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Multi-attribute utility analysis in set-based conceptual design

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ABSTRACT

During conceptual design, engineers deal with incomplete product descriptions called design concepts. Engineers must compare these concepts in order to move towards the more desirable designs. However, comparisons are difficult because a single concept associates with numerous possible final design specifications, and any meaningful comparison of concepts must consider this range of possibilities. Consequently, the performance of a concept can only be characterized imprecisely. While standard multi-attribute utility theory is an accepted framework for making preference-based decisions between precisely characterized alternatives, it does not directly accommodate the analysis of imprecisely characterized alternatives. By extending uncertainty representations to model imprecision explicitly, it is possible to apply the principles of utility theory to such problems. However, this can lead to situations of indeterminacy, meaning that the decision maker is unable to identify a single concept as the most preferred. Under a set-based perspective and approach to design, a designer can work towards a single solution systematically despite indecision arising from imprecise characterizations of design concepts. Existing work in set-based design primarily focuses on feasibility conditions and single-attribute objectives, which are insufficient for most design problems. In this article, we combine the framework of multi-attribute utility theory, the perspective of set-based design, and the explicit mathematical representation of imprecision into a single approach to conceptual design. Each of the component theories is discussed, and their combined application developed. The approach is illustrated using the conceptual design of a fixed-ratio power transmission as an example. Additionally, important directions for future research are identified, with a particular focus on the process of modeling abstract design concepts.

1. Introduction

According to the paradigm of systematic design [1], the conceptual design phase takes as an input a list of requirements and objectives, and yields as an output the principal solution structures to be pursued in embodiment design. The first task of conceptual design is to distill the problem down to its core, including identifying what functions the design must perform and how these functions interact at a high level through transfers of energy, mass, and information. For example, the functions of a photocopying machine might include "acquire source image", "move paper", "mark a piece of paper", and "interact with user". The development of this function structure is not the focus of this paper, but rather the focus is on the next step in conceptual design.

Once a function structure is defined, designers seek to enumerate and then compare possible physical implementations, known as working principles or *concepts*, for each function. For example, three working principles for the function "mark a piece of paper" could be "deposit material by friction" (e.g., a pencil), "melt material onto paper" (e.g., laser jet printing), and "burn away material" (e.g., scorching the paper with a laser). Since in general there are multiple functions, each with multiple working principles, they can be combined into an overall product in many different ways, each combination forming a possible *solution concept* for the final design. In traditional systematic design, a single principal solution concept must be chosen for continued development in the embodiment design phase.

The evaluation and comparison of concepts are inherently challenging tasks. A concept is not a highly detailed product, but rather a general approach to implementing a function or system. In essence, *each design concept is an abstraction of the large set of all possible design implementations* based on that same concept. For example, the concept of "melt material onto paper" does not include details such as what material to melt, how much of it to melt, or how to guide the material into an appropriate mark on the paper. Because concepts are not detailed descriptions but rather are sets of alternatives defined by incomplete specifications, it is

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challenging to make rigorous comparisons between them. How can one decide whether it is better to deposit material by friction or melt material onto paper if one does not know exactly how each of these concepts will actually be implemented? More generally, *given a set of alternatives, how can decisions be made at the general level of conceptual design when specific design details are unknown?*

Part of the answer is to create computer-aided engineering and design tools that can model the abstract characteristics of design concepts rather than the fully detailed design descriptions that most existing tools require. Before such tools for conceptual design can be developed, the fundamentally imprecise character of conceptual design must be appreciated and an effective means for comparing incomplete product descriptions must be developed. In this paper, research from several domains is brought together in order to form a framework for evaluation and comparison of alternative concepts during conceptual design. Specifically, we present a set-based approach to conceptual design using multi-attribute utility theory and imprecise probabilities.

2. Imprecision in conceptual design

In order to develop methods for making decisions during conceptual design, one must recognize the nature of the uncertainty that exists during this stage of the design process. In general, two aspects of uncertainty can be identified: variability and imprecision. While some authors doubt the philosophical distinction between variability and imprecision, such distinctions are useful in practice [2].

Variability, also called aleatory uncertainty (from the Latin aleator = dice thrower), is naturally random behavior in a physical process or property [3]. It is also known as objective uncertainty [4] and irreducible uncertainty [5]. Examples include manufacturing error, errors in communication systems, and radioactive decay. Inherent variability is best represented in stochastic terms, e.g., by a probability density function. Consequently, variability is compatible with decision approaches based on classical probability theory and expected utility maximization [6], which is the focus of most engineering research on decision making.

Imprecision, on the other hand, is due to a lack of knowledge or information [7] and sometimes is called epistemic uncertainty (from the Greek episteme = knowledge), reducible uncertainty [5] or subjective uncertainty [4]. Imprecision can be represented in terms of intervals if one wishes to avoid overstating what one knows to be true [8,9]. Consequently, such representations are not immediately compatible with most engineering research on decision making. This presents a potential problem for conceptual design, where a significant proportion of the uncertainty comes from imprecision, and motivates an investigation into new approaches to decision making.

We return later to the problem of making decisions in conceptual design under imprecision. For the remainder of this section, we examine the various sources of imprecision in conceptual design. These include the structure of the design process, scarcity of relevant data, expert opinion, and the use of abstract models.

2.1. Concepts are imprecise design alternatives

One can think of the exploration of design concepts as a breadth-first search of an alternative space in which the decision maker searches across high-level concepts rather than down to detailed descriptions. This approach leads to a sequential ordering of the design process from general to specific. Essentially, the guiding principle is that there is no reason to consider the detailed implementation of a specific alternative (e.g., marking paper by friction) if you can decide at a more general level that a different alternative (e.g., marking paper by melting material) is better for the given design problem (e.g., photocopier design).

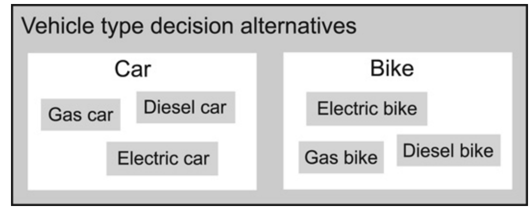

Fig. 1. Sets of design alternatives.

This process and the inherent imprecision of design concepts are illustrated using a simple design problem in which a decision maker wishes to design a vehicle that can transport a person. We assume that through some creative ideation process (which is not the focus of this paper), the decision maker arrives at two possible vehicle concepts: a car and a bike.

Clearly, neither "car" nor "bike" is a fully detailed design specification for a vehicle. For example, both concepts must have a source of power, such as a gas engine, a diesel engine, or an electric motor. The concept "car" contains the more specific design sub-concepts of "gas car", "diesel car", and "electric car", as shown in Fig. 1. Each of these sub-concepts has different characteristics. Even within a sub-concept, the characteristics of specific designs can vary significantly. For example, commercially available gasoline engines cover a large range of power and fuel efficiency. Consequently, the horsepower of the concept "gas car" is not a single number, but a set of horsepower values that correspond to every member of the set of possible implementations of the "gas car" concept.

At the end of the design process, a single detailed product specification will result. However, when a decision maker is comparing design concepts, he or she lacks knowledge about the final design since there are many decisions yet to be made beyond the one the decision maker is working on. Because of this inherent lack of knowledge, the decision maker generally can only characterize the performance of concepts imprecisely.

2.2. Analysis models yield imprecise predictions

In order to compare design alternatives, engineers frequently use behavioral models to predict the performance of the alternatives in terms of attributes that are important to them, such as physical behavior, cost, and reliability. Like all models, these are only abstractions and, consequently, their predictions are imprecise reflections of reality.

For example, although the laws of physics are known very precisely, one often makes significant assumptions when applying them to complex geometries, or one omits certain known—but less significant—physical phenomena from the model to reduce the complexity. For example, an engineer often models an internal combustion engine by reducing the detailed physical phenomena (including airflow, gas-mixture combustion, friction, and inertia) into one simple algebraic relationship between engine speed and torque. This simple relationship is an idealization that may contain significant error. There are unknown or unmodeled relationships between a variety of parameters that play a role in the engine performance, such as air density, acceleration, or engine temperature. Since there is no probability distribution associated with such modeling and systematic errors, one cannot express the likelihood of occurrence for a particular error but can at best bound the size of the error, in which case the errors should be represented in terms of interval-based uncertainty.

In the preceding example, designers can reasonably model the relationship between engine torque and speed with a simple