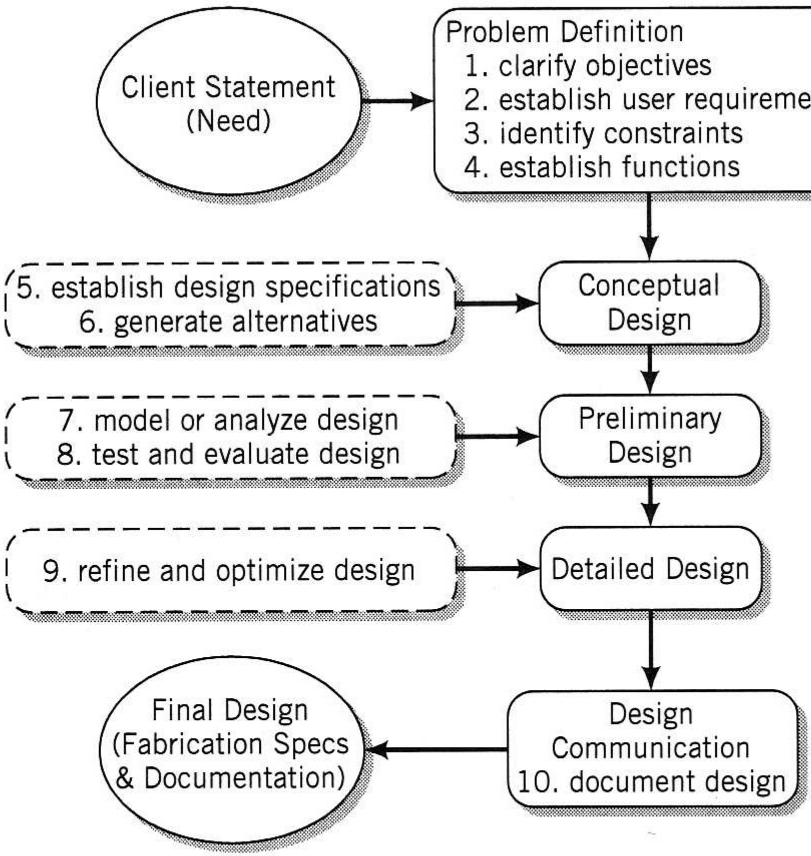
Formula Student Project
ETM 062

Engineering Design
Follow the Process $\rightarrow$ Be efficient

Dr Ahmed Kovacevic

School of Engineering and Mathematical Sciences
Room CM124, Phone: 8780, E-Mail: **Design@city.ac.uk**
www.city-design.tk **www.staff.city.ac.uk/~ra600/intro.htm**

Design Process Overview



1. Clarify Objectives – Objectives tree method
   - Prepare list of objectives
   - Order the list
   - Draw the objectives tree
2. Establish user requirements
3. Identify constraints
4. Establish functions - Functional model
   - Create ‘black box’ model of the product
   - Break down overall function in sub-functions
   - Connect sub-function chains together
   - Define the system boundaries (Constrains)

The Objectives Tree Method

- The objectives tree method is an approach to transform vague design statements into more specific customer requirements
- Make vague statements more specific by asking:
  - *What is meant by that statement?*
- Other useful questions to ask when expanding and clarifying design objectives:
  - *Why? How? What?*

The Objectives Tree Method (1)

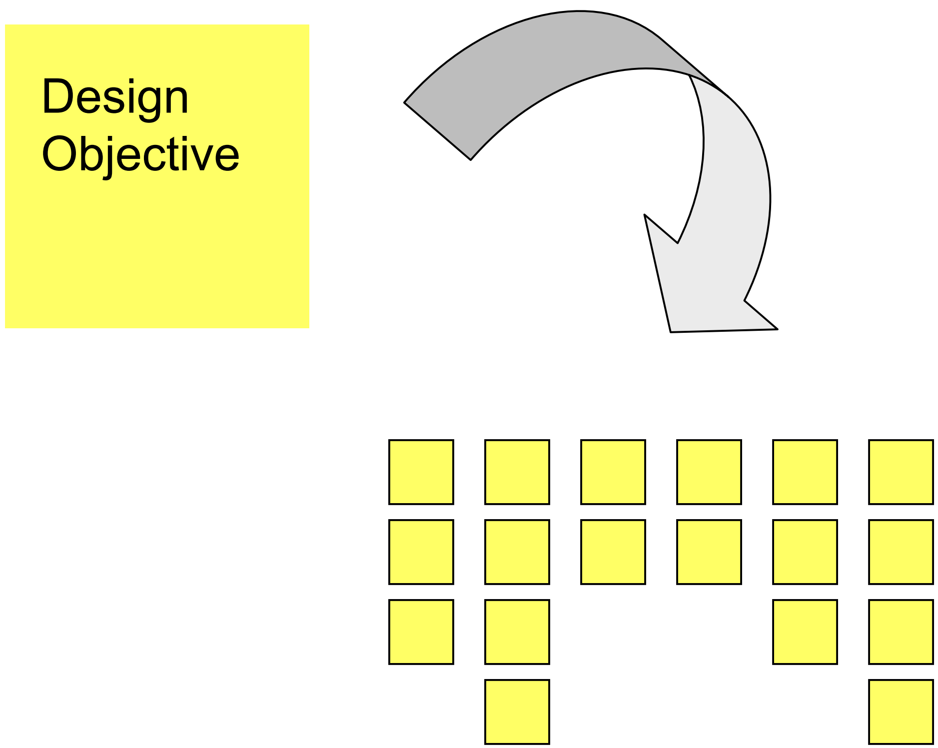
- Three step procedure:
  1. Prepare a list of design objectives
  2. Order the list into sets of higher-level and lower-level objectives
  3. Draw a tree of objectives, showing hierarchical relationships and interconnections

Step 1: Listing the Objectives

- This can be done by:
  - » Talking with (interviewing) customer
  - » Thoroughly reading any written design statements and requirements
- Take vague statements and make them clearer by asking “what is *meant* by this statement”

Step 2: Ordering the List

- Group the statements into related topics using an *affinity diagram*

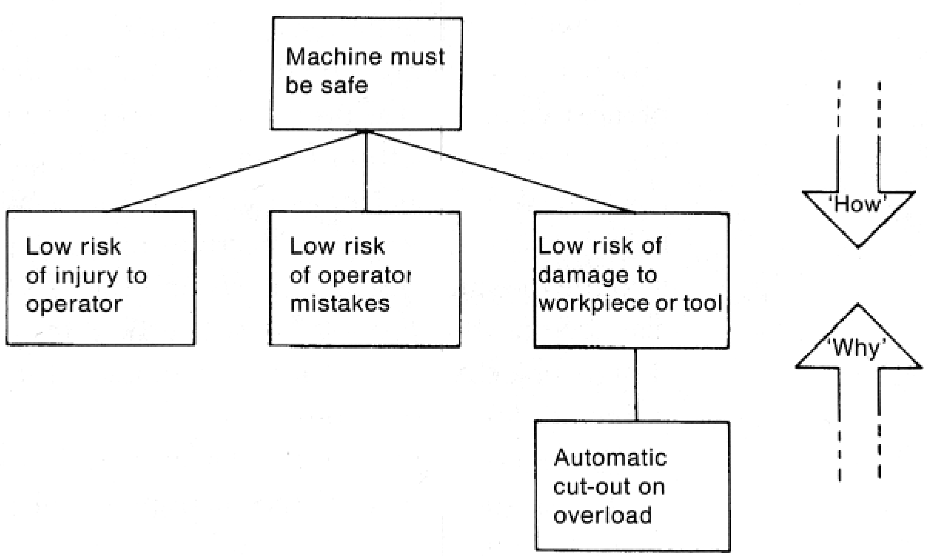


Affinity Diagram

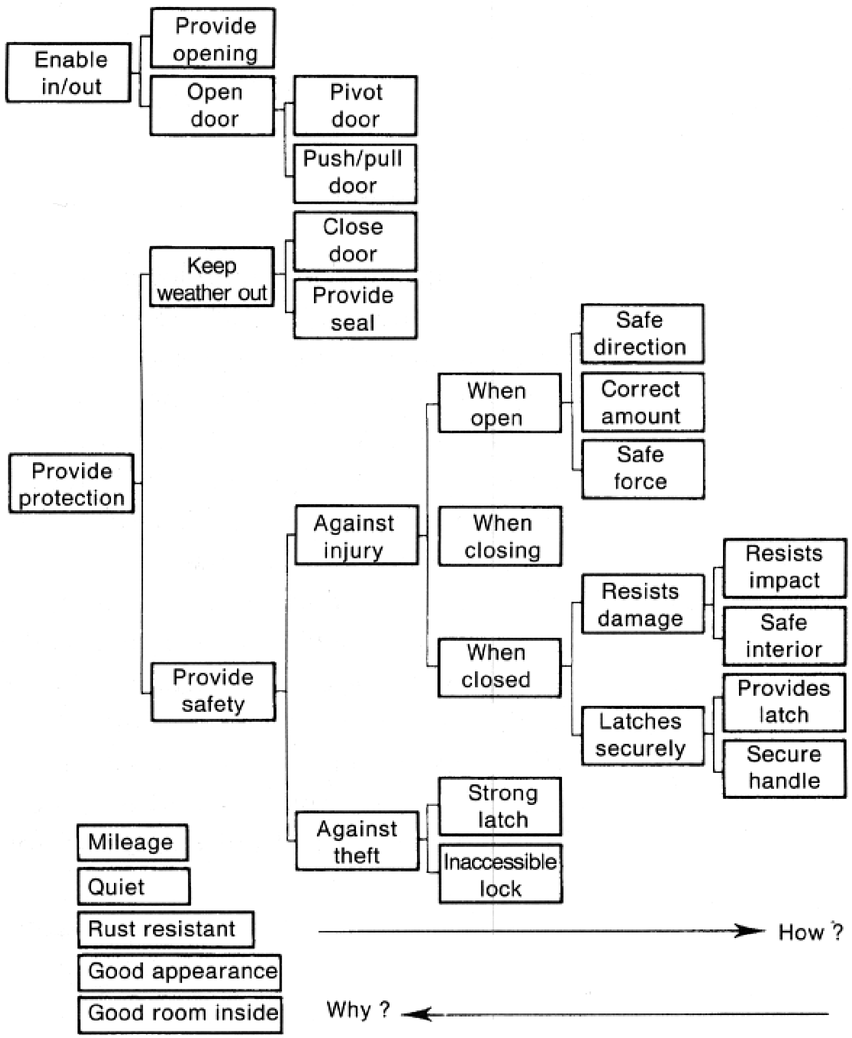
- Copy design objectives to post-it® notes
- Place one on a board
- Compare next objective card to the first
  - » If different, begin a new column
  - » If similar intent, place under the first column
- Repeat for all design objective cards
- Result: Objectives sorted by similar statement
  - » Within each column there may be levels of objectives
  - » Lower-level objectives answer the question “How?”
  - » Higher-level objectives answer the question “Why?”

Step 3: Draw the Tree

- The Objectives Tree diagram looks like an "upside-down" tree
  - » The overall objective of the tree is at the top
  - » Underneath it, branches break the objective into more detailed objectives
  - » Can have many levels and interconnections



Step 3: Draw the Tree (1)



- The objectives tree diagram may alternatively be drawn on its side
- Example: Car door

Try: Bumble Ball

- As a team, generate a list of objectives for the bumble ball toy
- Complete the affinity method for ordering the objectives in class
- Draw an objectives tree for the bumble ball

Objectives Tree and Functional Model

- Objectives are *qualities* the object should *have*
  - » *Clients* tend to speak in terms of objectives
- The Functions are *what* the product *does* without considering any particular solution
  - » *Engineers* tend to speak in terms of functions
- Identifying the basic functions an object does, and then determining solutions for these functions separately, leads to better solutions for the overall problem
- Two levels of functions:
  Overall functions and Sub-functions
- A product function is defined in a block diagram known as a *Functional Model*

Why to create and use Functional Models?

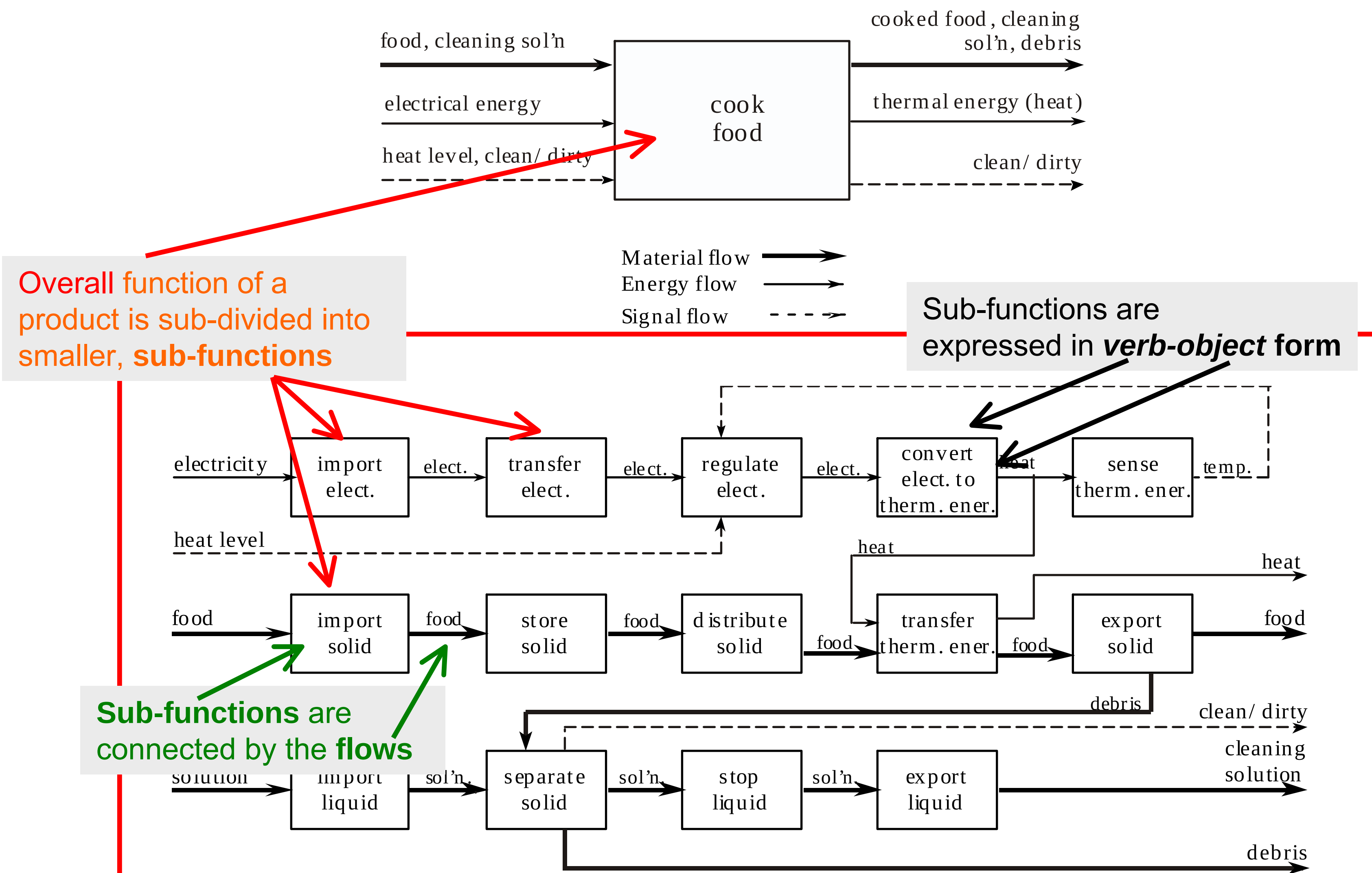
- It places the emphasis on *what* has to be accomplished rather than *how*
- It makes clear the various sub-systems or functions that need to be solved in order to solve the entire problem
- Enhances the creativity of the design team by allowing them to focus on one sub-function at a time
- Sub-functions may be derived from objectives tree (or customer needs)

Functional Model Definitions

- Functional model
  - It is a picture, a graphical representation
  - The overall function of a product is sub-divided into smaller, more elemental (i.e. atomic) **sub-functions**
  - The sub-functions are connected by the **flows** on which they operate
- Sub-functions
  - Simpler expressions of part of the product’s overall function
  - Expressed in ***verb-object*** **form** at a consistent level of detail

Visual Functional Mode - Definition

A **functional model** is a graphical representation of the functions a product performs on its inputs and outputs



Functional Model Basics

- A functional description is a combination of a function (verb) acting on a flow (object)
  - » *Function* - the operation that the product performs on a flow or a set of flows to transform it from its input state to its output state
  - » *Flow* - a material, energy or signal that is used by or affects the product
    - – Think of a flow as anything that is input to the product or an output of the product

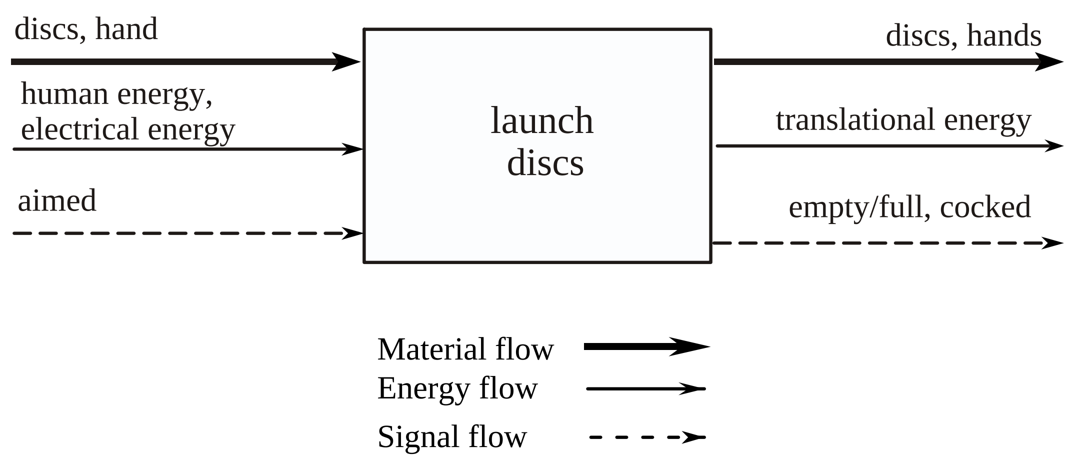
Functional Model Basics (1)

- Functional description form:
  Function (Verb)–Flow (Object)
  - » Examples of functional descriptions

	Function	Flow
The overall function of a student:	**Learn**	**Concepts**
The overall function of a bumble ball:	**Entertain**	**User**
The overall function of a mechanical pencil:	**Deposit**	**Lead**

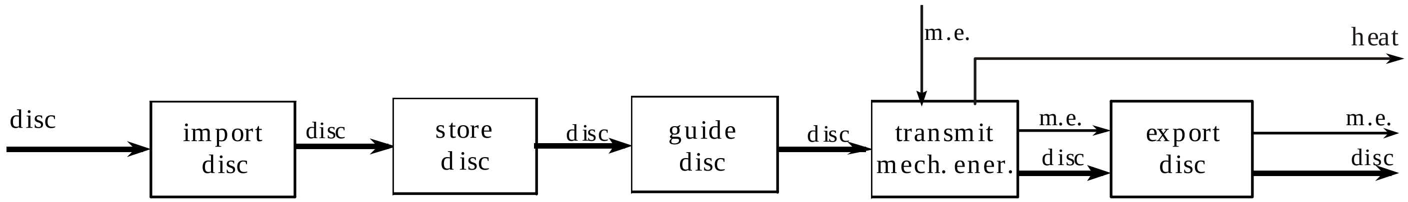
Functional Modeling Procedure

- Step 1: Create a “black box” model of the product
  - » State overall function of product
    - – Use your objective tree high level objectives to help determine the overall function
  - » Identify input and output flows
  - » Possibly related to lowest level objectives



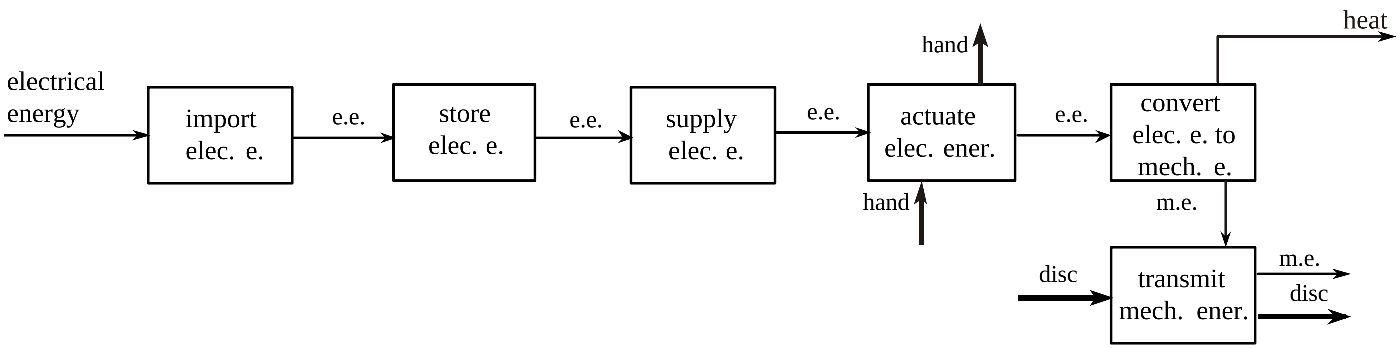
Functional Modeling Procedure

- Step 2: Break down overall function into sub-functions
  - » Follow each input flow through the product and imagine what function the product performs *on* the flow
  - » The *Zen* approach: *BE* the flow



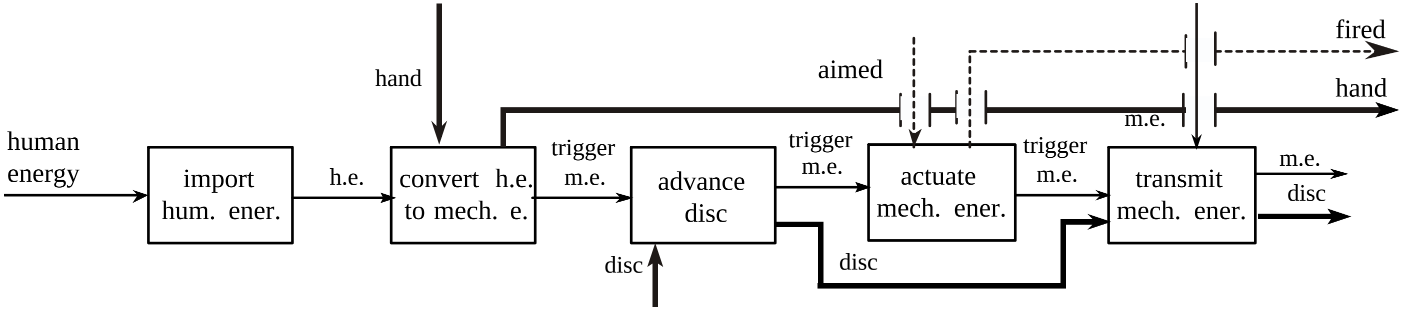
Functional Modeling Procedure

- For the flow of *electrical energy*, what is its associated sub-functions?



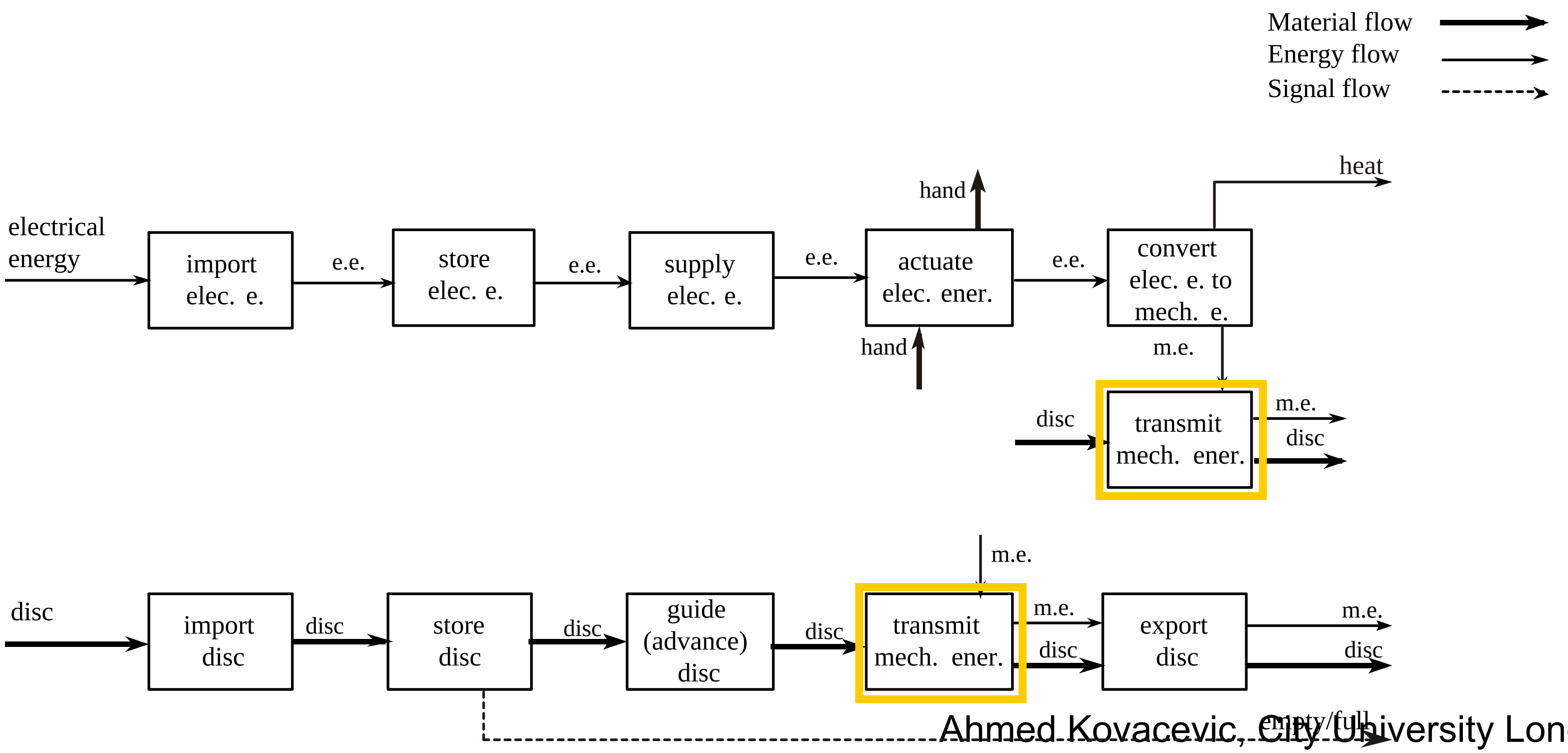
Functional Modeling Procedure

- Flow of *the user mechanical energy*,
- what are associated sub-functions?



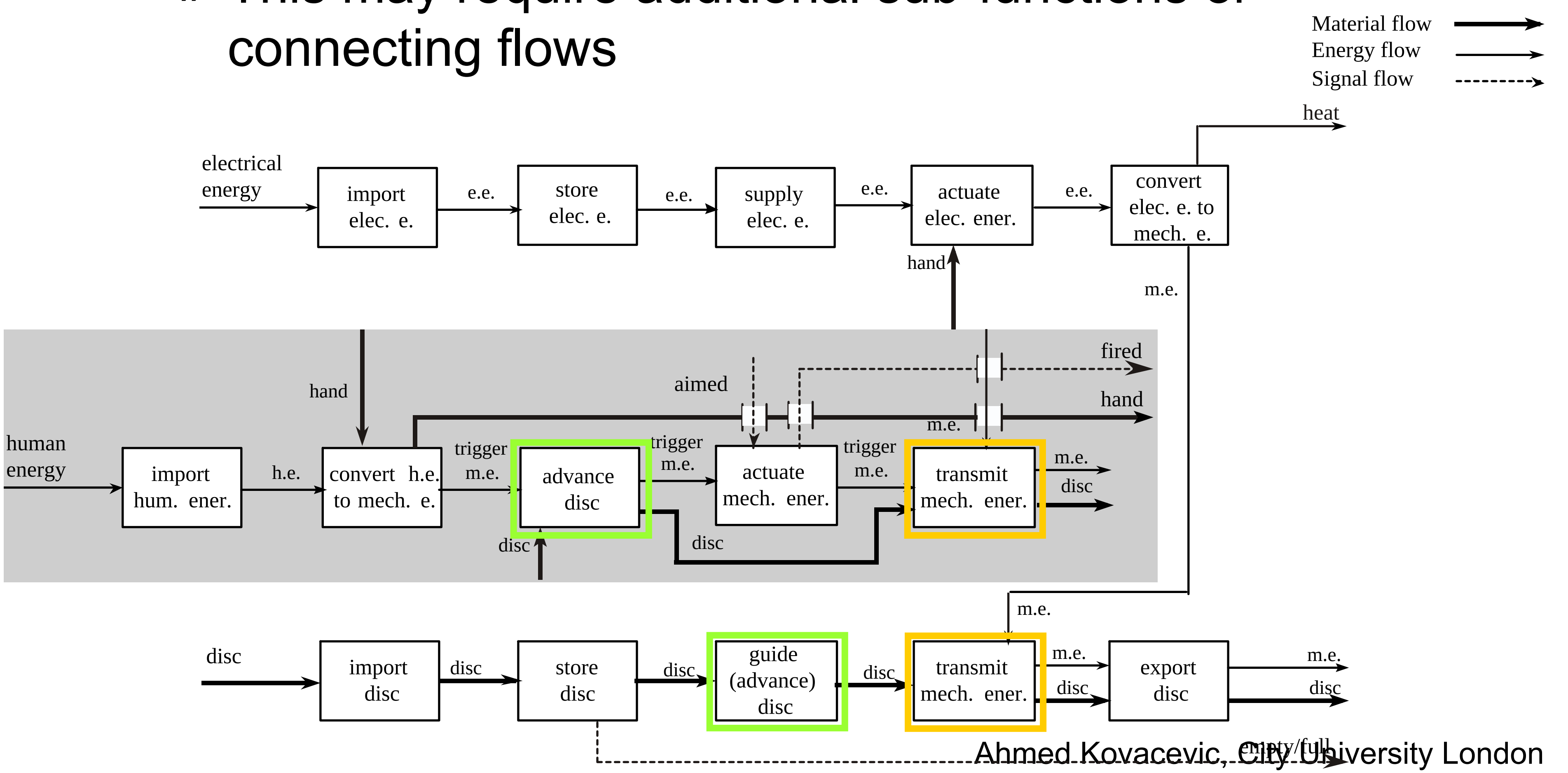
Functional Modeling Procedure

- Step 3: Connect the sub-function chains together
  - » This may require additional sub-functions or connecting flows



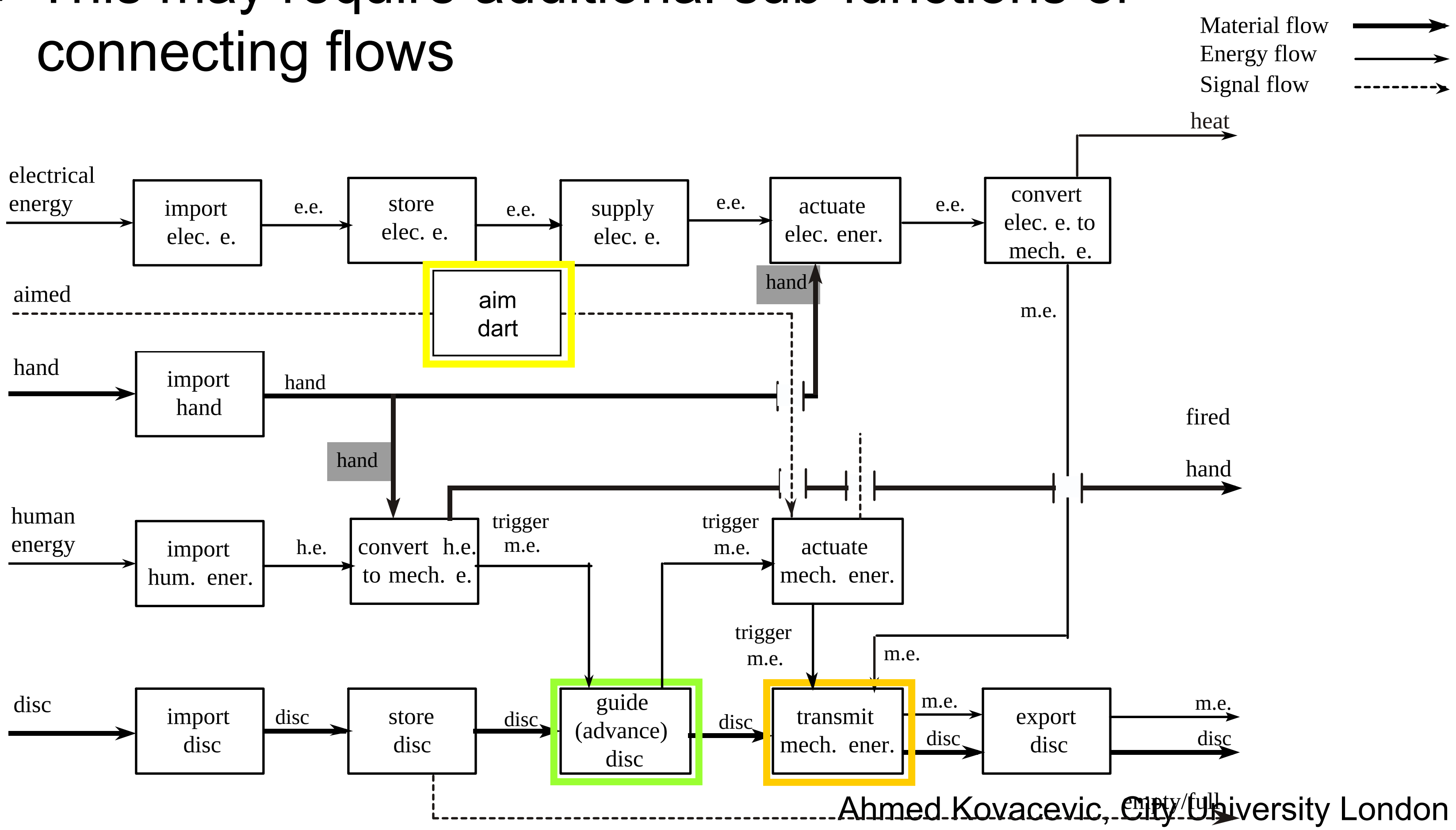
Functional Modeling Procedure

- Step 3: Connect the sub-function chains together
  - » This may require additional sub-functions or connecting flows



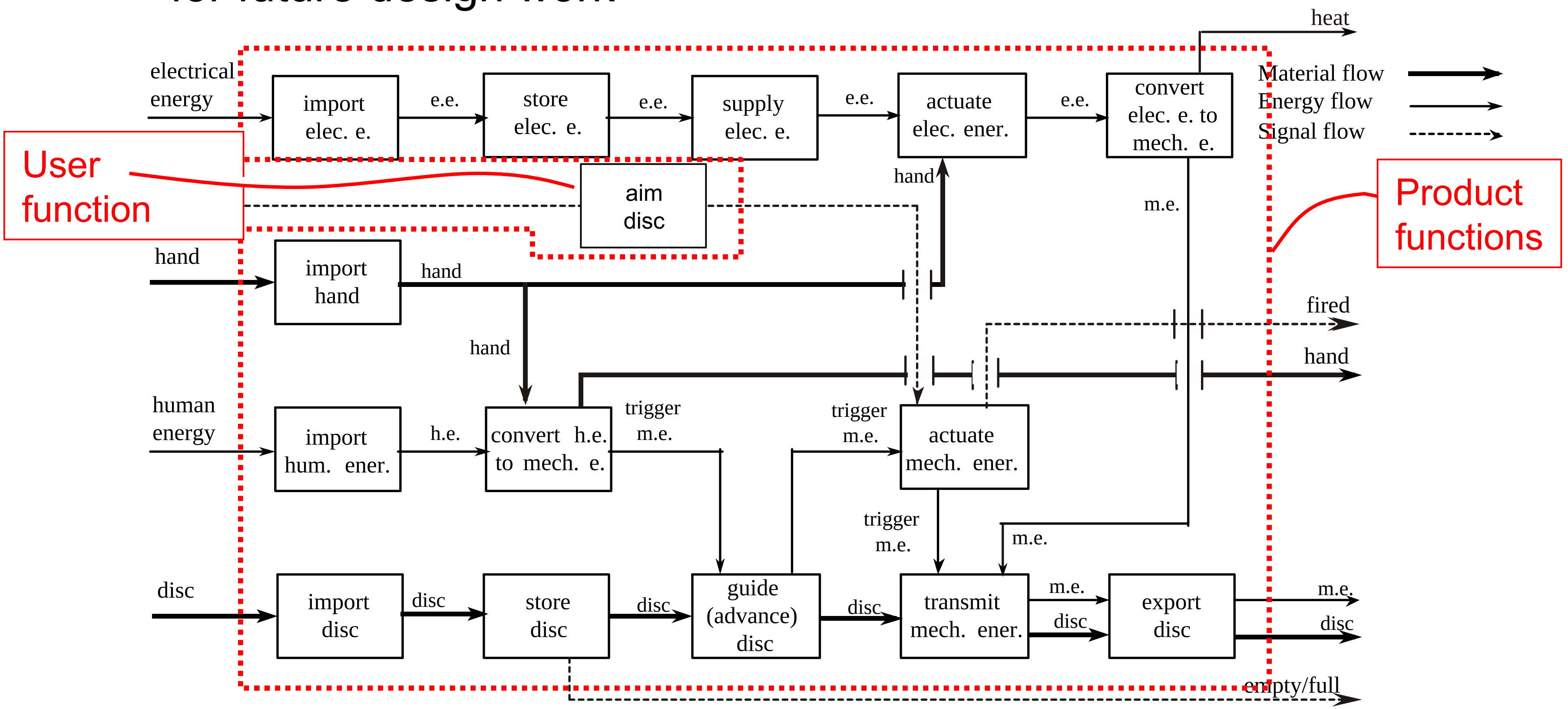
Functional Modeling Procedure

- Step 3: Connect the sub-function chains together
  - » This may require additional sub-functions or connecting flows



Functional Modeling Procedure

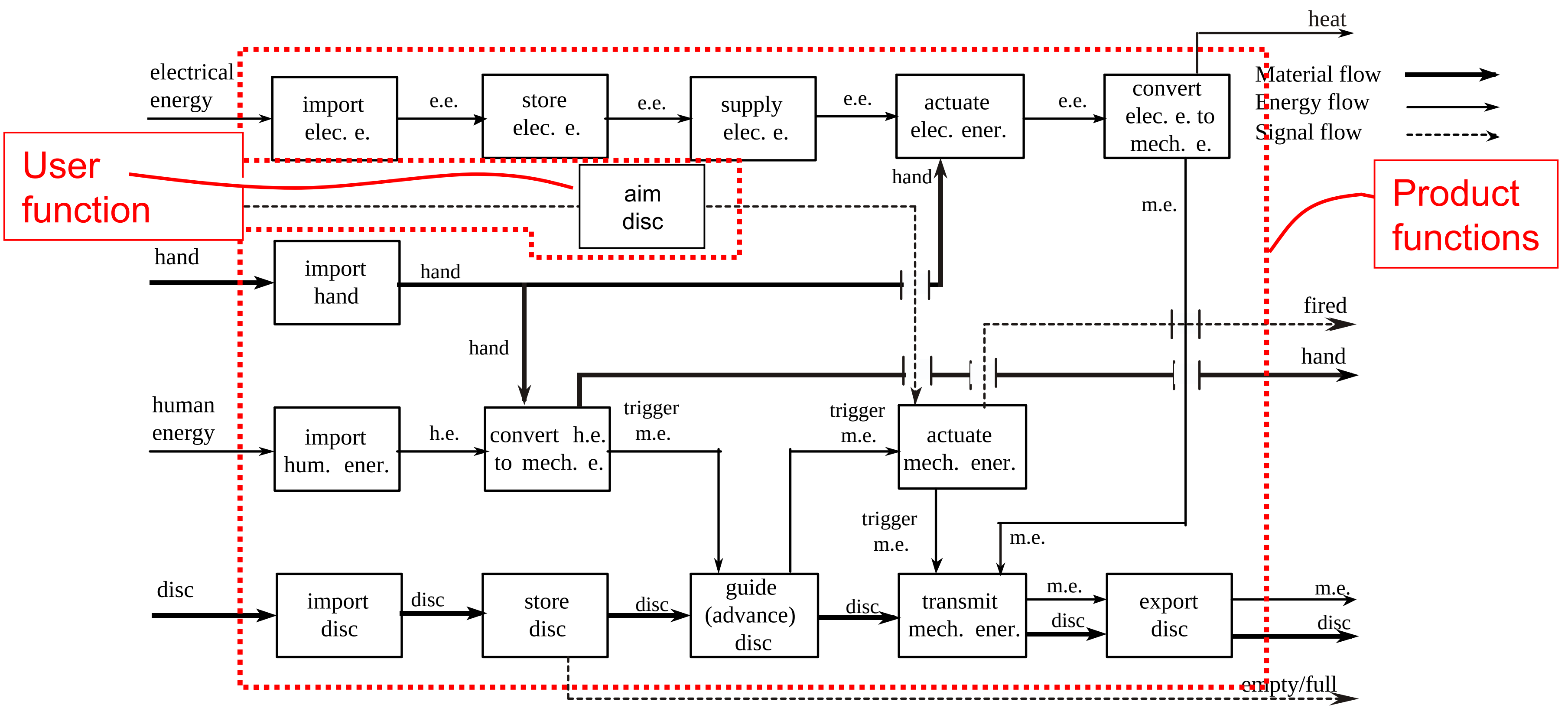
- Step 4: Define the system boundary
  - » This ensures that only product sub-functions are considered for future design work



Ahmed Kovacevic, City University London

Functional Modeling Procedure

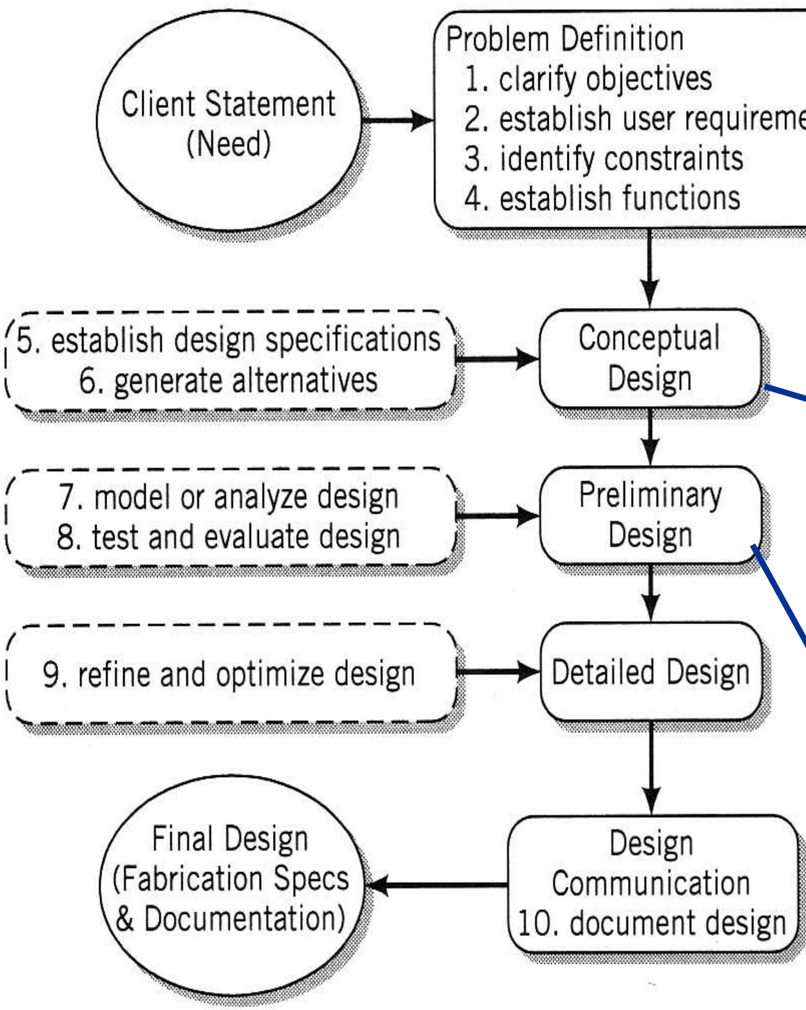
- Step 5: Identify appropriate components to perform sub-functions and their interactions
  - »



Functional Modeling Summary

- What's the difference between objectives and functions?
  - » Objectives tell us what the final product will "be", what qualities it will have
  - » Functions tell us what the object will "do", without regard to any particular form
    - – Functions will always relate input to output
    - – Functions capture the transformation that takes place between input and output
- Though the difference may seem subtle, it is a very important distinction

Why to follow a design process?



1. Clarify objectives
   The Objectives Tree method
2. Establish user requirements
3. Identify constraints
4. Establish functions
   The Function Analysis method

5. Establish design specification
   The Performance Specification method
   The QFD Method (Design Matrix)
6. Generate alternatives
   The Morphological Chart method

7. Model and Analyse design
   Mechanical Design methods
8. Test end evaluate design
   The Weighted Objectives method

Clearly understand the problem which has to be solved
Make sure not to overlook any of important aspects
Set the stage for UNBIASED solutions and Enhance team creativity

The Performance Specification Method

Setting Requirements

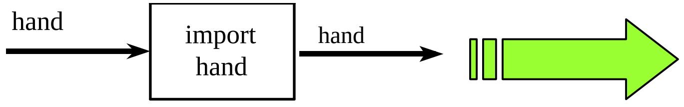
- After the objectives of *what* the product must do are set, its *performance* has to be specified
- It is formulating *Engineering Specifications*
- Engineering Specifications:
  - » Specify a target range for performance
  - » Define required performance, *not the solution*
  - » Provide a way to evaluate proposed solutions

Expressing Specifications

- Three ways to formalize what the user wants in terms more suitable for engineering design and analysis
  - » Prescriptive specifications (or constraints)
    - – Specify *values* for attributes of the designed product/process
    - – Ex.: *The ladder step length can not exceed 20 in.*
  - » Procedural specifications
    - – Identify specific *procedures* for calculating attributes or behavior
    - – Ex.: *Maximum bending stress on a step is computed from* $\sigma_{max} = Mc/I$ *and the step is safe if* σ_{max} *does not exceed* σ_{allow}
  - » Performance specifications
    - – Identify *performance levels* that signify the desired functional behavior has been achieved
    - – Ex.: *A step on a ladder is safe if it supports an 200 kg load*

The Performance Specification Method

- **Step 1**: *Compile specifications*
  - » Use the functional model as a starting point
  - » For each sub-function, write an associated specification (independent of any particular solution)
  - » For example:



Product accommodates various hand sizes

  - » Add any additional specifications (or constraints) from other project sources (such as the written project description)

The Performance Specification Method

Support for Step 1: Standard categories for searching for specifications

Specification category	Description
Geometry	Dimensions, space requirements, …
Kinematics	Type and direction of motion, velocity, …
Forces	Direction and magnitude, frequency, load imposed by, energy type, efficiency, capacity, conversion,…
Material	Properties of final product, flow of materials, design for manufacture, …
Signals	Input and output, display
Safety	Protection issues
Ergonomics	Comfort issues, human interface issues
Production	Factory limitations, tolerances, wastage
Quality control	Possibilities for testing
Assembly	Set by DFMA or special regulations or needs
Transport	Packaging needs
Operation	Environmental issues such as noise
Maintenance	Servicing intervals, repair
Costs	Manufacturing costs, materials costs
Schedules	Time constraints

The Performance Specification Method

- **Step 2:** *Sort the engineering specifications by type*
  - » Prescriptive (constraints)
  - » Procedural
  - » Performance
- **Step 3:** *Quantify each engineering specification*
  - » Engineering specifications should be quantified
  - » Express specifications as a range with limits or specific values (in the case of constraints)
  - » Quantifying may lead to more detailed specifications
  - » For example:

Product accommodates various hand sizes

•Grasping surface can be held by the 95 percentile 4 year old

•Average diameter of grasping surface < 25mm.

The Performance Specification Method

- **Step 4:** *Determine testing/verification approaches*
  - » Identify what procedure your team will use to check that each specification is met
  - » State *when* the test or verification will occur in project timeline
  - » Examples (from disc launcher):

Quantified specification:

•Grasping surface can be held by the 95 percentile 4 year old

•Average diameter of grasping surface < 1 in.

Test/verification measure:

•Review of concept variants (estimated size of grasping surface) during concept selection

•Verify with engr. drawings during preliminary design phase

The Performance Specification Method

- **Step 5:** Compile elements of engineering specification into a single document

Example: Specifications Sheet for Disc Launcher Toy (Partial)

Date	Specification	Resp.	Test/Verification
	Performance Specifications		
12-Feb	Grasping surface can be held by the 95 percentile 4 year old	RBS	Review of concept variants (estimated size of grasping surface) during concept selection
13-Feb	Average diameter of grasping surface < 1 in.	KLW	Verify with engr. drawings during preliminary design phase
14-Feb	Product stores > 80% of user input energy	REF	Measure energy storage potential during proof of concept
12-Feb	> 80% of stored energy is transferred to disc for launch	REF	Measure available energy during proof of concept
12-Feb	Excess energy is dissipated by product	KAG	Review of concept variants during concept selection
13-Feb	Force to press trigger < 0.5 lb.	KLW	Measure triggering force of alpha prototype
	Prescriptive Specifications (Constraints)		
12-Feb	Force to "cock" launcher ≤ 5 lb.	RBS	Review of concept variants during concept selection
12-Feb	Weight < 2 lb.	CAR	Weigh alpha prototype

The Performance Specification Method

- **Step 6:** Evaluate and update specifications as needed throughout the design project
  - » Make sure identified constraints are not too restrictive as to eliminate a better solution
  - » If specifications are updated, indicate so in the date column of the sheet

Date	Specification	Resp.	Test/Verification
	Performance Specifications		
12-Feb	Grasping surface can be held by the 95 percentile 4 year old	RBS	Review of concept variants (estimated size of grasping surface) during concept selection
13-Feb	**Average diameter of grasping surface < 1.25 in. (Due to new ergonomic data)**	KLW	Verify with engr. drawings during preliminary design phase
14-Feb	Product stores > 80% of user input energy	REF	Measure energy storage potential during proof of concept
12-Feb	> 80% of stored energy is transferred to disc for launch	REF	Measure available energy during proof of concept

Establish Design Matrix

The Quality Function Deployment Method

or

Design Matrix

or

House of Quality

The Quality Function Deployment method

- After the *Function* is analysed, designer has to define *Engineering characteristics* of a product.
- Designer defines → → → → *Physical properties*
- Physical properties determine→ *Engineering characteristics*
- Characteristics determine → → *Product attributes*
- Product attributes satisfy → → *Customer needs and requirements*
- Marketing people require ⇒ <u>desirable attributes</u>
- Designers and engineers speak in terms of ⇒ <u>engineering characteristics</u>

Steps in QFD Method

- QFD has background in Japanese design science. Concerned with the translation of customer requirements into engineering characteristics.

1. Identify customer requirements in terms of product attributes,
2. Determine the relative importance of attributes,
3. Evaluate the attributes of competing products,
4. Draw a matrix of product attributes against engineering characteristics,
5. Identify the relationship between engineering characteristics and product attributes,
6. Identify relevant interactions between engineering characteristics,
7. Set target figures to be achieved for the engineering characteristics.

Steps in QFD Method (1)

1. Identify customer requirements in terms of product attributes
   - Customer requirements should not be re-interpreted but only described in terms of product requirements.
2. Determine the relative importance of attributes,
   - Rank-ordering methods can be used to help determine the relative weights of each attribute.

To do that systematically compare pair of objectives, one against the other.

Objectives	A	B	C	D	E	row total
A	-	0	0	0	1	1
B	1	-	1	1	1	4
C	1	0	-	1	1	3
D	1	0	0	-	1	2
E	0	0	0	0	-	0

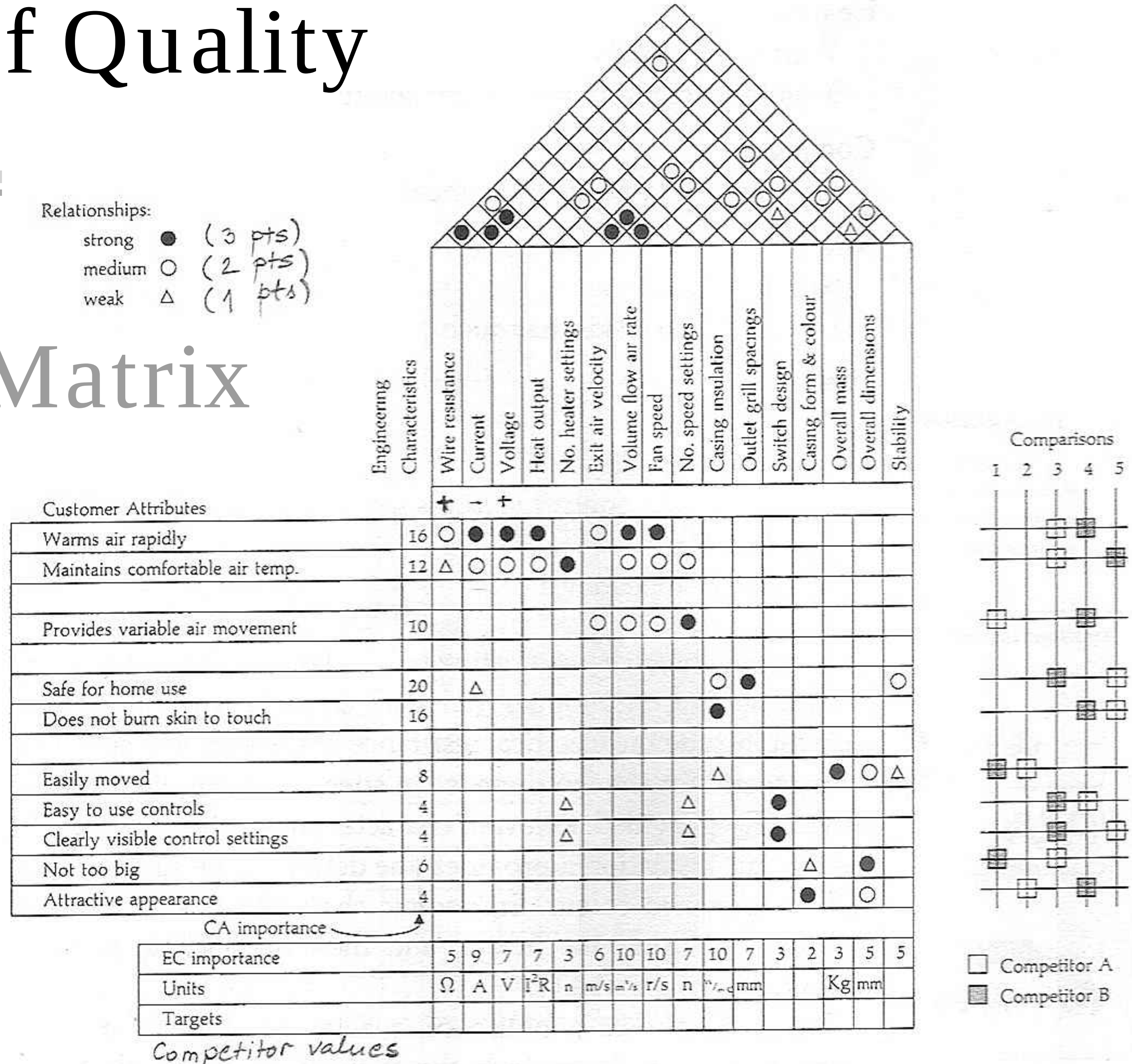
3. Evaluate the attributes of competing products,
   - Performance scores for competing products and the own product should be listed against the set of customer requirements

Steps in QFD Method (2)

4. Draw a matrix of product attributes against engineering characteristics,
   - All engineering characteristics that influence any of product attributes should be included and expressed in terms of measurable units.
5. Identify the relationship between engineering characteristics and product attributes,
   - The strength of the relationship can be expressed by numbers or symbols.
6. Identify relevant interactions between engineering characteristics,
   - The roof matrix provides the check and gives an opportunity to recognise strong connections
7. Set target figures to be achieved for the engineering characteristics.
   - These information are obtained from the comparison with competitor products or from trials with customers. These can be set comparative to competitors.

House of Quality

Design Matrix



Objectives, functions, characteristics v.s. alternative solutions

- Previously, problem was clarified by use of four design tools
  - » **Objectives Tree:** A way to analyze customer needs and to group them logically
  - » **Functional Model:** An engineering first step at thinking about the general functions that the device must be able to do
  - » **Engineering Specifications:** A first step to specifying performance of the product or process to be designed
  - » **The Quality Function Deployment Method – Design Matrix:** Tool which helps to specify what the product must achieve and the criteria by which the alternative solutions will be judged.

- These clarify the problem - ***they do not give the solution***

Background: Thinking Creatively

- Successful designers think creatively
- Successful designs are those that are fresh, innovative, and elegant, while yet being simple and direct
  - » They are artful *and* functional
- Many good designs, once unveiled, seem obvious
  - » People say, “Why didn’t I think of that?”
- Good designers “think of that” because they have developed the skills of:
  - » Brainstorming
  - » Lateral thinking

Brainstorming

- **Brainstorming** is process of generating as many ideas for solving a problem as possible in a short period of time.
- Keys to successful brainstorming:
  - » ***No criticism of ideas!***
    - – Evaluation comes later
    - – Criticism quenches creative fire; it shuts off the flow of ideas
  - » ***Welcome creative thinking***
    - – Encourage wild ideas
    - – They expand the envelope of ideas, possibly leading to workable solutions we otherwise never would have reached
  - » ***Aim for quantity of ideas***
  - » ***Allow combining and extending ideas***
    - – Encourage interaction among team members
    - – “Run the rut” on an idea

Preparing for Brainstorming

- Make sure the problem is clearly defined and understood by all
  - » **Objectives Trees** help with this
- Focus on a ***sub-function*** rather than on the whole product.
  - » **Functional Models** and **Morphological Charts** help with this
- Assign one person to be the ***moderator***
  - » Moderator manages the session
  - » Make sure the rules are followed
- Assign another person to be the ***note-taker*** or ***scribe***
  - » Scribe writes down **all** ideas suggested
  - » Rotate this responsibility so all have a chance to participate in brainstorming (scribes typically cannot record and generate ideas)

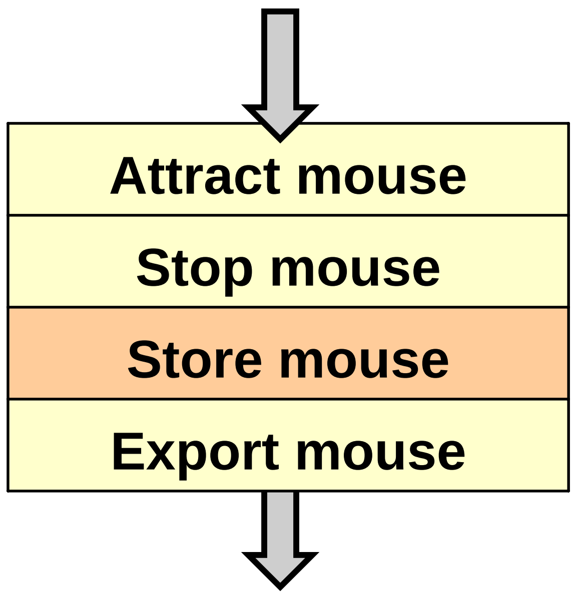
Vertical vs. Lateral Thinking

Vertical Thinking	Lateral Thinking
Goal: ***Selecting*** an idea	Goal: ***Generating*** ideas
focuses on “right or wrong”	no “right or wrong”
is sequential	jumps around
excludes irrelevant info	welcomes all info
tries to finalize	tries to expand possibilities

If vertical thinking is considered exclusively, one might never consider alternative ways to solve a problem

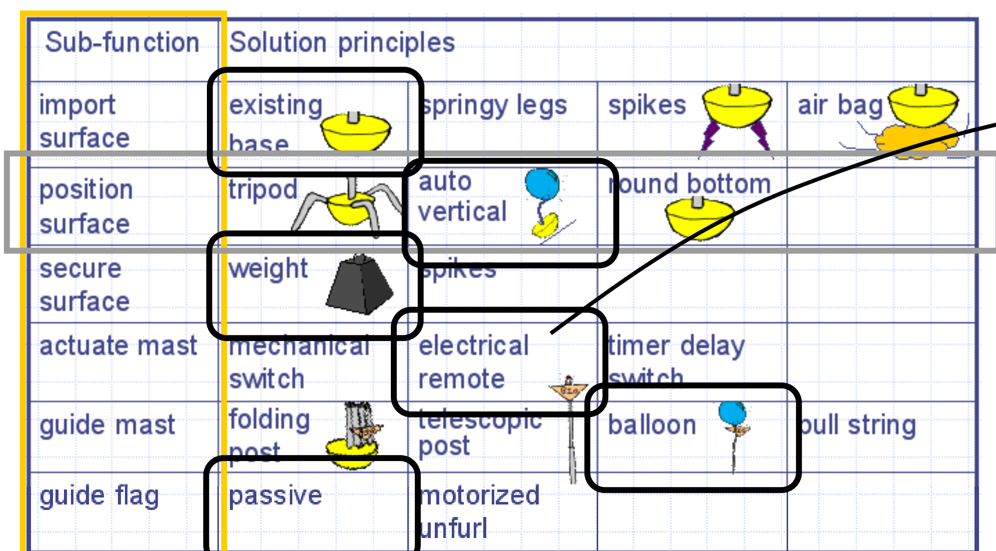
Brainstorming Exercise

- Use brainstorming session to generate as many ideas for each of four functions in a mousetrap design problem with the following required sub-functions:



Morphological Chart

- **<u>Used to generate</u>** possible design solutions
  - After the problem and the function of the device is understood, **brainstorming** can be used to generate potential solutions
- **<u>Very useful</u>** visual way of organizing and assessing the range of possible solution combinations for a problem
- **<u>Very simple</u>** – it is a **<u>table</u>**
  - Sub-functions listed in the first column
  - Possible solutions to each sub-function shown in the rows to the right
  - Possible solutions then selected to form a concept variant

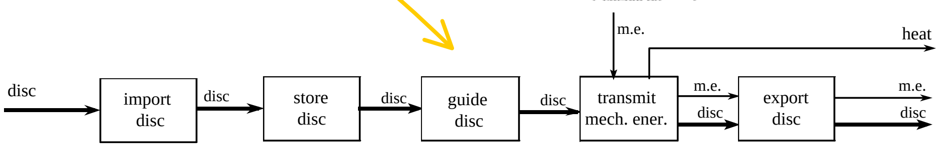


Concept variant

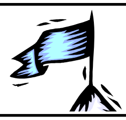
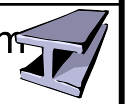
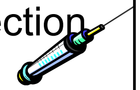
DECISION MAKING

Design Process Overview

- To clarify the design problem, we created:
  - » Objectives tree
  - » Functional model
  - » Engineering specifications
  - » Design Matrix



- To generate concepts, created are:
  - » Morphological chart
  - » Concept variants

Solutions / Sub-functions	Mech.	Electrical	Chemical	Structural
Function 1	flag 	light bulb 		beam 
Function 2 …			injection 	

Design Process Overview

- Where we are going
  - » Select a single concept to fabricate
    - – Concept selection by Decision Matrix
  - » Build proof of concepts to test critical components of the overall solution

Why to use a Decision Matrix?

- From the **Morphological Chart**:
  - Generated a large number of solutions
  - Assembled **“concept variants”**
- How to evaluate these solutions?

  What makes one “better” than another?
- Knowing how to choose between alternatives is an important design activity!
- One can choose by some arbitrary manner, but it is best to use **a *rational approach*** that can be clearly explained to managers and clients.
- What makes a Decision Matrix a rational approach?
  - **Weighted numerical scores** are assigned to various sub-objectives
  - Individual scores are **summed to give each overall solution choice a numerical score**

How to Create a Decision Matrix

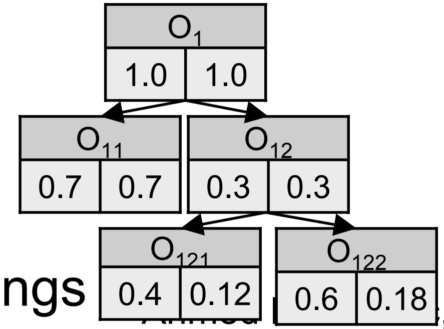
1. *List the design objectives*
   - Use the Objectives Tree
   - The initial list might have been changed
2. *Rank order these from most to least important*
   - A rank order is a list from most important to least. Pair-wise comparison may help in ordering them (see lecture 3).
   - Rank ordering is an example of and *ordinal scale*.
3. *Assign relative weighting to these objectives*

•Some objectives are *much* more important than others. These should be on the *interval* scale which usually is not a linear scale.

• *Interval* Scale 1-10 or 1-100

• Shared value list

• Objective tree based relative weightings



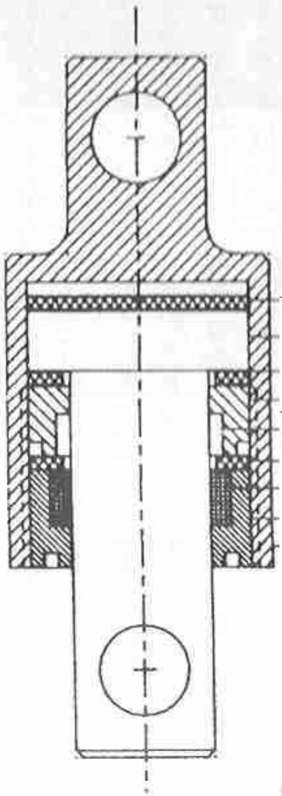
Shared value list	
35	B
25	C
18	D
15	A
7	E

Interval scale	
10	B
9	
8	
7	C
6	
5	D
4	A
3	
2	E
1	

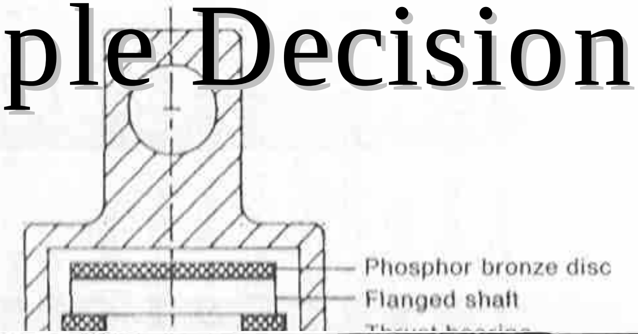
How to Create a Decision Matrix

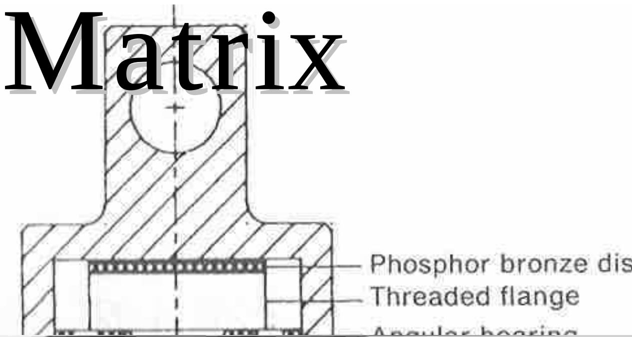
4. *<u>Establish performance parameters</u> (utility scores) for each of the objectives*
   - It is necessary to convert the statement of objectives into parameters that can be measured.
   - The easiest way is to use five grades scale (0-4) with the following ranking:
     - Far above average – Excellent (4)
     - Above average – Very good (3)
     - Average - Good (2)
     - Below average - Satisfactory (1)
     - Far below average - Not satisfactory (0)
   - Base the parameter estimation on common sense, your existing knowledge, calculations, research on web, catalogs, etc.
   - REMEMBER: If your estimates are bad, then the resulting decision matrix results will be bad
5. *<u>Calculate and compare the relative utility values</u> of the alternative designs*
   - In general, higher values mean better concept variant.

Example Decision Matrix



Design 1





	Design criteria	Weight	Design 1		Design 2		Design 3	
		W*	S	U	S	U	S	U
1	Cost							
	Materials	6	8.5	0.51	5.5	0.33	7	0.42
	Seals	2	8	0 16	8	0.16	8	0 16
	Bearings	4	9	0.36	5	0.2	8	0.28
	Washers	1	7.5	0.07	7 5	0.07	7 5	0 07
	Squeeze packing	2	9	0.18	9	0.18	9	0.18
	Bolts	1	9	0 09	9	0.09	8	0 08
	Labour	6	8	0 48	5	0 3	7.5	0.45
	Tools and equipment	6	8	0 48	5	0 3	7.5	0.45
	Indirect cost	20	8.5	1.7	7	1 4	7 5	1 5
	Marketing	2	7	0 14	8	0.16	9	0 18
2	Performance							
	Sealing	9	8	0 72	8	0.72	8	0.72
	Smoothness	9	5	0 45	9	0.81	8.5	0.76
	Alignment	6	5	0.3	7	0 42	8	0.48
	Growth formation	2	8	0 16	8	0.16	8	0.16
	Maintenance	4	8	0 32	8	0 32	8	0 32
3	Manufacturing							
	Ease	5	8.5	0.42	7	0.35	7.5	0.37
	Time	5	9	0.45	4.5	0.22	7.5	0.37
	Assembly	5	9	0.45	6.5	0 32	8	0.4
4	Strength	5	8	0 4	9.5	0.47	9 5	0.47
	The overall utility			7 84		6.98		7.82

*W = percentage weight of each criterion (from 100)
S = score of quality of each design (from 10)
U = utility (weighted score) of design = W × S

Design Reviews Objectives

» To encourage communication between team members and sub teams

» To review progress, time keeping and project standards

» To set targets for further tasks

» To meet experts when necessary

» To meet people from project management and planning, manufacturing or administration

Proposed VEB PAGE

- Development of virtual reality learning environment for Design teams at City University
  - » Project plan and specification
  - » Equipment: computers, cameras …
  - » Recording of all meetings and other phases of project
  - » Final report, oral presentations, panels …

$$E_{\text{fficiency}}$$

$$L_{\text{earning}} = mc^2$$

Learning = minds in communication^2

Efficiency = minds in communication^2