.

The first step in the formalization of the problem is the expression of more complete preferences $\mu_p(K_B)$ and $\mu_p(W)$ in place of the given hard constraints on the performance variables. Figure 7.2 shows preferences on the two performance variables. The information contained in these plots already provides the possibility for sensible trade-offs between the two using the formalisms of the MoI. Figure 7.3 shows the overall preference for W and K_B in a three-dimensional plot; the vertical axis is the combined preference using a compensating aggregation function:

$$\mu_o = (\mu_p(K_B)\mu_p(W))^{\frac{1}{2}}$$

Thus any two or more candidate designs can be compared by examining the combined preference for the two performances W and K_B.

The problem is more complicated, of course, because a design is not judged on the basis of weight and bending stiffness alone. Even if the design team is able find an "optimal" design in the sense of maximizing the combined performance shown in Figure 7.3, other aspects of the design's performance, such as the style, will need to be taken into account, and it is likely that this will be done through an informal negotiation.

In this case the engineers have a simple measure that can guide them in their work. The stylists have expressed a preference for a wide window opening; this is interpreted as a preference to locate the B-pillar as far aft as possible. This preference is shown in Figure 7.4 (the x-axis represents inches aft of center, with negative numbers being to the fore of center). Since this preference is expressed on a design variable (B-pillar location), the MoI treats it as a design preference. The location of the B-pillar will affect the bending stiffness; this will appear in the finite element calculation. There may well be other preferences for B-pillar location, for example, manufacturing concerns. The computations of the MoI take into account all of this information, with the possibility to assign weights and hierarchies. The overall preference for a design, calculated by the MoI, thus contains the analysis that has been performed (in

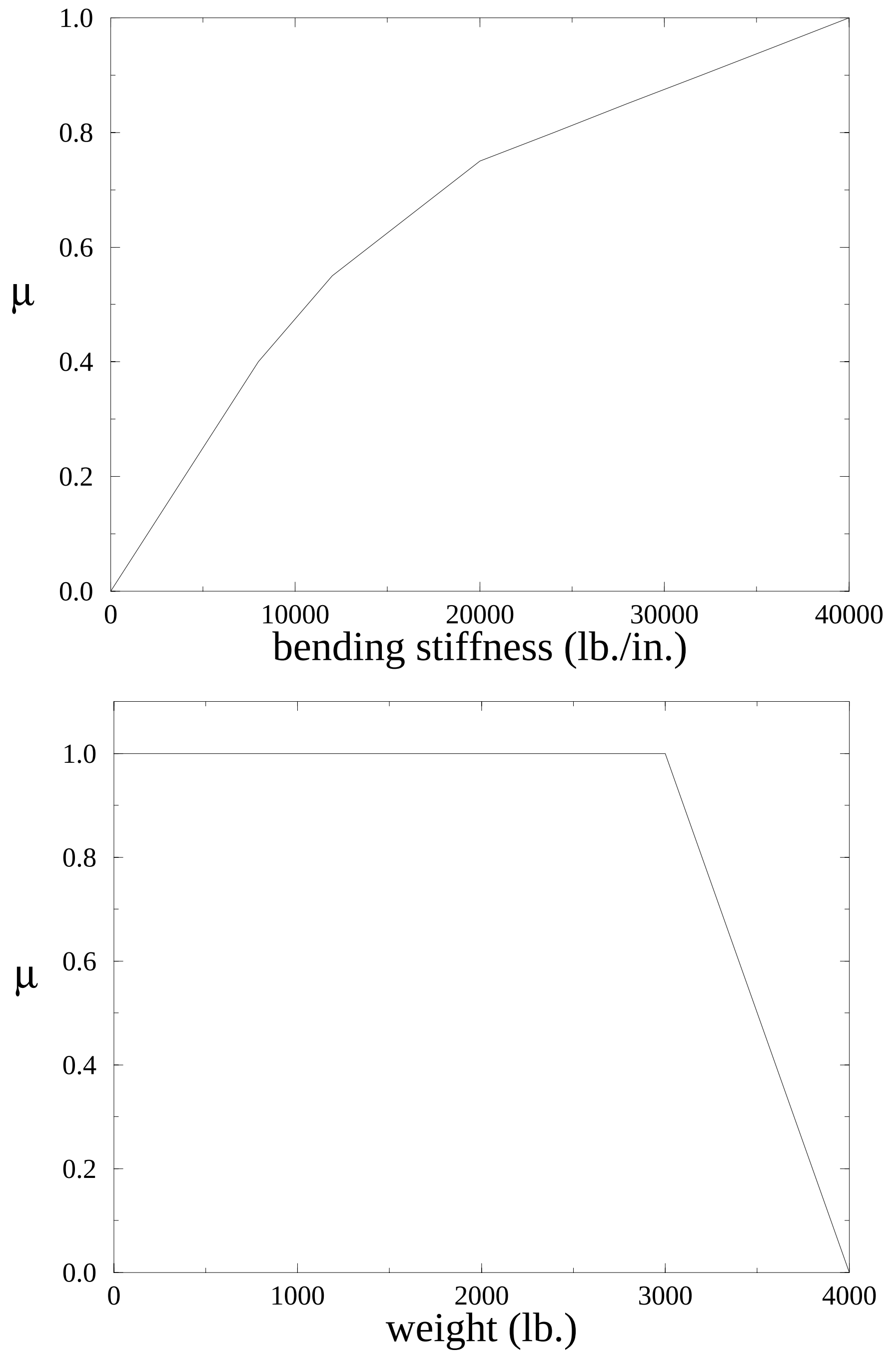

Figure 7.2 Performance preferences $\mu_p(K_B)$ and $\mu_p(W)$

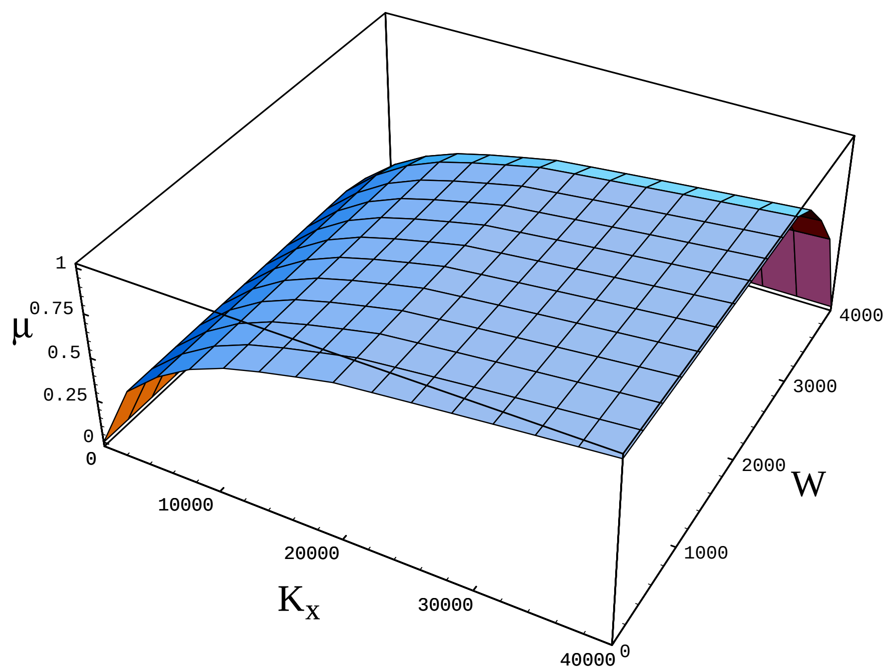

Figure 7.3 Combined preference $\mu_p(K_B, W)$

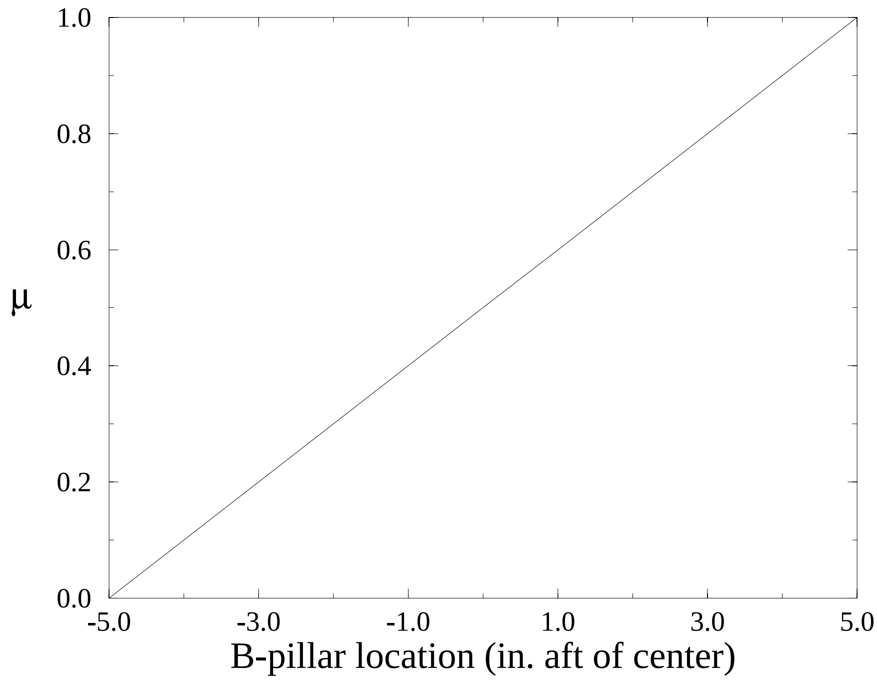

Figure 7.4 Stylists' preference for B-pillar location

this case, the finite element analysis) as well as preferences for the aspects of the design, such as style, that are not calculated by the analysis tools.

It is naturally not possible to represent the effects of all design variables on a single graph, but the effects of one or two design variables (with others held fixed at some nominal values) are easily plotted. Figure 7.5 shows the overall preference μ_o plotted for various B-pillar locations, with the other design variables held fixed. It is interesting to note that the optimal value for weight and bending stiffness alone is for the B-pillar location to be near center. Although bending stiffness is decreasing as the location moves further aft, reconciling the stylists' preference for a wider window requires some compromise in bending stiffness.

Conclusion

The issue of negotiation between engineering groups has been described and discussed. Different negotiation situations that may appear in industrial design settings have been considered. The application of the M_oI in these situations has been illustrated, and the benefits of such formalism have been discussed.

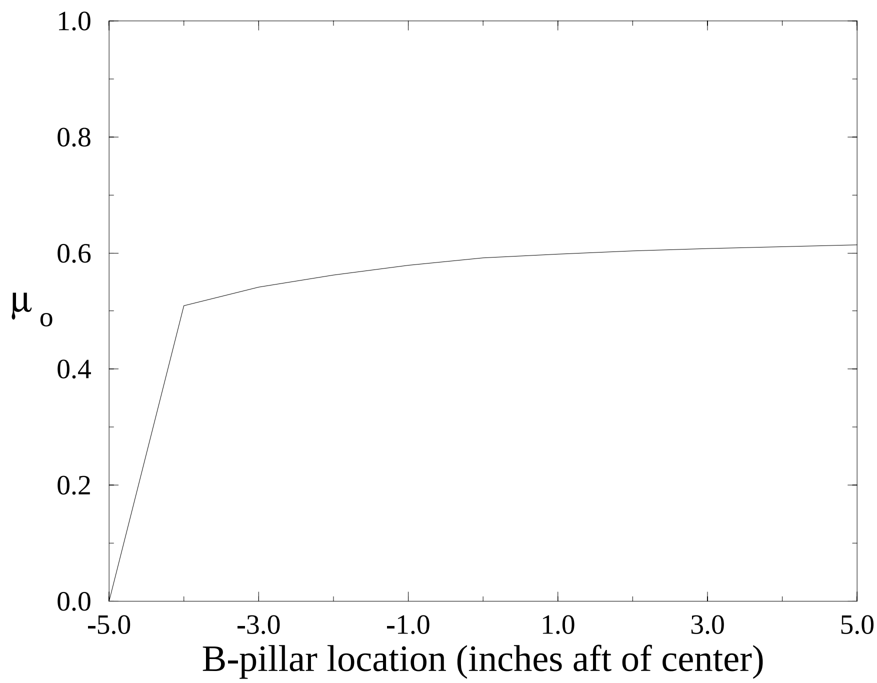

Figure 7.5 Overall preference for different B-pillar locations

The MoI has been developed previously for engineering design applications. This paper has suggested the extension of the method to encompass the domains of management and marketing, thus pointing out the possibilities for using the formalism of uncertainty in the entire design process.

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