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THE GAME OF RATIONAL ENGINEERING DESIGN

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Abstract

In conflict situations engineering decision-making rests on rational negotiation between intelligent agents. In economics and psychology the negotiation of conflicts is carried out by establishing appropriate measures of the desirability of outcomes (attribute utility, or payoff)) and using a suitable game strategy. The most difficult aspect of this approach is the elicitation or establishment of utilities. This paper introduces these basic ideas of decision technology and offers simple examples of how these ideas may be used in design decision making.

Keywords: Game theory, negotiation, conflict, utility

1. Introduction

Engineering design is executed by various agencies. An agent is either a participant in a negotiation process during design (e.g. engineering, marketing, manufacturing, production, sales) or one of the many objectives the design is to fulfil (e.g. weight, cost, stiffness, geometry, safety, maintainability, aesthetic appeal). As the design proceeds through its several stages, these agents will exert their various influences on the final outcome. Each agent is able to control one or more *input* design parameters, but the outcome of the design process results in a set of *output* design parameters that may be considered as being "shared" by all the design agents. Typically, *input* parameters for the design of a wheelchair would be construction material energy information and geometry. A change in these *inputs* will propagate through to the *output* (size and weight) shared by all the various design agents involved in the negotiation process. These agents are deemed to be *intelligent* (constantly aware of the influence of *input* on shared *output* parameters) and *rational* (make the best possible decision through the negotiation).

Negotiation between agents in simultaneous, or concurrent, engineering has received considerable attention in the literature.[1], [2]. One formal procedure for resolving interactions between design objectives is the House of Quality matrix used in QFD [3]. Yet ultimately, most design decisions are based on economic rationale and bargaining between intelligent agents.

Decisions in design determine the final design outcome and the decision making process is the most complex substantial cognitive load on the designer. As an example we consider the task of designing a "chair". The notion of a "chair" as a means of supporting a seated person is already embedded in our collective cognitive experiences. Yet the associated decisions leading to a design still conjure up many influences that will determine the chair design with the most desirable attributes.

Figure 1 sows range of possible designs, taken from catalogues of chair suppliers. Clearly there are many possible interpretations of the idea of a chair, yet even the last two examples in this set are clearly recognisable as belonging to the class "chair". Table 1 lists some possible desirable attributes to be assigned to the "chair", partly based on the two most likely uses for which these chairs might be purchased.

The two types of chair have quite different attribute requirements. The indoor service chair will be out of sight most times; hence its appearance is of less importance than that of the garden chair. Lightness and manoeuvrability conflict with strength and capacity to support the largest expected guest. Ease of cleaning involves material and assembly choices that could increase costs of manufacture.

Figure 1. Samples of chairs from suppliers catalogues

Table 1 – Some desirable Attributes for chairs

1. Service chair – indoor use	
Desired Attribute	Estimated Rank / Value
1.1 Low cost	6
1.2 Light and manoeuvrable	8
1.3 Easy to store	8
1.4 Easy to clean	5
1.5 Must support weight of 97.5th percentile male	10
1.6 Must meet ergonomic requirements for seat size and height from ground	10
2. Garden chair – outdoor use	
Desired Attribute	Estimated Rank / Value
2.1 Sturdy	8
2.2 Durable	9
2.3 Aesthetically pleasing	8
2.4 Must support weight of 97.5th percentile male	10
2.5 Must meet ergonomic requirements for seat size and height from ground	10
2.6 Low cost	3

The possibility of combining the attributes for both types of chairs (readily adopted in some households for economic reasons) should not be overlooked. Chair 6 in Figure 1 would satisfy this requirement. Chair 10 is known to be stackable and as it is made of a polymer it would also meet both types of requirements of indoor and outdoor use. Chair 8 is a bar stool and chairs 7 and 11 are the result of a much higher ranking on aesthetics requirements than the others in the example set.

Since the market economy in which the chair is produced, sold and used is a closed system financially, there are economic limits on the resources available for delivering these desired attributes. Also, some attributes conflict with each other and they may not be maximised independently of each other and tradeoffs are required. As the design proceeds a negotiating process develops between the various agents involved in the design. For each design agent (abstract in the form of some criterion) there needs to be an advocate for negotiation. Economic choices and tradeoffs between the various design agents are negotiated through a bargaining process that may be formalised in game theory. Ultimately, the object of this approach is to render the process autonomous in the form of a procedure or a computer programme. Game programmes that may be used for negotiation in simple games are already available, as are formal procedures for negotiation (see for example [4], [5]).

2. Games and decisions

Games and decision theory have received substantial attention in both economics and psychology. This seemingly odd combination of disciplines interested in these topics is a result of the coupled notions of rational economics and behavioural economics [6], 7], [8]. At the focus of research dealing with these issues is the notion of utility, or the value assigned to some specific outcome. Once utilities are assigned to outcomes, rational choices (strategies) might result from solving a "payoff" table as a game. The literature on games and decisions is large (see for example [8] through [11]). As Luce and Raiffa note [9]:

"One formulation of the class of conflicts of interest is this: There are 'n' players each of whom is required to make one choice from a well defined set of possible choices, and these choices are made without any knowledge as to the choices of the other players. The domain of possible choices for a player may include as elements such things as "playing an ace of spades" or "producing tanks instead of automobiles", or more important, a strategy covering the actions to be taken in all possible eventualities."

The basic game paradigm used in the literature is the two person zero sum (TPZS) game. A typical example is one where two players, arbitrarily named Red and Blue, shipwrecked on a desert island agree to toss coins to win or lose coconuts (the only substantial food source available) according to the outcome of the coin toss. Since they have no coins to toss they agree to simply write the outcome (H for heads, T for tails) on a piece of palm frond and simultaneously show it to each other. If the two fronds disagree the one showing T will pay one coconut to the other showing H. If the two displayed palm fronds show the same (H or T) the payment will jackpot to the next game. Clearly, Red's winnings are Blue's losses and they both wish to maximise their winnings or minimise losses. This implies a closed (zero sum) game with rational strategic choices. The game payoff table is shown in Figure 2.

Red		Blue	
		H	T
	H	0,0	1,0
	T	0,1	0,0

Figure 2. Game payoff table for "coin showing" game

In this game the best strategy both players should adopt is one where they show H or T at random. In the long term their winnings and losses will average out to zero. However, since even fair coins can generate uneven distributions of heads and tails over a many throws, one of the players might starve.

Games may have some "dominant strategy" that ensures either minimum loss to one player while maximising gain to the other. The paradigm for this type of game is the "prisoner's dilemma". Two criminals Ray and Bill are caught and given the following options (U = utility or subjectively assessed value of outcome):

- Confession by one and denial by the other (U =-10) will result in a large sentence for the denier and a small sentence (U = -5) for the confessor rewarded for turning State's evidence;
- Confession by both (U = 0) will result in a mild intermediate sentence for both;
- Denial by both will result in eventual release of both (U = 10) due to insufficient evidence.

The payoff table is shown in Figure 3.

Ray	Bill		
		D	C
	D	10,10	-10, -5
	C	-5, -10	0,0

Figure 3 Game payoff table for the prisoner's dilemma

If the prisoners could trust each other or could collude (from a coalition) their best strategy would be D; D. However (and this is the reason for the dilemma) since there is "no honour among thieves" the most reliable (dominant) strategy is to confess. This strategy ensures that neither player can improve their payoff by unilaterally changing their strategy.

John Nash's [12] contribution to game theory rests largely in the evaluation of games that have more "real life" character than those specified as TPZS games. Consider the following example. Two friends Bill and Roseanne are considering a list of plays to choose on their date. Bill prefers drama (D), while Roseanne prefers musical comedy (MC). They reason as follows:

Bill: If I choose D, I will be happy (U=10), but she may still be happy to be with me (U=5);

Roseanne: If I choose MC, I will be happy (U = 10) and he may still be happy to be with me (U=5);

Both: If we chose one and the other disagrees we quarrel (U=-10).

The payoffs are shown in Figure 4 as R, B.

Roseanne	Bill		
		D	MC
	D	5,10	-10, -10
	MC	-10, -10	10,5

Figure 4 Game payoff table for the dating game

Now Roseanne (showing a superior intelligence here) can see that if Bill chooses D and she agrees, then at least one of us is happy, while the other is happy to be together (U=5). Of course eventually the same consideration dawns on Bill.

Clearly, both players can minimise their losses by choosing whatever their partner chooses. This is a game with two equilibrium points (referred to as Nash equilibria). The result is that neither player can improve their payoff by unilaterally moving away from either of the chosen strategies. As to which payoff is realised is a function of probabilities and commitment. Depending on which player moves first, the other might adopt a strategy that will benefit both. Alternatively, one player might sense the wish of the other (through experience or wisdom) and commit to a course of action to match the desired choice of the other. In a longer-term arrangement both players may use a mixed strategy. In the design context, where a single strategy is needed, no such luxury exist.

Now returning to the business of designing chairs, we consider the conflict between Marketing (M) and Production (P). The company involved may have machinery designed to make timber chairs, hence P's preference is to continue with this product. On the other hand, (M) might view it more profitable to sell colourful chairs made in polymer and seems adamant to deliver this type of product to the market. We can appropriately draw up a diagram with assumed utility distributions for the two advocates M and P, where U_M and U_P are the representative subjective utility values of either courses of action (as judged subjectively by M and P individually). Note that for U=0 is a condition where the advocate is indifferent to the outcome in that region of production percentages.

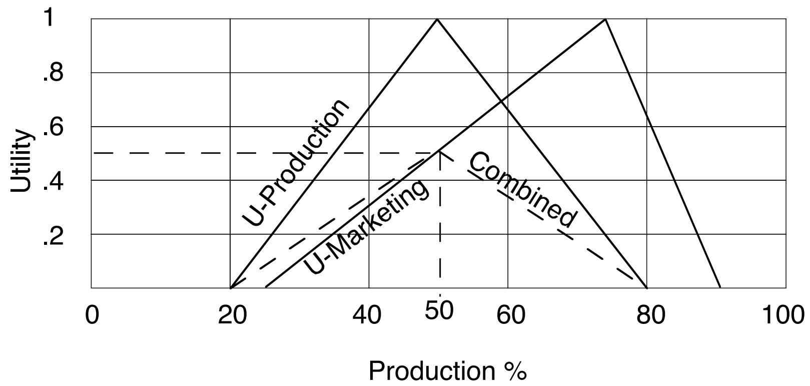
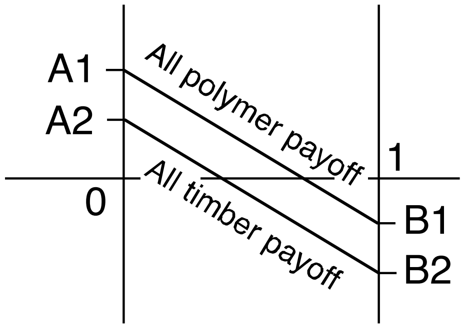


Figure 5. Material selection for chair design

The Nash equilibrium for this combination of alternative materials is the one where any individual change from the best production mix (one that maximises the combined utilities $0.5\ U_M + U_P$) is 50% polymer and 50% timber chairs. This is, due to our limited presentation, a major simplification of the type of conflict being resolved. Other influences will impose changes on the utilities adopted in the simple arrangement shown in Figure 5. Reduced availability of suitable rainforest timber (Teak, Jarrah, Cedar) in adequate quantities, or waste disposal problems with polymer by-products will influence the decision process. However, once the utilities have been determined, the solution or resolution of the game is a simple matter.

Another example of coalitions is one where several chair manufacturers might consider their individual payoffs when choosing their strategies. Suppose the several companies servicing the chair market decide that their payoff for chairs of one specific material is greater than that for chairs made of several different materials and hence all decide unilaterally to only produce chairs from one material. The payoff diagram is shown in Figure 6.



Horizontal axis is the proportion of manufacturers making chairs of specific material. The vertical axes show the payoff for each material choice. In this case we have assumed that payoffs are proportionately the same, but that for individual manufacturers choosing to make polymer chairs the payoff is always larger than for those choosing to make timber chairs.

Figure 6. Cartel decision on chair manufacture and payoff diagram

If all manufacturers of chairs make polymer chairs their payoff is B1, on average higher than B2 that available when they all agree to make timber chairs only. Now consider that a proportion of the manufacturers who make polymer chairs is X, less than 1. The payoffs may be calculated as follows:

PP = Payoff poly = A1-X (A1-B1).

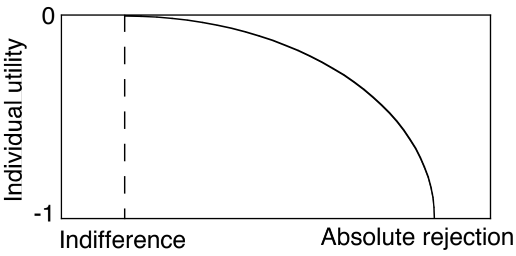
Similarly for the remaining manufacturers making only timber chairs the payoff is

PT = Payoff timber = A2 – (1-X)(A2-B2).

If we now choose A1 = 10, A2 = 5, B1 = -5, B2 = -10and X = 0.5 it is easy to show that PP = 2.5 and PT = -2.5. Hence on average all the manufacturers in each class are better off than if they choose one or other course of action as a cartel. However, from a purely selfish point of view it is easy to see why individuals might choose to work on the poly payoff curve only since they may not see the "whole picture". This is an example of the prisoner's dilemma extended to many players.

3. Measures and elicitation of utility functions

It is strange and a little disconcerting that in engineering design the term criterion has been adopted for some distinctly different concepts, yet in economics it has been defined quite precisely as the scale on which attribute values are judged. Samuel and Weir [9] also define it so and we adopt this definition within the context of this article. We also note that the criterion scales used to judge different attributes can be themselves quite different. For example, size is measured in (say) meters, while energy efficiency is measured in Watts. Utility is the unifying measure that permits evaluation of preferences among a range of attributes measured on different criterion scale. Unfortunately utility is a behavioural measure and it varies with individual preferences. Consequently, it needs to be elicited from the various human agents involved in the design bargaining process. We have shown some examples of linear or piecewise-linear utility functions for examples in Figures 5 and 6. In general, however, utility is a non-linear function. Suppose we are concerned with greenhouse gas emissions from a given process. Below some value G1 we are indifferent to emission rates. As emission increases from G1 to G2 our individual response, on a scale 0 to –1 might range from concern (U= -.3 say) to outright rejection (U= -1). In general the responses might have different value scales, but the example illustrates the nature of utility. Figure 7 shows the variation of utility with greenhouse gas emissions for the specific individual chosen.



This is an arbitrarily chosen utility function assigned to a specific individual. In general, these functions will vary with individual preferences. However, part of the bargaining process involves sharing of preferences and this sharing can lead to group decision.

Figure 7. Individual utility function for greenhouse gas emissions

A useful example to bear in mind when considering utilities is money. To the unwary it might seem that money is a useful universal utility scale. On the contrary, it is a non-linear individual preference scale. This is easily seen when considering the value of a coin toss gamble of (say) $1 million for a millionaire (Bill Gates for example) and a relative pauper (one of the authors for example). The consequence of these observations is that utility must be elicited from individuals and groups. Economists and political strategists use sealed bids and ballots as a means for eliciting group preferences. As noted by Von Neumann and Morgenstern [8]:

"If two or more persons exchange goods with each other, then the result for each one will depend in general not merely upon his own actions but on those of the others as well. Thus each participant attempts to maximise a function (the above-mentioned "result") of which he does not control all the variables. This is certainly no maximum problem, but a peculiar and disconcerting mixture of several maximum problems. Every participant is guided by another principle and neither determines all variables which affect his interest."

In engineering we often use scaled check lists (see for example [13]) to resolve conflict between various design alternatives. These lists are nothing more than estimated preference values for the attributes of design alternatives, or utility values. In general these values are probabilistic estimates based on experience with previous outcomes. An example is the strong (weak) preference for a specific supplier given that in past experience the supplier delivered on time (was late in delivery). The formal procedure for these types of estimates is Bayesian statistics [5]. The predictive features of Bayesian Systems' products are based on a fundamental principal of logic known as Bayes' theorem, or the fundamental mathematical law governing the process of logical inference—determining what degree of confidence we may have, in various possible conclusions, based on the body of evidence available.

Cognitive maps show relationships between concepts or ideas as seen by individuals. These maps can be used effectively to represent the interrelationship of concepts in design problems [14]. Langan-Fox et al. [15] used cognitive maps to elicit shared team and mental models of engineering managers in a cleat bargaining situation of service conflict management. The latter approach may well lead to a useful process of eliciting shared or team utility functions. Cowan et al. [2] construct the game theoretical approach to solving design conflicts but they fail to address the elicitation of utility functions. Kannapan et al. [11] examine a relatively simple mechanical design problem using bargaining with assumed utility functions. They identify the Nash and the modified Nash (Kalai-Smorodinsky [16]) bargaining solution to the conflict between a valve lift and spring rate in a poppet valve design without any deliberations on how the implied utility functions might be elicited.

Our contention is that the major focus of study for application of rational game theory in design must be the appropriate elicitation of individual or team preferences. As an example it is clear that in a structural system (such as a bridge or a column) we have deterministic preferences. These are $U=1$ for success and $U = 0$ for failure. In the design of an airconditioning system the preferences are not so clear. Would we assign U=0.75 for a system that conditions 75% of the building? Alternately, given that supplier S1 has delivered on time in the last n projects under our control, what preference value should we assign to the same supplier in the next project all other things being equal?

4. Concluding comments

In this brief article we have explored some elements of rational games and solutions to bargaining problems with special reference to the use of these in co-operative or team bargaining in engineering design. Clearly, the procedures have been used informally by engineering design teams. However, the formal processes of Bayesian estimates of utility functions (preferences) coupled with gaming to resolve commonly encountered multi-criteria decision making problems has not been widely used by engineering designers. These procedures will require considerable introductory learning by classical proponents of conflict resolution in design, although these methods have wide application in economics and the development of strategies in international conflict and public policy.

Quality Function Deployment (QFD) has been used effectively in evolving conflict resolution in design [3]. A QFD matrix could be used to represent not only interactions between quality attributes but also utility or preference values associated with attribute values. Consequently we argue that rational gaming is not too radical an approach for classical engineering designers. However there is considerable work required to develop a proper framework for rational bargaining and the elicitation of appropriate utility functions. This paper merely sets the scene for these approaches.

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