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# Unifying Design Education through Decision Theory*

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*Teaching design effectively is challenging. The state of design as a discipline leaves us with disjoint methods and methodologies that model various aspects of the design process but do not work together. This paper proposes decision theory as a means of potentially unifying design as a process of decision-making under uncertainty. A design exercise is described which strives to model the richness of a real design problem compressed in time and scale to a manageable size. Experience with this exercise reveals decision-based design as a promising pedagogical approach for design education. However, before we can use decision theory to unify design, we must first embrace uncertainty in problem solving throughout the engineering curriculum.*

## INTRODUCTION—THE PROBLEM

AS WE MOVE into the 21$^{st}$ century, the nature of engineering is changing. The traditional 'back of the envelope' is augmented by ever more accessible simulation and computational models. Information exchange is nearly instantaneous. The pressure on designers remains unchanged: make better products faster using fewer resources. This boils down to making better decisions not only about the product being designed but the process by which it is designed and realized. In the typical engineering curriculum, little focus is given to these decision skills and less to formalizing decision-making. Students are often required to make the leap from engineering scientist to designers in one or two final project-based courses. Having focused primarily on predicting behavior, these fledgling designers do not have a 'big picture' understanding of the overall process of engineering: unexpected failure leads to analysis and experimentation which lead to theories useful for preventing future failure.

This view of engineering casts the designer as an information manager:

What alternatives were generated?
Which failed to meet expectations?
What analyses were done and how well did they predict the behavior?
Can analysis be refined or are experiments necessary to empirically describe the behavior?

Designers must know both when to ask these questions and when they have been sufficiently answered; uncertainty often prevents absolute answers. Rooted in probabilistic design methods, decision theory can help focus a design process characterized by necessarily (according to Simon's principle of bounded rationality) incomplete knowledge.

The questions facing design education is how to best underline the centrality of uncertainty in engineering and which techniques for managing/reducing it to teach. As the various engineering disciplines vie for less and less curricular space, the capstone design class is the main vehicle for introducing these concepts. The remainder of the paper discusses the results of focusing on resolving uncertainty as a unifying concept in design. First, an argument is made for a design process based on decision making. A project is then described which demonstrates to students the role of uncertainty in the design process. A formal definition of decision-based design is given. Experience on the impact of this project/theory presentation on subsequent design projects and conclusions to be drawn from them are then presented.

## DESIGN AS DECISION MAKING UNDER UNCERTAINTY

Decisions operate over a finite set of options. In design, options come from two general sets: product and process. Product options (design alternatives) and the metrics used to evaluate them co-evolve as the design process progresses. Decisions reduce the set of design possibilities, allowing the designer to direct attention toward promising options [1, 2]. Descriptive studies of design reveal that high level abstractions (often evaluated subjectively) give way to increasingly detailed designs (evaluated more objectively). The primary emphasis during this progression from abstract to concrete is on developing information [3]. Process options can focus on reducing uncertainty in the evaluation model (e.g. doing more

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detailed analyses, running experiments, eliciting more detailed customer preferences, etc.) or improving the set of design alternatives (e.g. searching for existing solutions, combining/repairing current alternatives, brainstorming for new alternatives, etc.). Decisions over process options should be as carefully considered as decisions about product.

Pedagogically, the goal of this work is first to motivate students to observe how uncertainty impacts both design process and product and then to provide them with more formal means for managing it. The intention is to unify design techniques around decision making under uncertainty, providing product-oriented focus to the design process. Significant decision theory concepts are demonstrated by their application to a shared prior design experience:

- *Probabilistic Modeling*—Material properties, dimensional tolerances, modeling errors, uncertainty in the objective for a design, etc. all inject uncertainty into the design process. In analysis, factors of safety can account for at least the first three of these. But to compare competing design alternatives, a distribution of evaluations for each is more useful—prompting further analysis of product options with overlapping evaluations and identifying dominated options to be rejected.
- *Expected Value Decision-Making*—The uncertainty under which a set of alternatives is compared can be 'integrated out' by calculating the expected value (or potentially expected utility) to be derived from each option. Alternatives can be ordered, the best ones identified, or at least the worst eliminated.
- *Information Value Theory*—Uncertainty in design evaluation can be reduced, usually at some cost. Various sources of uncertainty can be analyzed to see if they impact the ordering of design alternatives; uncertainty that could change this ordering is potentially worth reducing. Information value theory provides a means for bounding the value of developing information (i.e. reducing uncertainty).

While students reflect on the results of a shared design experience, they apply lessons in a team-based design project of their choosing. One of the main lessons is that there is no single 'design process'. Instead, design process options are selected and strung together in a way that is sensitive to the context of each design project. The above decision theory concepts guide the students as they design both a product and the process that produces it.

A symptom of a poor design process is one in which arbitrary decisions are made simply to 'advance' the design process. Students tend to want to get to the 'engineering' (i.e. analysis) as quickly as possible. The design process has at each stage many options in addition to analysis: generate new design alternatives, perform more careful evaluations, build a prototype, run some experiments, understand better what the 'customer' wants, etc. By defining design as the co-evolution of information and artifact, we build on students' preparation in engineering science: Theories based on first principles provide broadly useful methods for predicting behavior. Experimentation assesses the validity of these theories in the imperfect world to which they are applied. Where first principles fail to provide an adequate model, empirical models are substituted. Toward making these models generally applicable similitude is used. Prediction and uncertainty are linked as irrevocably as prediction and design. By directing design students to identify sources of uncertainty, assess their impact on the current design state, and reduce it where beneficial, we are really teaching students how to learn. When prediction fails, we either discount it by increasing the uncertainty we associate with it or refine it to cover the new evidence. This is the process of engineering inquisition.

## A MOTIVATING PROJECT

The impact of uncertainty on design is motivated through a team-based design project shared by the entire class—building a paper helicopter. The project is authentic in many ways: students are rigorously charged for design time, materials, testing, manufacturing infrastructure, etc. Design success is evaluated based on profit in a competitive marketplace. The project entails two product design cycles: a preliminary market introduction is followed by redesign. In the redesign cycle, students reflect on the failure mode(s) of their designs, identify the design process causes of these failures, and work to resolve these problems. Most failure modes can be associated with failure to properly manage uncertainty. Some of the typical sources of uncertainty and failure modes associated with them were:

- *Similitude*—Teams are permitted scale model tests (i.e. they can drop the helicopters in the classroom) at no cost, or can pay for full-scale testing (i.e. a 20 ft. drop). Failure Mode I: *Instability not present in the scale testing was revealed at full scale.* Failure Mode II: *Designs were often deemed too similar in the short duration tests so one was arbitrarily selected.*
- *Environment*—All three team members must drop a helicopter; the worst performance is recorded as the team's score. Failure Mode: *Sensitivity to dropping method was revealed, in extreme cases a secondary tumbling mode resulted.*
- *Manufacturing*—Each team is required to build six samples, of which three are randomly selected for flight. Teams are charged for accurate manufacturing technology (i.e. tearing the paper is free, they must pay for scissors,

templates, cutting 'machines', etc.). Failure Mode I: *Difficult to manufacture designs revealed defects in serial production that had been 'tuned' out of prototypes.*

- *Unexplored Options*—For many teams a contributor to failure was stopping exploration after a single working prototype had been found. Development ignored simple variations like size, dihedral angle, etc. Brainstorming for new concepts stopped as well. Failure Mode I: *Concepts were considered as points rather than sets. Good design concepts failed because they were too large or too small. Others became unstable due to low dihedral angle or poor weight distribution.* Failure Mode II: *Too few concepts were explored. The value of concept generation was underestimated with respect to the value of development.*
- *Marketing*—The 'market' for the problem is a simulation in which a price/performance ratio (i.e. time of flight divided by selling price) determines revenue but not necessarily profit. Failure Mode I: *Teams did not appreciate the single objective: profit.* Failure Mode II: *Teams had difficulty integrating the actions of others into their analysis.*

One source of uncertainty missing from the above list is modeling accuracy. Students applied only simple, first-order models of system behavior (e.g. system mass should be minimized, center of gravity should be low). The aerodynamic aspects of the project could explain the absence of models—empirical methods are still the standard in this domain. Notable, however was an absence of consideration by the teams of non-aerodynamic models like moment of inertia, wing stiffness, body stiffness, the use of dihedral angle to promote stability, etc.

While redesign did not change the degree to which teams applied theoretical models, it was successful in reinforcing that uncertainty had been a primary cause of failure in the first phase. All designs showed marked reduction in time of flight variability. Teams chose several paths toward improving performance:

doing parametric studies on their prototypes followed by full-scale tests;
refining manufacturing plans or redesigning for more consistent production;
developing new concepts;
combining their concepts with aspects of more successful designs;
using the results of phase one to predict market and set price for maximum profit; etc.

Each of these activities cost engineering hours, potentially reducing profitability.

## DECISION-BASED DESIGN

Armed with experience in design failure rooted in uncertainty, the class is then introduced to decision-based design [4]. The particular instantiation with which we are concerned proceeds as follows: First, the expected value of selecting from among the options available for each possible decision are evaluated in the following equation:

$$E[obj|dec_i, c, u] = \int_{\Omega_u} obj(dec_i, c, u) P(obj|dec_i, c, u) du \qquad (1)$$

where:

$obj$ is the value of the objective function;
$dec_i$ is one of the discrete decision under consideration;
$c$ is the set of certain design parameter values;
$u$ is the set of uncertain parameter values.

For each of these decisions, the impact of a particular source of uncertainty can be evaluated by allowing the uncertain parameter to take on certainty at its possible values and allowing the decision maker to 'change his mind' from the best decision under uncertainty. The value to be gained from knowing the parameter with certainty (i.e. the expected value of perfect information—EVPI) is then:

$$EVPI[u_j] = \int_{\Omega_{u_j}} \{(\max_i E[obj|dec_i, c, u, u_j]) - E[obj|dec^*, c, u]\} P(c, u, u_j) du_j \qquad (2)$$

where:

$obj$ is the value of the objective function;
$dec_i$ is one of the discrete decision under consideration;
$c$ is the set of certain design parameter values;
$u$ is the set of uncertain parameter values (other than $u_j$);
$u_j$ is the uncertain parameter being evaluated.

These two equations capture the essence of the design process. The first equation focuses designer attention on the best current options—*design decisions*, the second evaluates the impact of gathering information on the selection process—*design process decisions*. The generality of the theory is presented as two main points:

1. Delay commitment for design decisions where there is no clear best choice (i.e. because of uncertainty):
   - Identify sources of uncertainty whose resolution could simplify the decision.
   - Try concept generation/combination to produce better options.
2. The act of creating information is a design process decision whose value can be compared not only to other process decisions but also to product decisions.

Because decision processes are, by nature, oriented to choosing from a predefined set of options, neither is able to introduce new options into the process. However, creativity techniques (e.g. concept combination) can be triggered when dissimilar product options produce similar evaluations. When to end brainstorming/concept generation is a problem solved only be experience.

The unifying aspects of the above framework are manifold. First, design process decisions and design product decisions can be compared on the same scale – the design objective. Second, uncertainty that results from such varied aspects of life cycle design as need identification, evaluation model error, experimental error, manufacturing capability etc. can all be included as the design progresses. Finally, defining a single design objective is an important unifying factor [5].

## DISCUSSION

*Observations from semester projects*

We would like to be able to say that students applied the lessons of decision-based design motivated by the paper helicopter project to their semester-long design projects. Unfortunately students seem to forget the lessons learned in the 'toy project':

- Students continue to make decisions based on small differences in concept evaluations.
- Students attempt to develop models where experimentation or prototyping would develop information.
- Students search for 'book answers' and apply them without assessing their validity in the design context.
- Students 'average out' uncertainty to get their design to fit a standard model.
- Students run computer simulations without understanding their underlying assumptions and failure modes inherent to them.

It is a difficult challenge to overcome a 'single number' or 'plug and chug' mentality instilled by drilling students in mathematical theories, one that we will continue to try to meet. Freed from the expectation of calculation in the paper helicopter design exercise, students generally applied more appropriate design process options. As students rely on engineering science to predict the behavior of their 'real' design projects, they ignore the uncertainty that they know from experience is a large part of design.

*'Realistic Toy' projects vs. 'Toy Real' projects*

Significantly, semester-end surveys of students point to the paper helicopter as the most educational activity in the class. As project-based learning pervades design education, we must address the type of project that is done. The design course in question takes place over a single semester and includes: the paper helicopter project (a 'toy' project carefully constructed to mimic a realistic engineering context) and a semester design project (a 'real' project which results in an untested paper design) with supporting lectures. Students claim to have learned more in the two weeks of the 'toy' project than in the fourteen weeks of solving a 'real' problem. This is a significant problem, especially considering the difficulty of producing 'real' design problems for students to work on. In reflections on the helicopter project, students write that the most educational aspect of the paper helicopter project is the cycle of failure, analysis, and redesign. Should design education focus on a series of realistic design exercises carried out to completion or on a single design project (simplified to 'fit' into a single semester)? The results of our student surveys seem to indicate the former, especially if the simplification of the latter prevents construction, testing, development, manufacture, etc. In 'realistic toy' problems, students are faced with all of the design process options. In 'toy realistic' problems students are often too resource-limited (e.g. in access to computational tools, in access to prototyping equipment, in access to manufacturing information) to follow through on a good design process.

*'The' design process*

A final point of discussion relates to the pedagogy of design. Some propose specific steps for a designer to take [6, 7]—'the' design process. Others define axiomatic evaluation metrics to be applied [8] in a looser definition of process. Many describe design as a progression of tools to be applied where appropriate [9–11]. Decision theory unifies this tool-based approach around the concept that the primary goal of 'the' design process is twofold: find a good solution while at the same time finding out what 'good' means.

## CONCLUSIONS

We characterize the process of design by ambiguous goals, uncertain metrics, and limited resources. Designers must develop options, predict their behavior, and evaluate this behavior with respect to the demands of an uncertain world. Engineering science is integral to design. Predicting behavior plays a vital role in design decision-making. However, we must teach students that engineering science is, at its core, a set of useful approximations with limitations and error.

Whether it is choosing the best design direction or the best design process direction, decision-making is a large part of the design process. Design is fundamentally a process of developing information whether it is brainstorming for new options, getting a better understanding of customer needs, or refining predictions about the service environment. The final artifact is just that, an artifact of the process that created it; its quality is directly related to the quality of the process.

Toward improving this process, this effort to introduce decision theory as a backbone for managing activity in design will continue. Based on the observation that students are still more comfortable with single numbers, the next step will be to introduce Monte Carlo methods for dealing with uncertain design variables and propagating this uncertainty through models.

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