Course: **Introduction to Engineering**

Unit: **Engineering Design**

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1. INTRODUCTION

1.1 IMPORTANCE OF DESIGN FOR ENGINEERS

- One of the definitions given for engineering in the first lecture was: *The application of scientific and mathematical principles to practical ends such as the* ***design****, manufacture, and operation of efficient and economical structures, machines, processes, and systems.*
- Design is an integral part of engineering.
- Design problems may involve many levels of sub-problems, where the plan of attack will need to first identify these sub-problems (**analysis**), before their individual solutions are found and combined into a total solution (**synthesis**).
- Having design skills is one of the features distinguishing real engineers from the pseudo engineers.

1.2 SCOPE OF THIS LECTURE

The focus of this lecture is on engineering design, and it provides students with an introduction to:

- The definition of *design*; an example of a systematic design process; and the importance of documenting the design process.
- An overview of different stages of systematic design, with emphasis on objectives and functions, constraints, concept design, analysis and choice reduction, and detail design.
- A simple design example, to illustrate some of the above.

2. DESIGN FUNDAMENTALS

2.1 WHAT IS DESIGN?

- "Engineering design is the systematic, intelligent generation and evaluation of specifications for artefacts whose form and function achieve stated objectives and satisfy specified constraints" (DYM & LITTLE 2004, p.6).
- Design is influenced by *function*, *structure*, and *culture*:
  - **Function** – what a product must do dictates a lot about its design. To design a light for a room, largely dictates the type of possible solutions.
  - **Structure** – the implementation of a design dictates some structure (it can be physical structure or abstract structure as for software). For the light design, we typically need some glass bulb or tube to provide the structure for the light element.
  - **Culture** – we can choose to make the light very basic or to make it good looking, all depending on our culture.

- It is important to remember that design does not only apply to products (*created systems*), but

also to plants and processes (*creating systems*) necessary to make the products.

- In times past the designer was also the maker, and design was an individual activity.
- In the aviation industry there is a saying: *In the old days, aircraft designers were also the makers and the testers. This had the positive effect that poor designers were automatically removed form the system.*
- Now:
  - ∗ The user has the need.
  - ∗ The client identifies that need and prepares an initial requirements statement.
  - ∗ The system engineer clarifies the project statement and translates it into technology-based specifications (system level design).
  - ∗ Engineers design the system detail.
  - ∗ Other members of the technical team make the system.
- The designers are bound by ethic considerations to the public and to the profession, as well as by the limits of current technology.
- The design environment may range from small start-up ventures, where everybody is aware of everything and where the system engineer is also the detail designer, to large organizations, where the detail designer may be totally insulated from the client and user.
- Most modern design projects depend on teamwork – interdisciplinary members; concurrent activities; two-way communication links to user and client; the need for project management and good communication skills.
- Nowadays design is mostly separated from making. However, **feedback** is essential to ensure that the designer understands the user's requirements and the practical constraints; and that the fabricator understands designer's intent.
- Engineering design problems are generally not well structured initially (there is no unique approach) and open-ended (there is no unique solution) – i.e. a design project is often an **iterative** activity without a guaranteed outcome.
- Management tools can help to clarify choices and decision making.
- Design considers the form (shape and structure), fit (interfaces), and function (what it does) of an object – sometimes called F^3**.**
- Design is a thought process, so thinking tools and problem solving are essential.
- Even "Blue-sky" creativity has some initial thinking behind it. (*Design is 1% inspiration and 99% perspiration*.)

2.2 THE DESIGN PROCESS

- There is no single "recipe" for design that will guarantee an optimal solution to any given problem.
- There is also no guarantee that an optimum solution exists, or that the optimum would be recognized even if it did exist.

- *It is an unfortunate fact of life that the client does not attached worked solutions to the back of their specifications*!
- However, there is a series of well-defined steps that, if followed, will increase the chances of a successful outcome to a design task.
- For successful design it is very important to first define the question, and then seek the answer!
- Feedback is also very important.
- The following are the major steps in one possible systematic design process (refer to BLANCHARD & FABRYCKY 1990, figure 4.1):
  - System requirements definition
  - System functional analysis
  - Preliminary design and allocation of requirements
  - Trade-off and optimization
  - Decision-making, feedback to previous steps, and re-work
  - Advanced design
  - Design review
  - Decision-making, feedback to previous steps, and re-work
  - Approval for further development
- (Also refer to HAWKES & ABINETT 1984, MONDS 1984 and SHELLY *et al* 1995, for other discussions on the different phases of system design.)

2.3 DESIGN REPORT

- A *design report* is a description of a design process followed; and is just one of many essential documents to underpin a successful engineering project.
- The main purpose of a design report is to provide a record of a designer's thinking, and a rationale for decisions made during the design process.
- It is typically a supporting report for a *specification*.
- A design report can be written at various levels of detail, depending on factors such as the stage in which the design process is, contractual requirements, scope of the design effort, whether the design report is a formal deliverable to a client, the type of system which is designed, etc.
- In engineering, the formality of design reports is often discipline dependent, e.g.:
  - Software- and electronic engineers can easily change their designs by adding/removing a program line or a component. Maintaining the design report at a level where it is a true reflection of the product therefore requires a dedicated and structured approach to documentation.
  - Electrical-, mechanical-, and chemical engineers typically work with larger components, making changes to prototypes more difficult, and making it imperative to spend more time on the design phase and on reporting the designs, instead of making changes "on the go".
  - Civil engineers have to carefully report every stage and component of their designs, and

usually cannot allow deviations from the designs when actual construction commences.

- GOUWS & GOUWS 2006 provide an example of a framework for a design report.

3. PHASES OF THE DESIGN PROCESS

3.1 FUNCTIONS AND OBJECTIVES

- ***Functions*** define what a system (or object) must do.
- ***Objectives*** of the design task define what we want the system (or object) **to be.**
- In the early stages of design, it is usually desirable to keep descriptions of the functions as general as possible.

- In general, the object will perform a range of functions.
- A primary function is explicitly linked to the stated objectives.
- Secondary functions, may be:
  - ∗ Auxiliary functions that enable the basic function to be carried out, or
  - ∗ A consequence of a primary function that may be wanted or unwanted.

- Find suitable ways to ***measure*** the success or failure in meeting the objectives and functions.
- Defining the objectives and functions, and ways to measure whether they had been reached are usually carried out in consultation with the client, potential users, and other stakeholders.
- **N.B.** Refer to the discussion on Requirements Definition, in the lecture on System Engineering.
- Tools to help define objectives and functions include:
  - ∗ ***Questioning*** the client and other stakeholders (users, experts in technology and marketing, etc.). It pays to do your homework before interviewing stakeholders.
  - ∗ ***Brainstorming*** to generate uninhibited ideas.
  - ∗ ***Mind maps.***

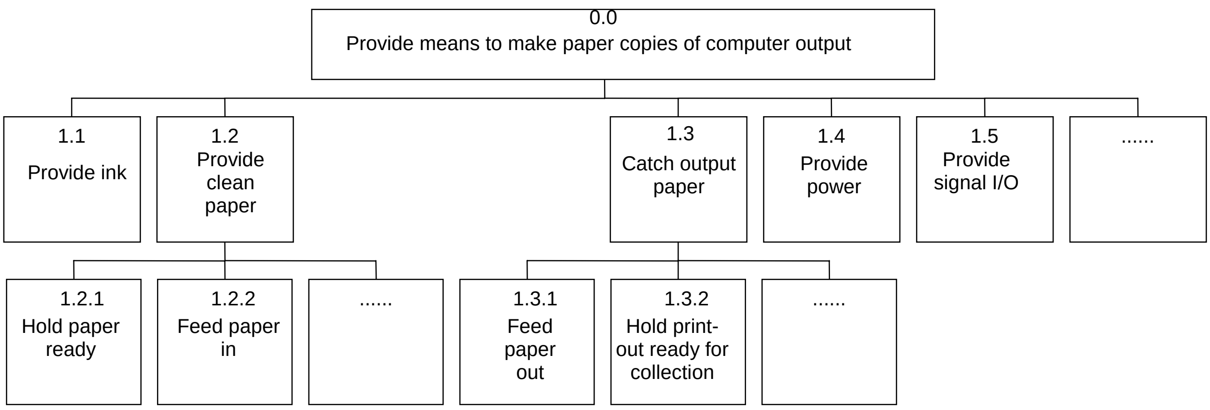
- It is very important to separate the following, in order to limit bias and pre-conceived ideas:
  - ∗ ***objectives*** (what we want the object **to be**);
  - ∗ ***functions*** (what we want the object **to do**);
  - ∗ ***constraints*** (what is possible); and
  - ∗ ***implementations*** (how we will meet objectives and perform functions).

- Objectives can be represented as a hierarchical structure called an ***objective tree***, in which goals are linked to sub-goals.
- The objective tree can be initiated and updated at any time during the requirements definition phase.
- Objectives specified for engineering projects often address aspects such as:

* Aesthetics – be appealing to the eye of the user.
* Performance – be effective and efficient in carrying out the prescribed tasks.
* Quality – be fit to use.
* Human factors – be user-friendly.
* Cost – be inexpensive, both in initial capital cost and life-cycle cost.
* Safety – be safe to the user and others.
* Operating environment – be effective in the specified operating environment.
* Interface with other systems – be compatible with connected systems.
* Effects on surroundings – be environmentally friendly.
* Logistics – be viable through scheduling of available resources.
* Reliability – be reliable.
* Availability – be readily available through local vendors.
* Maintainability – be maintainable (local repair; available parts).
* Serviceability – be serviceable, in that all parts that are prone to failure can be accessed, repaired and replaced.

3.2 FUNCTIONAL ANALYSIS

- Functional analysis involves decomposing the stated system functions into discrete tasks or activities.
- It is often best done top-down, by breaking down the total system function into successive layers of smaller functions, down to the level of single functions.
- This can be a complex process, since tasks can have sequential relationships, can be independent, can run in parallel with others, etc.
- The following diagram is a simple example of elements of the first three layers of functional analysis of the problem to make paper copies of what is seen on a computer screen.



- Note that no specific relationships between functions are yet shown in this diagram, nor do the blocks imply any specific implementations yet.

- During the next design phases, functions will be allocated, first to possible implementations, and then through analysis and choice reduction, to final implementations.
- As a next step, the functions can be described as boxes that transform inputs into outputs.
- Refer to BLANCHARD & FABRYCKY 1990 for examples of functional analysis at increasing levels of detail.

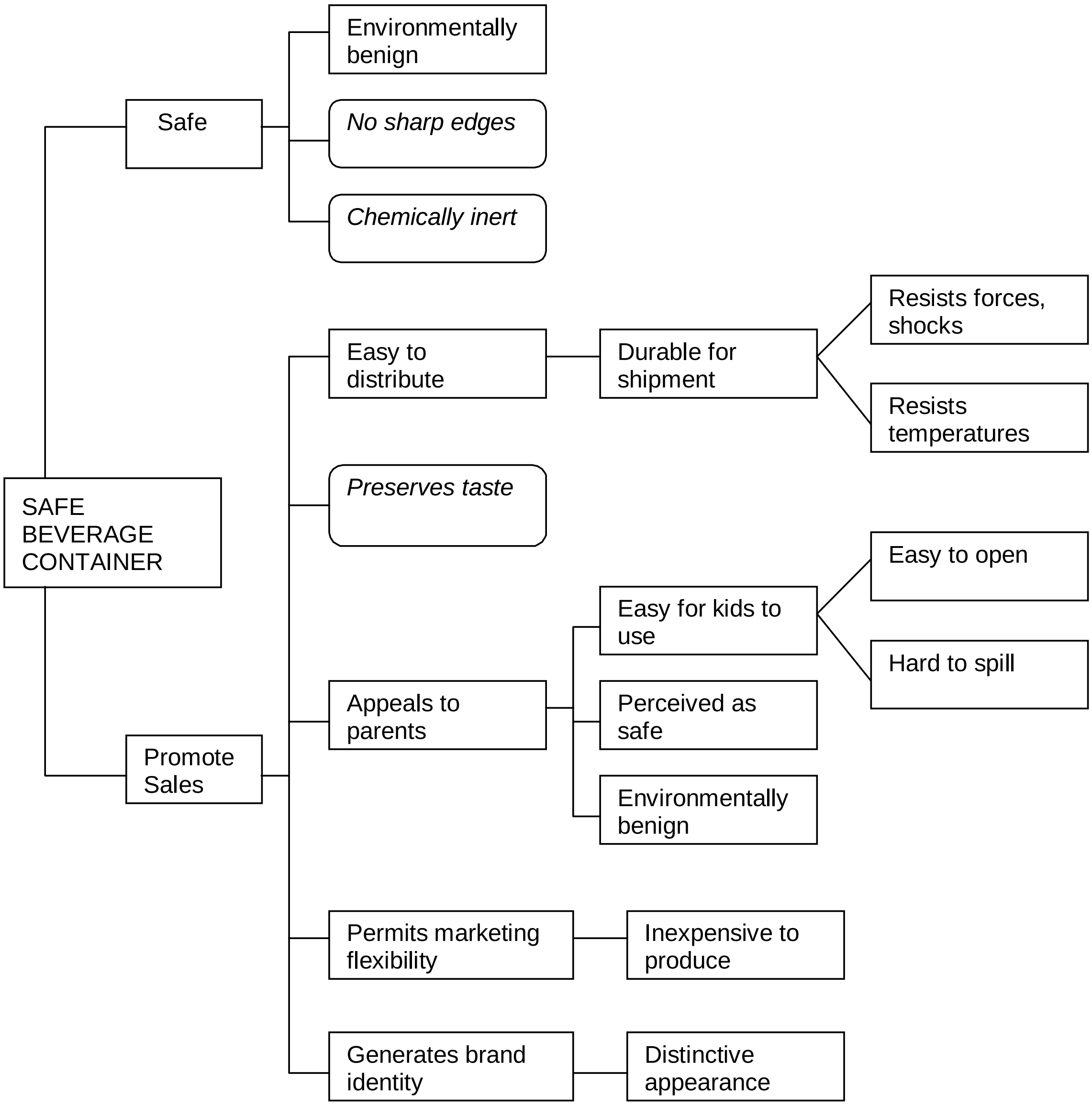
3.3 CONSTRAINTS

- The ***design space*** is an abstract space that contains all viable solutions.
- This space is bounded by ***constraints*** – i.e. what is possible?
- Constraints are conditions imposed on a solution that should not be violated.
- Constraints may be real or imagined. (If imagined, then the design space may be unduly restrictive.)
- You can increase the size of your design space by commitment to life-long learning, by working in multi-disciplinary teams, and by applying suitable problem solving techniques.
- The initial client statement may contain errors and biases (or previous conditioning) of the client, which may unnecessarily restrict the design space, e.g.:
  - ∗ "A highway is congested and causes troublesome delays for commuters. Re-design the road so that it can take more lanes of traffic." (HOLTZAPPLE & REECE 2005)
  - ∗ This statement includes an implied solution that may not be the best solution.
  - ∗ Better options may exist by providing other commuting options or by changing commuter habits.
  - ∗ A better statement is: "A highway is congested and causes troublesome delays for commuters. Re-design the transportation system to move more people quickly and efficiently."
- Constraints place hard limits on the design space.
- They are similar to objectives except that they ***have to be satisfied*** in order for the design to be accepted.
- They can be included in the objective tree, but their roles as constraints must be clearly identified.
- Examples of constraints are:
  - ∗ Budget (cost) – upper limit to funding.
  - ∗ Time (schedule) – upper limit to *time-to-market.*
  - ∗ Available technology.
  - ∗ Personnel – number and discipline mix of design team.
  - ∗ Legal – environmental, patents.
  - ∗ Material properties and availability.
  - ∗ Off-the-shelf construction (or is custom design a possibility / necessity?).
  - ∗ Competition – limits set by other products in the marketplace.

* Manufacturability – is mass production viable? (I.e. can a suitable *creating system* be designed?)

3.4 OBJECTIVE TREE EXAMPLE

- An example of an Initial Client Statement can be: "Design a bottle for our new juice product".
- From brainstorming and questioning of the client and potential users, the following objective tree was developed (DYM & LITTLE 2004):



- Notice that as the tree is traversed from left to right (actually top-to-bottom), goals branch out into sub-goals.
- Each sub-goal adds further detail to the goal at the higher level.
- The three entries that are placed in round-cornered boxes are actually constraints and not objectives – the product must satisfy each of these constraints.

- In the light of a study of the objective tree, the original client statement is modified to read (DYM & LITTLE 2004, p.58): "Design a safe method of packaging and distributing our new children's juice product that preserves the taste and establishes brand identity to promote sales to middle-income parents."
- Notice that the objectives given in the client statement are extracted from a relatively high level in the tree, where the main goals are clearly identified, without listing every instance of what the main goals mean.

3.5 CONCEPT DESIGN

- This step is called *Preliminary synthesis and allocation of requirements* in the flow diagram above.
- Once the objectives and the functions had been defined, different possible solutions for the stated problem can be identified.
- Once again, brainstorming and mind mapping are useful aids for this.
- Compiling successive block diagrams at increasing levels of detail are also very helpful.
- It is important to think laterally in order to identify various possible solutions.
- Don't discard ideas too early – even if they seem to violate constraints or if they seem unsuitable.
- Analysis of the different options is the next step, and this should eliminate the impossible and the poor solutions.

3.6 ANALYSIS AND CHOICE REDUCTION

- This step is called *Trade-off and Optimization* in the flow diagram above.
- Analysis of concepts can involve a variety of techniques, e.g.:
  - Scientific analysis.
  - Mathematical modelling and computer simulation. (Remember the analysis is only as good as the model!)
  - Prototyping (initial stages of making an XDM – refer to lecture on System Engineering).
- It is important to carefully document all the analysis steps and results.
- It is also important to use more than one analysis technique, in order to verify the analysis from different angles.
- Remember to break the problem down into small chunks, and not to try and analyse too large parts.

- Once the analysis had been done, choice reduction can be done, e.g. by means of a trade-off study (see GOUWS & GOUWS 2006 or RUBINSTEIN & FIRSTENBERG 1995).
- A *trade-off* is performed in order to objectively compare different solutions to a problem.
- The aim of a trade-off is to find the most suitable solution **in terms of a pre-defined value**

system – for design this is the objectives and the functions.

- There are many different techniques to perform trade-off studies, but most of them follow a similar pattern:
  - ∗ a description of the different available options for solving a specific problem;
  - ∗ a list of decision criteria to be used for choosing amongst the options;
  - ∗ a quantification of the decision criteria;
  - ∗ an evaluation of the options in terms of the decision criteria;
  - ∗ a ranking of the options; and
  - ∗ recommendations regarding the most suitable solution for the stated problem.
- Since the outcome of the trade-off process strongly depends on the value system (decision criteria and quantification thereof), different people can reach different conclusions from a trade-off, depending on the value system used.
- To remove personal bias from the value system, it is important to involve as many as possible of those who have an interest in the outcome of the trade-off process - provided that they have knowledge about the specific decision-making problem - in compiling the value system and in doing the trade-off.
- Often the process of identifying options, deriving a value system, evaluating the options, and reaching conclusions is more important than the conclusion itself, because it forces all role players to think about various aspects of the problem to be solved.

3.7 DETAIL DESIGN

- This step is called *Synthesis and Definition* in the flow diagram above.
- Once the identified concepts had been narrowed, the one or two most likely ones must be taken further, in the form of detail design.
- In the aviation industry it is common to ask two contractors to do independent designs, and to compare their results later before a final choice is made.
- In ***concurrent design***, different systems may be designed at the same time by different design teams:
  - ∗ In this case, extreme care is needed to define system boundaries, especially at interfaces where the output of one system is the input to a following system.
  - ∗ In 1999 NASA had a major failure on a mission to Mars, because of the mismatching of metric and imperial units on different subsystems.
- Detail design will involve further and more extensive analysis and trade-offs.
- Feedback is essential, and changes will result from extensive development test and evaluation.
- This phase of design aims at providing a "blue-print" for the experimental implementation phase of the work (XDM → ADM → EDM → PPM).
- It is important to include extensive **feedback** into the design process.
- The final design review is very important, and it is a more extensive version of the document

review process described in an earlier lecture.

4. EXAMPLE: DESIGN OF A CATAPULT

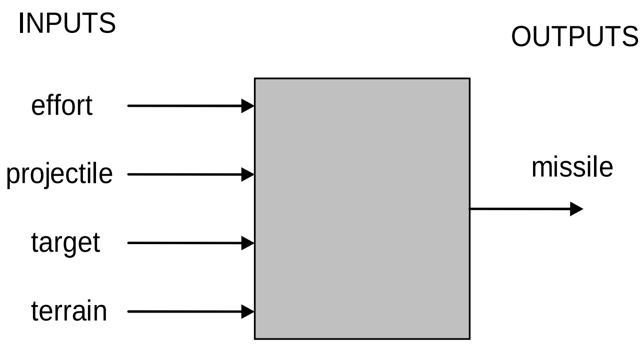
4.1 OBJECTIVE STATEMENT AND -TREE

- The siege general has requested a device that is capable of breaching the walls of an enemy fortress.
- In addition, the device will be used to lob incendiary and biological objects into the enemy enclosure.
- The device must be mobile, so that it can be used from various locations on the battlefield.
- The following objective tree can be compiled:

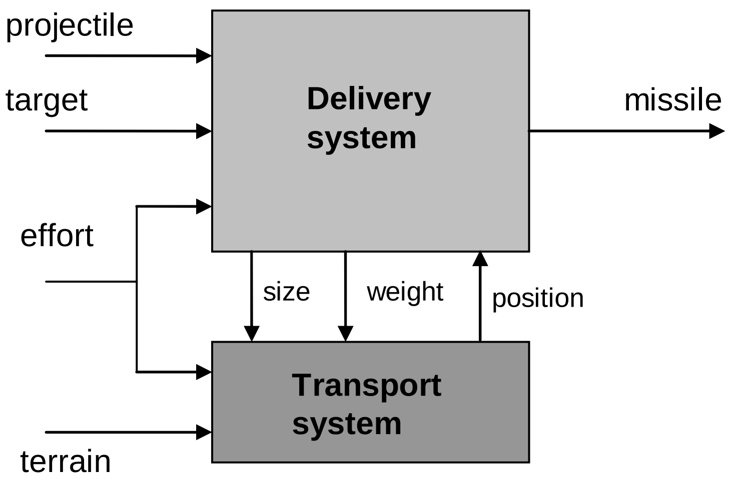
1. Mobile
    - 1.1 Hilly terrain
    - 1.2 Mud
2. Effective
    - 2.1 Lobbing
        - 2.1.1 Object
            - 2.1.1.1 biological
            - 2.1.1.2 incendiary
        - 2.1.2 Trajectory
            - 2.1.2.1 Range
            - 2.1.2.2 Height
    - 2.2 Breaching
        - 2.2.1 Object
        - 2.2.2 Trajectory
            - 2.2.2.1 Velocity
            - 2.2.2.2 Range
3. Efficient
    - 3.1 Rapid reload
    - 3.2 Minimal manpower

4.2 FUNCTIONS AND FUNCTIONAL ANALYSIS

- First Iteration (Starting from the top)

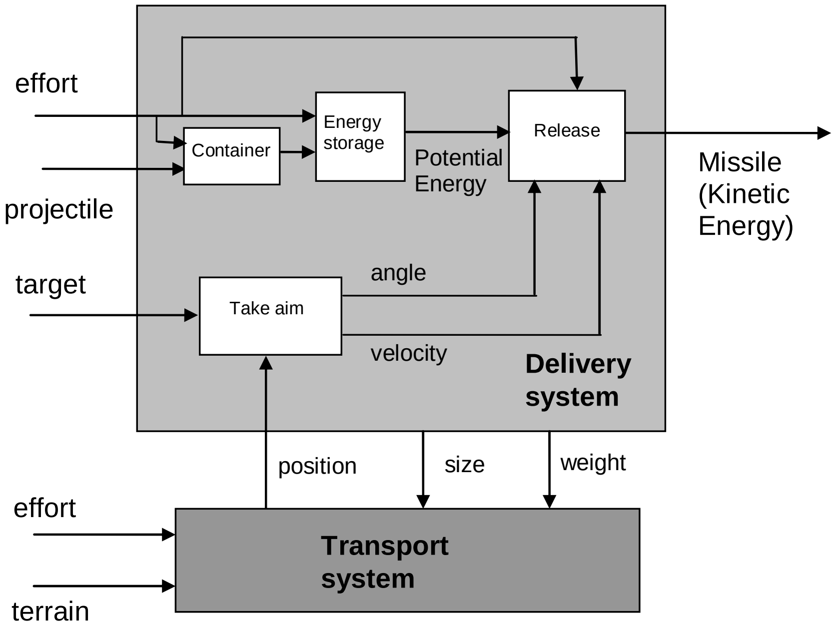


- This basic catapult system can be separated into two subsystems:
  - ∗ The (primary) delivery system.
  - ∗ The (secondary - but still important) transport system.



4.3 CONCEPT DESIGN

- The delivery system can be separated into separate sub-systems for storing the potential energy in the projectile, for targeting (setting the angle and velocity of release), and for the release mechanism:



4.4 ANALYSIS AND CHOICE REDUCTION

- When the functions are defined, performance measures are needed in order to assess how well that function is performed when the function is implemented.
- For example, several different devices may be proposed for implementing the function of converting effort and the projectile into a projectile with potential energy (such as a spring, or an elastic band, or a heavy counter weight).
- Some measure of potential energy could be used to choose between these alternatives.

4.5 DETAIL DESIGN

- With two sub-systems, it is possible to employ separate design teams to design these two sub-systems concurrently.
- This would speed up the completion of the project.
- However, the size and weight of the delivery system could affect the design of the transport system, so size and weight may become constraints in both systems.
- Note that the terrain may influence the design of the transport system, but it may also be that the terrain can be modified to suit the transport system if this leads to a better outcome.

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6. SELF-ASSESSMENT

6.1 TRUE / FALSE QUESTIONS

Indicate which of the following statements are TRUE and which are FALSE.

1. Design is an integral part of engineering.
2. Culture should have no influence on engineering design.
3. Engineering design is concerned with products, not with plants and processes to make products.
4. Once designed, engineers always make their designed systems and products too.
5. Engineering design problems are generally well structured initially.
6. A *design report* is just one of many essential documents to underpin a successful engineering project.
7. "Always find the optimum solution" is the ultimate design approach.
8. The sooner relationships between functions and specific implementations are identified in the design process, the better.
9. The ***design space*** is an abstract space that contains all viable solutions.
10. Discard ideas as soon as you think they violate constraints.

6.2 MULTIPLE CHOICE QUESTIONS

Choose the one correct answer for each of the following questions:

1) Designs are influenced by:
    - i) function, structure, and culture
    - ii) ethic considerations
    - iii) limits of current technology

    a) Only (i) and (iii).
    b) Only (ii) and (iii).
    c) By (i), (ii) and (iii).

   d) None of the above.

2) Modern design projects depend on teamwork, including:
   a) Interdisciplinary members.
   b) Current activities.
   c) One-way communication.
   d) All of the above.
3) Engineering design problems are generally:
   a) Well structured initially.
   b) Solvable with a unique approach.
   c) Without a unique solution.
   d) Without optimal solutions.
4) Design considers the following aspects of an object:
   a) Form (interfaces).
   b) Fit (shape and structure)
   c) Function (what the object is).
   d) None of the above.
5) The main purpose of a design report is:
   a) To protect the designer.
   b) To provide a record of a designer's thinking, and a rationale for decisions made.
   c) To support test results.
   d) To provide answers for future design problems.
6) Tools to help defining objectives and functions include:
   a) Quest for zero defect.
   b) Blame storming.
   c) Mind mapping.
   d) None of the above.
7) Objectives specified for engineering projects do not include:
   a) Legal matters.
   b) Aesthetics.
   c) Performance.
   d) Quality.
8) The design space is:
   a) A physical space that contains all viable solutions.
   b) Bounded by what is possible.
   c) Limitations imposed on the designer by lack of training.
   d) An imaginary concept.
9) Concept design:
   a) Aims at providing blueprints for further work.
   b) Is a nice theoretical concept.
   c) Must be used to discard as many options as possible.

d) Aims at identifying various possible solutions.

10) Analysis of concepts can involve a variety of techniques, e.g.:

i) Scientific analysis.

ii) Mathematical modelling and computer simulation.

iii) Prototyping.

a) (i) and (ii) only.

b) (i), (ii) and (iii).

c) (iii) only.

d) None of the above.

6.3 ESSAY QUESTIONS

Write an essay worth 20 marks on one of the following topics. Do not merely copy the course notes, but write the essay **in your own words** such that your understanding of the topic becomes clear.

1) The design space.
2) Functional analysis.
3) Concept design.
4) Detail design.
5) The design process.

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