Chapter 13

Engineering Design

Rational Approach to Design

- The ad hoc approach to design has served engineering needs since the dawn of history.
- What is the problem with the traditional design approach?
  - Poor design practice results in a long design process.
  - Incorrect or excessive Functional Requirements (FR)
  - alteration of the FRs during the design process
  - poor design decisions
  - inability to recognize faulty decisions prior to making faulty prototypes.
- Example: if it takes the U. S. Army 17 years to develop a new tank, it will be impossible to deploy this weapon in a war which only lasts one-four years.

Design Disasters

- Space Shuttles Challenger and Columbia
- The near melt-down at Three Mile Island Nuclear Power plant
- The meltdown at the Chernobyl Nuclear Power plant
- The chemical plant failure in Bhopal, India
- Airplane crashes, which result from design failures,
- Firestone tire/ Ford Explorer disaster
- Tacoma Narrows Bridge

The Performance Envelope

- The <u>Performance Envelope</u> is the range of conditions under which the design is expected to be used in service.
- Designs which push closer to the edge of the performance envelope or which exist in environments for which little design data is available, are less safe.
- Design conservatively.
- Poor decision making and a lack of a metric against which a design can be considered good or bad, result in costly designs.
  - unnecessary parts, vestigial parts, or excessive/expensive materials.
  - difficult/costly to manufacture or maintain.
- Products will always be used outside the performance envelope (see any movie about a submarine for an example).
- Engineers must make sure that their products function properly inside any reasonable performance envelope.
- It is not sufficient to issue special "operator instructions" when a design flaw is encountered.

Hierarchical Decision Making

- The design process is a hierarchical decision making process.
- A hierarchical decision making process is one in which decisions must be made in order (similar to a linear computer program).
  - Decisions can be made in parallel (called parallel path engineering).
  - The parallel process must synchronize periodically to pass information between the separate processes. In other words, the hierarchical nature of design can be relaxed somewhat. It cannot be entirely removed.
- This is similar to organizing a computer program into a parallel program in which chunks of the code will run simultaneously on separate processors.
- The design process is usually done with low or uncertain information content.
- Entities which fail to recognize the hierarchical nature of design and organize themselves accordingly, perform design on an ad hoc basis.

Example

- Goal: develop a national policy to strengthen international competitiveness.
  - Decision 1: Is such a program desirable?
  - Decision 2: Should the program be run by a public or private agency?
  - Decision 3: Which agency/private entity should carry out the task?

How Not to Accomplish This Design

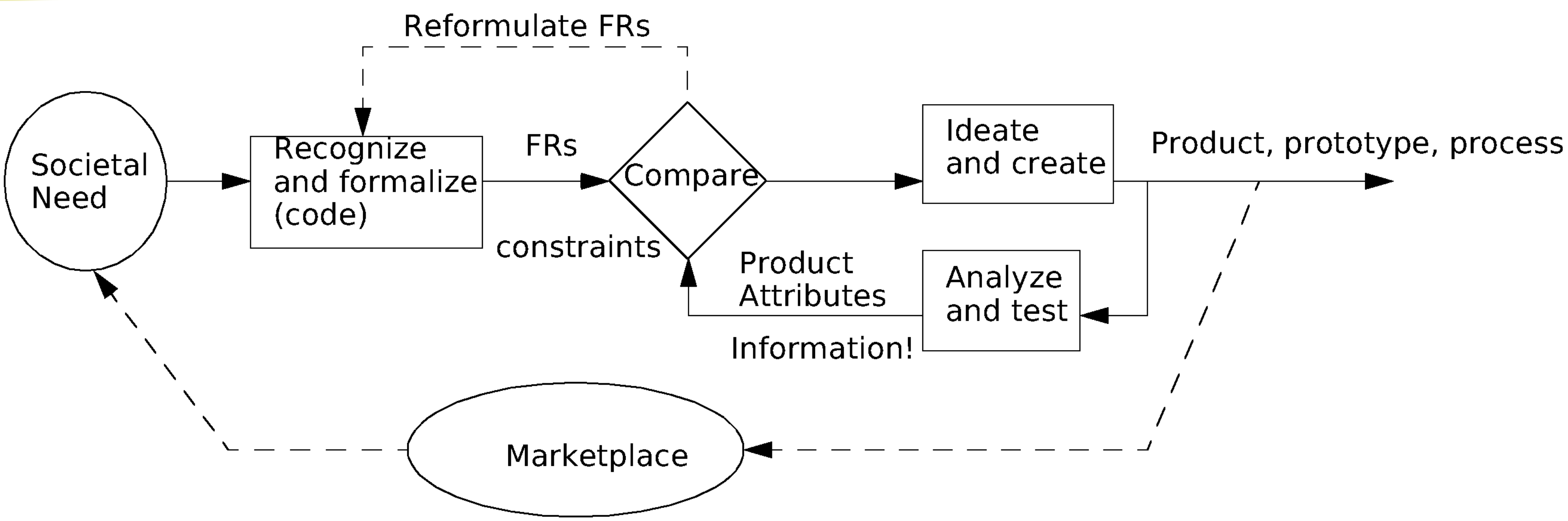
- If the entity did not carry out this decision making process in a hierarchical scheme, it would begin assigning the agency or private entity prior to deciding whether the program is desirable.
- If it was later decided that the program is not desirable, then the effort focussed on implementing the program (decision level 3) would be wasted.
- If the decision to implement through a public agency or private agency (decision level 2) is not done prior to deciding the agency (decision level 3), either an erroneous agency will be identified or wasted effort will be invested in identifying multiple agencies.

What is Design?

- Design is a <u>synthesis</u> process supported by analysis.
  - Synthesis means to combine multiple entities to achieve something new
  - Analysis can remove uncertainty from the decision making process.
  - Analysis is -not- the point of engineering!
- Needs are fulfilled through creation of physical, informational, or organizational structures.
  - Structures could be a machine, a software program, an algorithm, an organizational chart, a system of electrical, mechanical, and software elements, etc.
  - Structures, such as a machine, are not necessarily purely mechanical. They may be a combination of mechanical, electrical, algorithm, and software elements. (This is called mechatronics.)
- Given a set of specified inputs, the result of the design process has an output which satisfies the perceived goals.
- Design is a creative process, similar to an artistic pursuit.

The Design Loop

D. R. Wilson, An Exploratory Study on Complexity in Axiomatic Design, Ph. D. Thesis, MIT, 1980



The Design Process

1. Identify the problem
2. Define the working criteria/goals
3. Research and gather data
4. Determine physical embodiment of solutions (Brainstorm ideas)
5. Analyze the feasibility of potential solutions
6. Develop and test models (check on the fidelity of the final design)
7. Make decision
8. Communicate decision
9. Implement and commercialize decision
10. Perform post-implementation review

Problem Definition

- The problem definition process is subjective (not objective). There may be many correct (but different) definitions to the same problem.
- It is not unusual for engineers to impose a known solution on a new problem.
  - Failure to define the correct problem inevitably results in successfully solving the wrong problem!
  - This is actually worse than incorrectly solving the right problem.
- Sources of ideas for new product
  - R&D, University research
  - Survey of Customer Needs
  - Government priorities

Stakeholders

- Identifying the share-holders in the design endeavor is important.
- Customers (or potential customers) are very important share-holders.
  - The customer is always right. Unfortunately, the customer does not know what he wants or is not willing to pay for everything that he wants.
  - "Registering" the customer base is the starting point for a design.
  - Example: in the 1950s, automobile safety was considered important by consumers. However, they were not willing to pay for it. Rather, style was more important.

Functional Requirements

- Functional requirements (FR) define the abstract functions that the design must achieve.
- What do we want to achieve?
- Example: what are the functions of an automatic coffee maker?
  - Brew the coffee
  - Hold and dispense the coffee

Constraints

- A constraint is a boundary on the physical embodiment of the design, rather than a function that the design must fulfill.
  - “Minimize cost” or “The unit cost may not exceed $2.”
  - “The device must fit within a 5 cm by 5 cm footprint” or “The device must have a 5 cm by 5 cm footprint.”
- There are two kinds of constraints:
  - input constraints (constraints on design specifications)
  - system constraints (constraints imposed by the system in which design solution must function)
- Higher level design decisions generate constraints on a lower levels.

Working Criteria

- Having quantitative criteria against which the evaluate the design will improve the process
- Many working criteria are numerical values from constraints.
- Others may be standards that the product must satisfy (e.g., "the test article must withstand vibration per MIL-STD 810F Method 514.5")

Design Parameters

- The physical solutions which satisfy the functional requirements are design parameters.
- “How do we want to achieve the objective.”
- Example:
  - “Brew coffee” is satisfied by “Water reservoir, heating element, filter and grounds holder”
  - “Hold and dispense coffee” is satisfied by “Caraffe and heating element”

Design Environments

- There are two circumstances under which FRs are defined:
  - Develop a new design (solution neutral environment)
  - Improve an existing design
- New Design
  - a preliminary set of FRs should be identified.
  - One or more iterations on FRs will be done.
  - Each iteration on FRs brings more information into the process.
- Existing Design
  - FRs should be reverse-engineered from the design.
  - New requirements should be integrated into the existing FRs.
  - If necessary, FRs should be made independent or abandoned.

Research and Gather Data

- After a Societal Need has been identified, as much information as possible related to this need should be gathered.
- A more experienced designer will have more information at his disposal.
- This designer will require fewer iterations to achieve an independent set of FRs than a less experienced designer.

Hierarchy of FRs

- Functional Requirements follow a hierarchy
  - Keep breaking the problem down until there is one function that must be fulfilled
  - Combining FRs at the top level can yield a larger set of solutions
- Functional Requirements are not unique.
- Each designer may define the need differently and generate different FRs for the same design.

Example: Coffee Maker

- Brew the coffee
  - Store the ingredients
    - Store the grounds
    - Store the water
  - Prepare and Mix the ingredients
    - Heat the water
    - Convey the water to the grounds
    - Mix and filter the water/grounds
- Hold and dispense the coffee
- Note: Hold and dispense the coffee would yield a different solution space than two requirements “Hold the Coffee” and “Dispense the Coffee”

Attributes of a Good Designer

- Identify those FRs which are independent and which are essential.
- Ignore/remove redundant or unnecessary FRs.
- Understand what is possible (the boundaries of the physical domain),
  - What manufacturing processes are available
  - What are the laws of nature
- Achieve a solution and then achieve the simplest solution

Creativity in Design

- Be a risk-taker who can accept failure
- Develop a good, well-organized memory
- Acquire lots of knowledge and experience from many disciplines
- Understand analogy
- Interpolate and extrapolate as appropriate
- Reduce complex array of facts, data, supposition into a simple set of the most important bits
    - Grasp the nub of the situation
- Use your mind as a great melting pot to combine the complex array of facts into a solution (synthesis)
- Know when to start the synthesis
- Know when to gather more information

Design Outputs

- The output of the design process is Information (or preferred choices)
- Design process information for a mechanical design
  - Drawings and tolerances
  - Assemblies
  - Manufacturing techniques
  - Parts lists
- The design is not just "the thing" but also how to make it.

Hazelrigg Design Definitions

- Knowledge: An agreed upon set of facts.
  - Knowledge is defined as an understanding of the laws of nature and the ability to apply those laws to predict the behavior of physical systems.
  - Knowledge is the contents of a database, with elements such as F=ma.
- Decision: An irrevocable allocation of resources.
  - The selection of design parameters for an engineering system such as a computer or an automobile constitutes an allocation of resources.
  - Design is a decision-making process, and the selections of design parameters represent decisions.

Rules of Thumb

- Make the functional requirements independent.
  - If functions become interdependent in the decision process, redefine the FRs.
  - Pick the smallest set of FRs and constraints to achieve the goal.
  - If multiple functions can be satisfied by a single physical part, combine the FRs
- Use standardized or interchangeable parts where possible.
- Use symmetrical shapes or arrangements where possible.
- Specify the largest allowable tolerance.
- Uncoupling a design usually reduces the information.