Imprecision, Trade-Offs and Negotiation in Engineering Design

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Abstract: Recent work on Imprecision in Engineering design has extended the basic methodology to negotiation among groups within the design process, and to highly computationally efficient exploration of the design space. Recent industrial applications of the Method of Imprecision have been to passenger vehicle structure design and spacecraft reentry aeroshell design.

Introduction: Engineering design, the process of creating a new device to perform a desired function, intrinsically involves imprecision. This imprecision arises from the nature of the design problem, where one or more concepts are refined into a final design. At the concept stage, the designs are only vaguely, or imprecisely, described. Once the design process is complete, the design is described sufficiently precisely that it can be manufactured. During the process of the refinement of a concept into a finished design, most information describing the design will be imprecise to some degree, reflecting the degree to which the designer has made final design decisions and refinements. To facilitate solving engineering design problems, and to assist design refinement, advanced design methods must represent and manipulate this intrinsic design imprecision.

A method, utilizing the mathematics of fuzzy sets, has been developed over the past 15 years at Caltech. This "Method of Imprecision" (M_oI) has been shown to be effective in solving engineering design and trade-off problems in several diverse industries, including aircraft gas turbines [2, 3, 6], passenger automobile structures [4, 7, 9], and spacecraft reentry aeroshells [8]. Current work is applying this method to passenger automobile and spacecraft configuration and design.

To evaluate sets of designs an overall best design variable set must be found. Preference information (μ_d) on the design variables (d_i) and requirement preferences (μ_p) on the the performance variables (p_j) can be combined into an overall preference rating (μ_o) for that design variable set ($\vec{d}$). This computation and combination is discussed further below.

Aggregation Functions: Nearly all formal design methods for representing uncertainty or imprecision utilize one or more functions to aggregate information from multiple attributes. The aggregation calculation performs a (possibly weighted) trade-off, among aspects of a design.

Noise: Having formulated the overall preference function (by inducing the designers preference μ_d on the performance variables, and combining the induced preferences with the performance specifications μ_p), there may still be uncertainties (noises) that confound the search for the design variable set which provides the highest overall preference despite variations. A modeling scheme for tolerances on uncontrolled variations and methods for selecting an overall best design variable set in the presence of such variations is introduced in [5].

Mapping Design Imprecision: In implementing the Method of Imprecision, a key step is mapping design preference μ_d from the n-dimensional DVS to the q-dimensional PVS. For one simple aggregation function the combination of design preferences can be easily computed with a method such as the Level Interval Algorithm (LIA). The key limitation of the LIA, that it requires monotonicity, stems from the assumption that the extreme values of f_j will occur at the corner points of $D^d_{\alpha_k}$, the n-cube which is the α-cut at α_k in the DVS. The algorithm may thus be improved by relaxing this assumption. The computational implementation employed by the M_oI uses Powell's method, a calculus-based optimization algorithm. Extensions to the LIA are presented in detail in [1].

The approach used in the M$_o$I is similar to *response surface methods*, which seek to optimize a response that is influenced by several variables. The function f_j is approximated over the search space D_ϵ^d. The linear approximations $f'_1, ..., f'_q$ are obtained using techniques adapted from statistical design of experiments.

Conclusion: Imprecision and uncertainty occur throughout the engineering design process. Many methods for incorporating uncertainty (*e.g.*, utility theory, probability methods, Taguchi's method, *etc.*) are in common use, however, methods to represent imprecision in engineering design are only now under development. The Method of Imprecision (M$_o$I) is a formal method for incorporating the natural level of imprecision that occurs throughout the engineering design process, and can include: many incommensurate aspects of a design, imprecise constraints, compensating and non-compensating trade-offs, hierarchical trade-offs, importance weightings, and judgement and experience. Uncontrolled variations (noise) can also be incorporated so that the design with the greatest overall preference and most robustness to the noise can be found.

By providing the designer and customer with a technique to specify preferences on design and performance variables, design communication will evolve from individual "point" designs to (fuzzy) sets of designs. Since a range of possible design variable values can be released to downstream design processes earlier than a completed individual design, the M$_o$I facilitates (fuzzy) set-based concurrent design.

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