Module 01
Course Overview

Dr. Jitesh H. Panchal

Decision Making in Engineering Design

PURDUE MECHANICAL ENGINEERING

School of Mechanical Engineering
Purdue University, West Lafayette, IN

Introduction

Jitesh H. Panchal, Ph.D.
Associate Professor
School of Mechanical Engineering
Purdue University

- At Purdue University since Fall 2012
- *Assistant Professor* at Washington State University (2008-2012)
- *Visiting Assistant Professor* at Georgia Tech (2006-2008)
- Education
    - Ph.D. in Mechanical Engineering, Georgia Tech (2005)
    - M.S. in Mechanical Engineering, Georgia Tech (2003)
    - B.Tech. in Mechanical Engineering, Indian Institute of Technology, Guwahati (2000)

Module Overview

1. Why Study Decisions in Engineering Design?
   - Decisions are ubiquitous, and they affect the design outcomes
   - Limitations of decision-making methods
2. Decision Making in Engineering Design: The "How"
   - How should decisions be made?
   - How do humans *actually* make decisions?
3. Course Structure
   - Course contents
   - Grading scheme

Why Study Decisions in Engineering Design?

Design is a decision making process

Designing is the process of converting information about needs and requirements for a product/system into a complete specification of that product/system.

Role of decisions in design:

- Design is to a large extent decision making.
- The process of design involves choosing the most preferred option in a sequential manner.

Decisions determine the success of a design project.

What is a Decision?

A decision is a choice among alternatives, driven by a preference.

A decision is:

- A present action to achieve a future outcome
- An irrevocable allocation of resources, in the sense that it would take additional resources, perhaps prohibitive in amount, to change the allocation (Matheson and Howard, 1968).

Can you think of decisions made in the design process?

J.E. Matheson and R.A. Howard, 1968, *An Introduction to Decision Analysis*, from Readings on The Principles and Applications of Decision Analysis, Strategic Decisions Group.

Who are the decision makers?

Decisions are everywhere...

1. Decisions made by customers in choosing products to purchase
   - Product selection
   - ...
2. Designers as decision makers
   - Concept selection
   - ...
3. Responding to decisions made by competitors
   - Pricing
   - ...
4. Others?

Example – Decisions Made by Customers

Example – Decisions Made by Designers

Conceptual design – morphological matrix

Principal Solution Alternatives

Sub-functions

	1	2	3	4
Store Energy	Potential energy	Spring	Battery	Capacitor
Force Cycle	Pendulum	Coil Spring	Oscillating Crystal	
Change Signal	Gears	Meter	Electrical Motor	Stroke Magnet
Display Time	Analog	Digital		

Example – Decisions Made by Designers and Manufacturers

Design of steering wheel shaft:

- Rigid
- Multi-joint
- Flexible
- Hydraulic
- Electrical

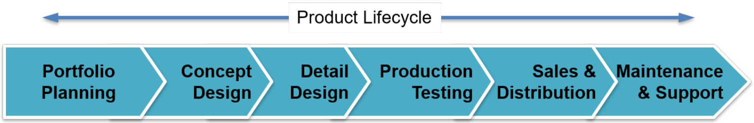
Selection of cutting tool:

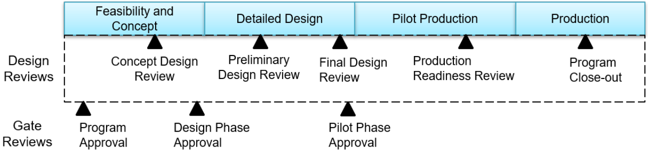
- Solid
- Liquid
- Gas/Plasma
- Laser

Mobile telephone design:

- Monolithic
- Two-piece
- with a flexible casing
- with liquid crystal display

Example – Decisions are Made Throughout a Product/System Lifecycle



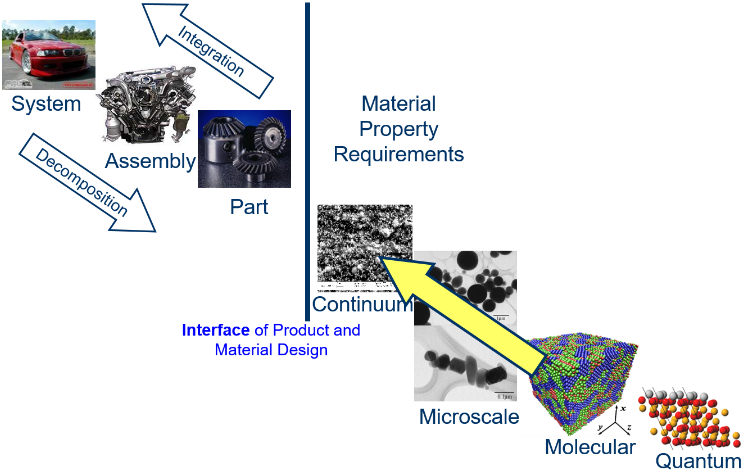


Example – Key Decisions in an Automotive Product Lifecycle

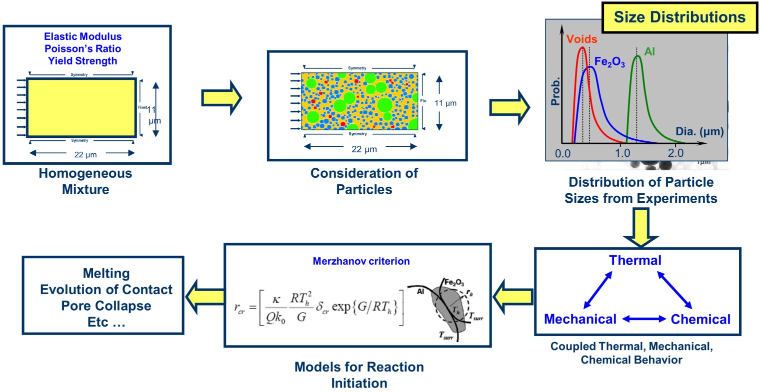
1. Program kick-off
2. Program confirmation
3. Product concept freeze
4. Engineering sign-off
5. Production release
6. Periodic reviews
7. Product discontinuation and replacement

V.D. Bhise, 2017, *Automotive Product Development: A Systems Engineering Implementation*, CRC Press, Boca Raton, FL, pp. 269-270.

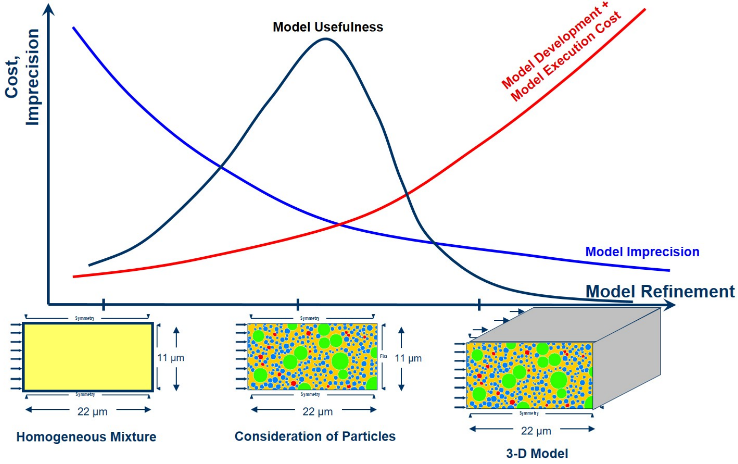
Multi-level Design



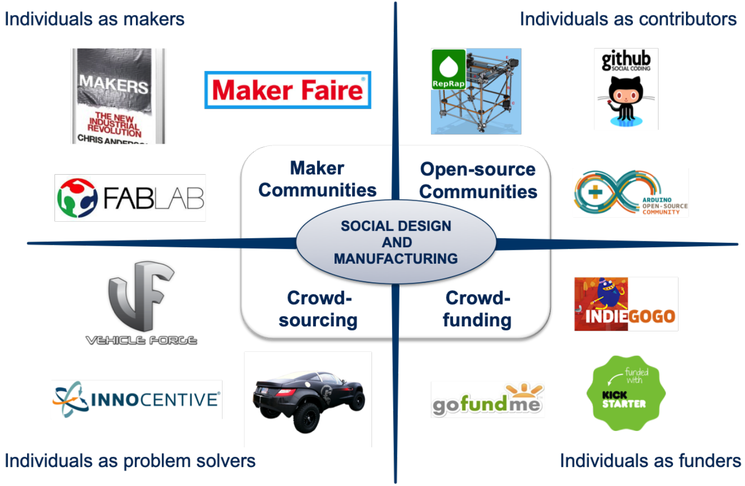
Decisions in Modeling and Simulation



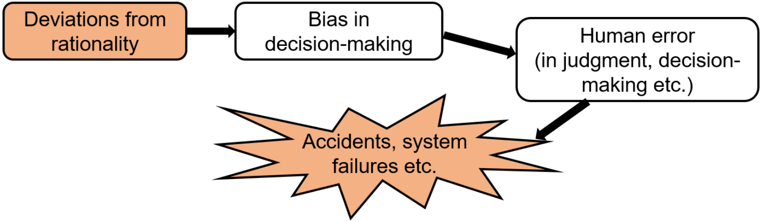
Decisions Made by Analysts (contd.)



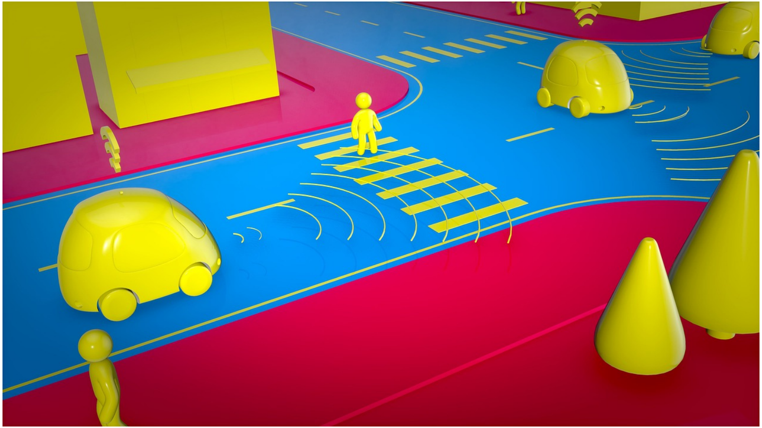
Decisions Made by Participants in Open Innovation



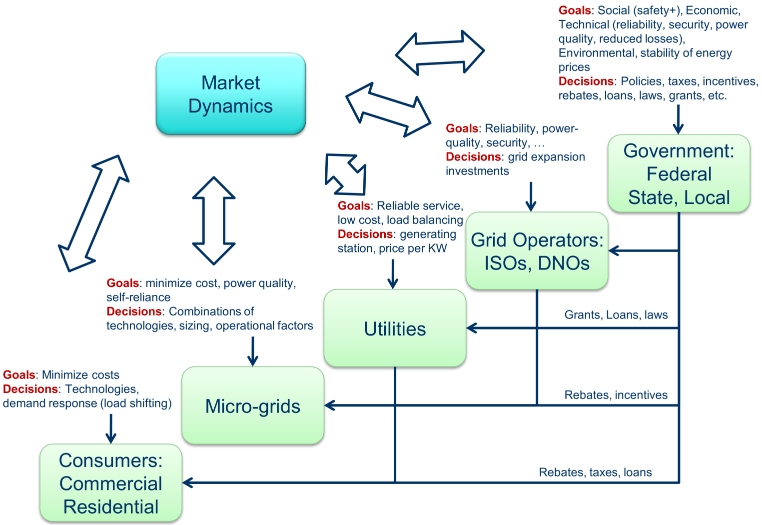
Failures in Space Systems



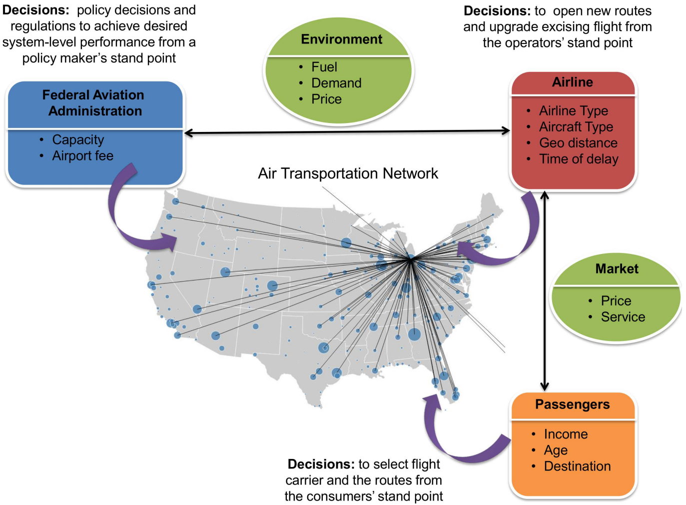
Example – Decisions in Autonomous Transportation Systems



Example – Decisions Made by Participants in Power Systems



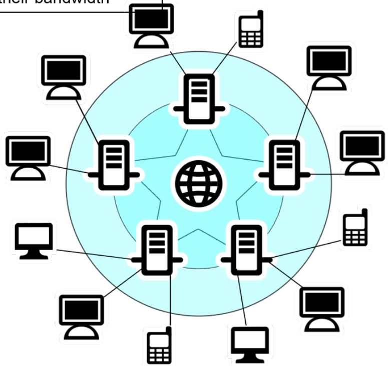
Example – Decisions Made by Participants in Air Transportation System



Example – Decisions Made by Participants in the Internet

Decisions of existing AS: to select ISP to buy additional Internet service to enlarge their bandwidth

Decisions of existing AS: to select another existing AS to establish a P2P connection



Decisions of new AS: to select target ISP to buy the Internet service or select existing AS to establish a P2P connection

Decision Criteria

- Transit price
- Quality of service
- Cost
- Reliability
- Performance of provider
- Geographic reach
- Prior acquaintance
- Customer service
- Technical support
- Traffic volume
- Number of current customers
- Market benefits

Why do we need to study decision making?

Because poor decisions increase the likelihood of poor outcomes!

Poor decisions can result from:

1. Limitations of decision making methods
2. Human biases

Example 1: Voice of the Customer

Question

What is your preferred choice of product color? A, B, C, D, or E

- A = Black
- B = Blue
- C = White
- D = Red
- E = Pink

Survey Results (100 customers):

- 45 prefer A
- 25 prefer B
- 17 prefer C
- 13 prefer D
- No one prefers E

Inference from the Survey: $A > B > C > D > E$

Hazelrigg, G. A., 2003, "Validation of Engineering Design Alternative Selection Methods," *Engineering Optimization*, Vol. 35, No. 2, pp. 103-120.

Preference Ordering

If designer considers **preference ordering** instead of just the top alternative, the following results are seen:

- 45 customers: $A > E > D > C > B$
- 25 customers: $B > E > D > C > A$
- 17 customers: $C > E > D > B > A$
- 13 customers: $D > E > C > B > A$

Verify that this preference structure will give the same results as seen on previous slide.

In fact, there are 120 such preference orderings that will give same survey results.

Preference Ordering (contd.)

1. Count the number of customers that prefer A to E... = ???
2. Count the number of customers that prefer E to A... = ???

Perform similar pair wise comparisons for each pair.

What is the customers' **ACTUAL** preference?

Preference Ordering (contd.)

1. Number of customers that prefer A to E... = 45
2. Number of customers that prefer E to A... = 55

By performing similar pair wise comparisons, it can be seen that the customers' **actual** preference is: $E > D > C > B > A$, which is exactly opposite of the survey results!!!

Conclusion

The method is not reliable!!!

It is also possible that there is no alternative preferred by the group.

Decision Making in Engineering Design: The "How"

Let us think about "how" decisions are made

1. **Customer's perspective**: Deciding among a set of *products*. How would you do it?
2. **Designer's perspective**: Deciding among a set of *concepts*. How would you do it?
3. **Competitor's perspective**: Deciding among a set of *prices*. How would you do it?

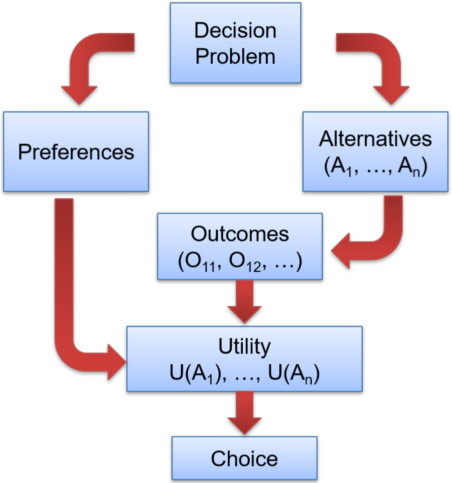
Are there any **commonalities** among these decisions and decision-making methods?

Are there any **differences** between these decisions and decision-making methods?

Structure of a Decision

What are the basic elements of (any) decision?

Basic Elements of a Decision



Utility-theory for decision making

[vonNeumann and Morgenstern]

IF an appropriate utility is assigned to each possible consequence,
AND the expected utility of each alternative is calculated,

THEN the best course of action is the alternative with the highest *expected utility*.

Behavioral Axioms

Behavioral axioms that form the basis of expected utility:

- **Ordering of alternatives**: Decision maker can order any two alternatives and the ordering is transitive.
  Transitivity: If $A_1 \succ A_2, A_2 \succ A_3$, then $A_1 \succ A_3$
- **Reduction of compound uncertain events** using complicated mixtures of lotteries using probability theory.

$$\langle x^*, 0.2, x_0 \rangle \sim \boxed{???}$$

$$\langle \langle x_1, 0.2, x_2 \rangle, 0.5, \langle x_3, 0.5, x_4 \rangle \rangle \sim \langle \boxed{???}, 0.2, x_0 \rangle$$

$$\langle \langle (x_1, y_1), 0.2, (x_2, y_2) \rangle, 0.5, \langle (x_3, y_3), 0.5, (x_4, y_4) \rangle \rangle \sim \langle \boxed{(???, ???)}, 0.2, (x_0, y_0) \rangle$$

- **Substitutability**: reverse of reduction (i.e., the decision maker is willing to substitute a deterministic outcome with a lottery).

Clemen, R. T. (1996). *Making Hard Decisions: An Introduction to Decision Analysis*. Belmont, CA, Wadsworth Publishing Company. Chapter 14.

Behavioral Axioms (contd.)

- **Continuity**: If $A_1 \succ A \succ A_2$, then we can construct a lottery between A_1 and A_2 with probability $0 \leq p \leq 1$ so that the decision maker is indifferent between A and the lottery.
- **Monotonicity**: Decision maker prefers the gamble which has higher probability of achieving the preferred outcome.
- **Invariance**: All that is needed to determine a decision maker's preferences among uncertain events are the payoffs and the associated probabilities.
- **Finiteness**: No consequences are infinitely good or infinitely bad.

Clemen, R. T. (1996). *Making Hard Decisions: An Introduction to Decision Analysis*. Belmont, CA, Wadsworth Publishing Company. Chapter 14.

Do people follow this normative model?

Do people really satisfy these behavioral axioms?
Are people rational (as defined)?

Tversky and Kahneman

Kahneman: 2002 Nobel Memorial Prize in Economic Sciences

"People reply on a limited number of heuristic principles which reduce the complex task of assigning probabilities and predicting values to simpler judgmental operations."

Examples of heuristics that people use in assessing probabilities:

1. Representativeness
2. Availability
3. Adjustment and anchoring

The use of these heuristics can lead to **systematic** errors!

Tversky, A. and Kahneman, D., 1974, "Judgment under Uncertainty: Heuristics and Biases," Science, 185(4157), pp. 1124-1131.

In Summary

1. Most decision support tools in design and systems engineering (e.g., QFD, Six Sigma, Pugh, Robust Design, Axiomatic Design, etc.) violate the basic principles of decision theory. These methods are flawed, or at best, rough approximations of normative decision theory.

Therefore, we must understand what the approximations are, and when these methods can be used safely.

2. Humans typically do not follow the basic principles of decision theory. They exhibit biases and follow heuristics for making decisions.

Therefore, we must understand how humans deviate from the ideal decision making behaviors.

Course Structure

Introduction to "Decision Making in Engineering Design"

So, what is this course about?

Catalog Data: Multi-objective decision making under risk and uncertainty; Group decision making; Sequential decision making; Model-based and data-driven decision making; Heuristics and biases in design decision making. Applications to engineering design including estimation of customer preferences, simulation-based design, and sustainable design.

Course Objectives

Upon completion of this course, students will be able to:

1. Learn to formulate design decisions under risk and uncertainty.
2. Learn to apply multi-attribute utility theory to make decisions in engineering design.
3. Assess the assumptions and limitations of commonly used decision-making methods.
4. Identify and reduce biases in design decision making.
5. Adopt an interdisciplinary approach to design across engineering, economics, and social sciences.

Overview of Topics (1)

1. Course Overview
2. Engineering design and systems engineering through the lens of decision making
3. Framing a decision problem
4. Decisions under certainty: The tradeoff problem
5. Modeling uncertainty
6. Single-attribute utility theory
7. Multi-attribute utility theory
8. Sequential decision making

Overview of Topics (2)

9. Value of information
10. Group decision making and aggregation of individual preferences
11. Rationality and bounded rationality
12. Cumulative Prospect Theory
13. Decision Field Theory
14. Descriptive models of sequential decisions
15. Estimating customer preferences
16. Introduction to interactive decision making and game theory
17. Review and Research Topics

Grading Scheme

Assignments	40%
Mid-term Project	30%
Final Project	30%

Key References

1. R. T. Clemen, 1996, *Making Hard Decisions: An Introduction to Decision Analysis*. Belmont, CA: Wadsworth Publishing Company.
2. R. L. Keeney and H. Raiffa, 1976, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. New York: John Wiley and Sons.
3. R. Hastie and R.M. Dawes, 2010, *Rational Choice in an Uncertain World: The Psychology of Judgment and Decision Making*, 2nd Edition, Sage Publications.
4. R. A. Howard and A. E. Abbas, 2016, Foundations of Decision Analysis, Pearson Education.
5. G. A. Hazelrigg, 2012, *Fundamentals of Decision Making For Engineering Design and Systems Engineering*: `http://www.engineeringdecisionmaking.com`.

Additional References

1. P.K. Dutta, 1999, *Strategies and Games: Theory and Practice*, Cambridge, MA: MIT Press.
2. R. L. Keeney, 1992, *Value Focused Thinking*. Cambridge, MA: Harvard University Press.
3. K. E. Lewis, W. Chen, and L. C. Schmidt, eds., 2006, *Decision Making in Engineering Design*. New York, NY: ASME press.
4. W. Chen, C. Hoyle, H.J. Wassenaar, 2013, Decision-based Design: Integrating Consumer Preferences in Engineering Design, Springer USA.
5. R. B. Myerson, 1991, *Game Theory: Analysis of Conflict*. Cambridge, MA: Harvard University Press.
6. C. D. Aliprantis and S. K. Chakrabarti, 1999, *Games and Decision Making*. New York: Oxford University Press.
7. D. Fudenberg and J. Tirole, 1993, *Game Theory*. Cambridge, MA: MIT Press.