University of BRISTOL

Lecture 2. Axiomatic Design principle

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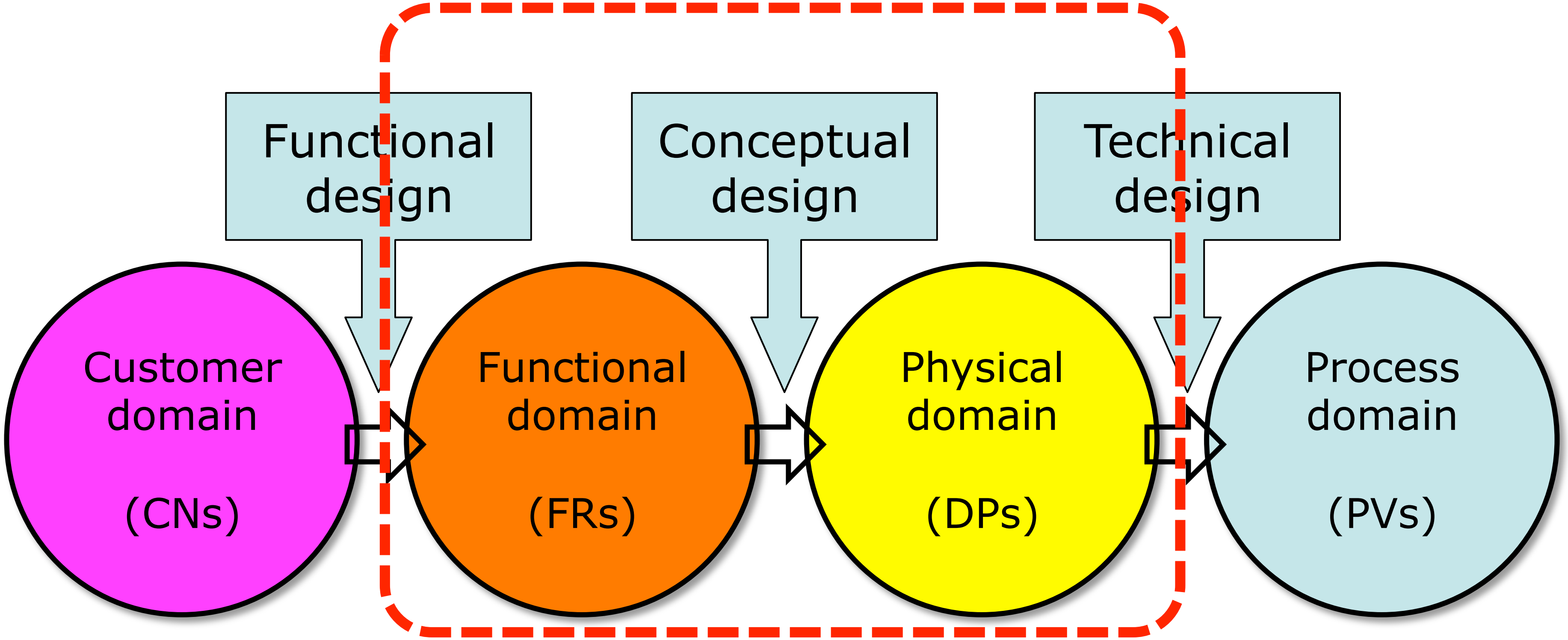
Axiomatic design framework

- Design is an interplay between “What we want to achieve” and “How we achieve it”.
- 4 domains & terminologies in AD framework
- Mapping process: CNs to FRs, FRs to DPs, DPs to PVs



< Domains and mapping >

How can we design a good product?

Which one would you like to use? Why?
Please discuss with the person next to you.

1 minute

Anyone who wants to share your thought?

What you could realise

- ***Were you able to clearly explain why you feel more uncomfortable with one of them?***

If yes, you knew what you want to achieve with the tap.

If no, you didn’t know what you really want clearly.

- ***Did your partner agree with your opinion?***

If yes, both of you had the same FRs for the tap in your mind.

If no, you were expecting different FRs of the tap.

What is Axiom?

- Self-evident or fundamental truths that cannot be derived from other laws of nature or principles, but for which there are no counterexamples or exceptions.

- Examples of axiom
  - For every two points, there is no more than one line incident with both points.
  - There exist at least two points incident with each other.
- It sounds abstract and irrational, but Axioms have played a major role in developing science and engineering.
  - Three laws of thermodynamics
  - Newton's three laws
  - Einstein's theory of relativity
  - Euclid's geometry

What is good design in AD ?

- ***Axiom 1***
  - Maintain the independence of the functional requirements (FRs)

What is a good or an acceptable design?
- Making the design more controllable

- ***Axiom 2***
  - Minimise the information content of the design

If you have multiple good designs, which is better?
- Making the design more robust, maximising the chance of success

Good design should satisfy both axioms.

Axiom 1: Independence of FRs

FR vs. DP

- ***Functional Requirement (FR)***: A minimum set of independent requirements that completely characterises the functional needs of the product *(Defined by an imperative sentence)*

What we want to achieve

Mapping

- ***Design Parameter (DP)***: Key physical variables that characterise the design that satisfies the specified FRs *(Defined by a noun)*

How we achieve it

FR-DP mapping

What are the FRs?

FR1: Provide a sharp tip to leave thin marks on a paper
FR2: Provide a part to grip
FR3: Have high bending stiffness and strength

What are the DPs?

DP1: Lead core
DP2: Stick shape
DP3: Wooden shell

FR-DP mapping

What are the FRs?

FR1: Provide a sharp tip to leave thin marks on a paper
FR2: Provide a part to grip
FR3: Have high bending stiffness and strength
FR4: Prevent rolling on a table

What are the DPs?

DP1: Lead core
DP2: Stick shape
DP3: Wooden shell
DP4: Hexagonal cross-section

FR-DP mapping

What are the FRs?

FR1: Provide a sharp tip to leave thin marks on a paper
FR2: Provide a part to grip
FR3: Have high bending stiffness and strength
FR4: Prevent rolling on a table
FR5: Provide a tool to erase marks

What are the DPs?

DP1: Lead core
DP2: Stick shape
DP3: Wooden shell
DP4: Hexagonal cross-section
DP5: Rubber eraser

Solution-neutral thinking

What else can you come up with to meet these FRs?

FR1: Provide a sharp tip to leave thin marks on a paper
FR2: Provide a part to grip
FR3: Have high bending stiffness and strength
FR4: Provide a tool to erase marks

These have more DPs than needed.

Remarks

- You’ve just put yourself in the designer’s shoe, and guessed the FRs of the original design. Thus, the original FRs might be different from your guess. (Your FRs might be better for two reasons; i) You were the customers who knew the CNs better and defined the FRs based on those. ii) For most of the products in the market, the designers do not clearly define the FRs.)

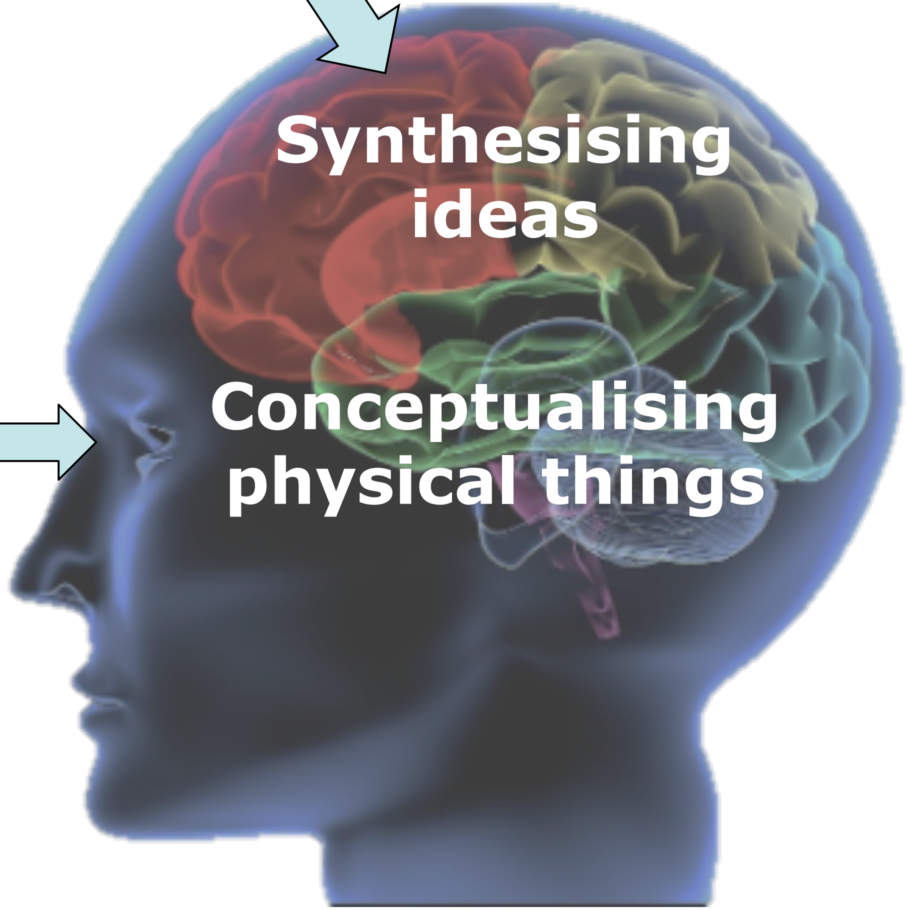
- You defined the FRs and mapped into the DPs, but…
Was it a good design? How can we know that?

Note) If you define the FRs for what you newly develop, defining FRs and the mapping process will be much more challenging.

How do people usually design something?

- Take various thoughts out of your brain to visualisation means (e.g. papers, LCD screen)
- Find out or judge their relativity.
- Assemble or organise them.
- Finally make a clear coherence of your thoughts for the idea.

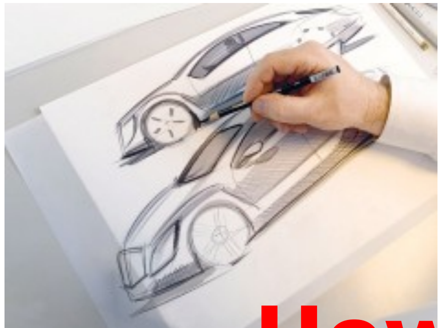
Engineering problems



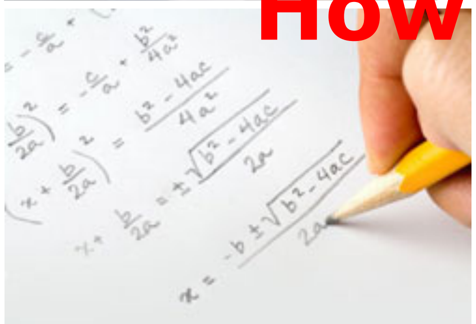
Synthesising ideas

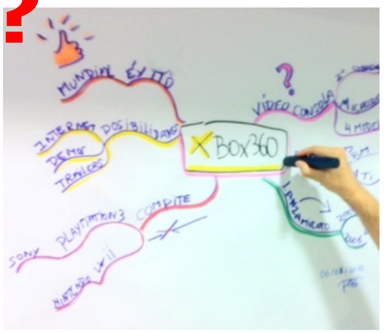
Conceptualising physical things

Analysing and organising ideas



How?





Axiom 1: Independence of FRs

- Independence axiom
  - Maintain the independence of FRs
  - Alternative statement 1: An optimal design always maintains the independence of FRs.
  - Alternative statement 2: In an acceptable design, <u>DPs (Design Parameters) and FRs are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements.</u>

Functions of your product

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

Physical means controlling the functions

Design matrix [DM]

- For the students who are not good at matrix calculation

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

$$\underline{FR_1 = A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3}$$
$$FR_2 = A_{21}DP_1 + A_{22}DP_2 + A_{23}DP_3$$
$$FR_3 = A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3$$

Axiom 1: Independence of FRs

- *How to configure the design matrix A* by manipulating DPs is crucial.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \underbrace{\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix}}_{\text{Full matrix}} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

Coupled design
- Impossible to control each FR independently

(Bad design)

$$FR_1 = A_{11}DP_1 + A_{12}DP_2 + A_{13}DP_3$$
$$FR_2 = A_{21}DP_1 + A_{22}DP_2 + A_{23}DP_3$$
$$FR_3 = A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3$$

Axiom 1: Independence of FRs

- *How to configure the design matrix A* by manipulating DPs is crucial.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \underbrace{\begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix}}_{\text{Triangular design matrix}} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

$$FR_1 = A_{11}DP_1$$
$$FR_2 = A_{21}DP_1 + A_{22}DP_2$$
$$FR_3 = A_{31}DP_1 + A_{32}DP_2 + A_{33}DP_3$$

Decoupled design
- Still coupled, but possible to control each FR independently by determining each FR in order

(Good/Acceptable design)

Axiom 1: Independence of FRs

What about this case?

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & A_{23} \\ A_{31} & 0 & A_{33} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

$$\Downarrow$$

$$\begin{bmatrix} FR_1 \\ FR_3 \\ FR_2 \end{bmatrix} = \underbrace{\begin{bmatrix} A_{11} & 0 & 0 \\ A_{31} & A_{33} & 0 \\ A_{21} & A_{23} & A_{22} \end{bmatrix}}_{\text{Triangular design matrix}} \begin{bmatrix} DP_1 \\ DP_3 \\ DP_2 \end{bmatrix}$$

Decoupled design

- Still coupled, but possible to control each FR independently by determining each FR in order

(Good/Acceptable design)

Axiom 1: Independence of FRs

- *How to configure the design matrix A* by manipulating DPs is crucial.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \underbrace{\begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix}}_{\text{Diagonal design matrix}} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

$$FR_1 = A_{11} DP_1$$
$$FR_2 = A_{22} DP_2$$
$$FR_3 = A_{33} DP_3$$

Uncoupled design

- Easy to control each FR independently

(Excellent/Ideal design)

Example: Refrigerator door

FR1: Provide access to the items stored in the refrigerator
FR2: Prevent energy loss

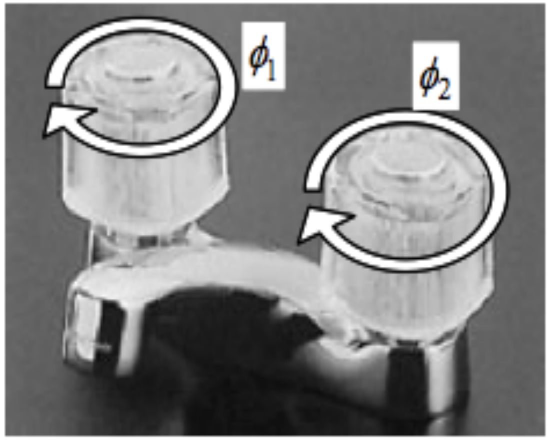
(a) DP1: Door with vertical hinges
DP2: Thermal insulation material in the door

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

(b) DP1: Door with horizontal hinges
DP2: Thermal insulation material in the door

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

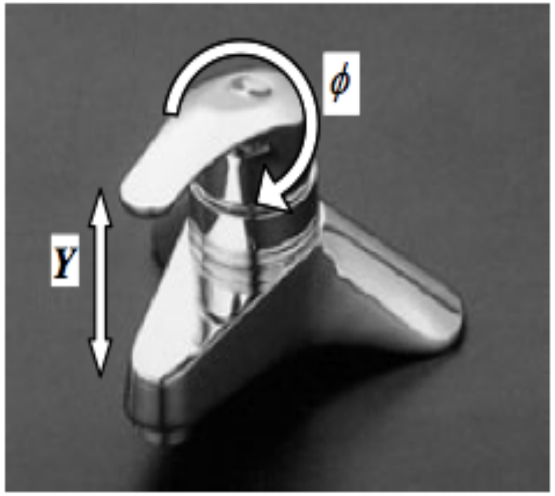
Example: Water tap



FR1: Control the flow of water (Q)
FR2: Control the temperature of water (T)

(a) DP1: Rotary knob A (Angle ϕ_1)
DP2: Rotary knob B (Angle ϕ_2)

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$



(b) DP1: Height of the lever, Y
DP2: Rotation angle of the lever, Angle ϕ

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

Axiom 1: Independence of FRs

- If the number of FRs ≠ the number of DPs ?

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \\ A_{31} & A_{32} \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

Coupled design

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} \cancel{A_{11}} & 0 & \cancel{A_{13}} & \cancel{A_{14}} & \cancel{A_{15}} \\ \cancel{A_{21}} & \cancel{A_{22}} & 0 & \cancel{A_{24}} & 0 \end{bmatrix} \begin{bmatrix} \cancel{DP_1} \\ \cancel{DP_2} \\ \cancel{DP_3} \\ \cancel{DP_4} \\ \cancel{DP_5} \end{bmatrix}$$

You can make the number of FRs the same with that of DPs by fixing some DPs. But, depending on which DPs you fix, the nature of design can be changed.

1) If DP_2, DP_3, DP_5 are fixed,

Coupled design

2) If DP_1, DP_4, DP_5 are fixed,

Uncoupled design

3) If DP_1, DP_4 are fixed,

Uncoupled redundant design

Redundant design

- When two or more DPs control a single FR without affecting other FRs.
- Redundancy can be ***negative*** or ***positive***.

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} 0 & A_{12} & A_{13} \\ A_{21} & 0 & 0 \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix}$$

Negative

Duplication

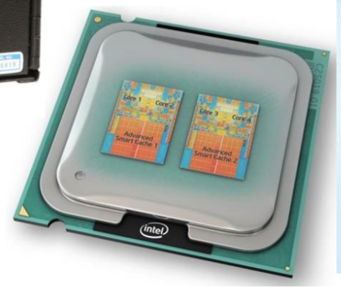
Increasing manufacturing cost

Less intuitive

Positive

Increasing Safety or Security

Increasing Energy-efficiency



Quiz. True or False

A coupled design is a design in which functional requirements are dependent on all design parameters. (False)

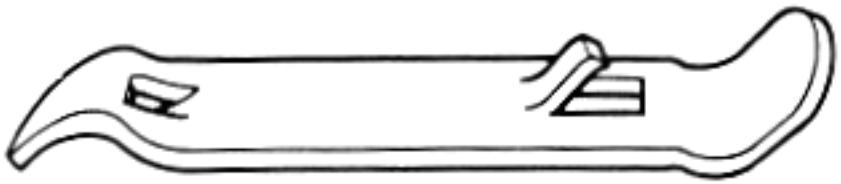
*FRs are always dependent on DPs. The **'coupling'** in a design is about dependency among FRs.*

A coupled design is defined as a design in which a design parameter could affect more than one functional requirement. (False)

*A **'decoupled design'** also contains FRs affecting each other, however FRs can be determined sequentially so that each FR could be controlled independently.*

Physical integration

- Functional independence ≠ Physical independence

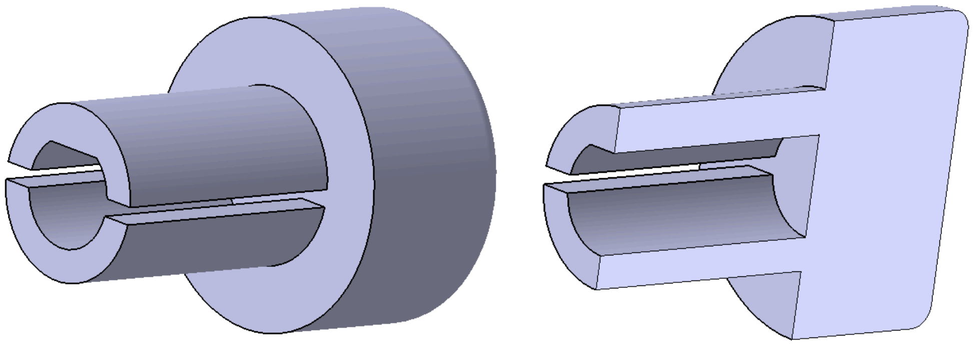


A bottle-can opener
- FR1: Provide a tool to open bottles
- FR2: Provide a tool to open cans

Many FRs of a beverage can
- Contain axial and radial pressure
- Withstand a moderate impact when the can is dropped
- Allow stacking on top of each other
- Provide easy access to the liquid in the can
- Minimise the use of aluminium
- Be printable on the surface
- …

But it has only 3 physical pieces (Body / Lid / Opener tab)

Example of wrong physical integration

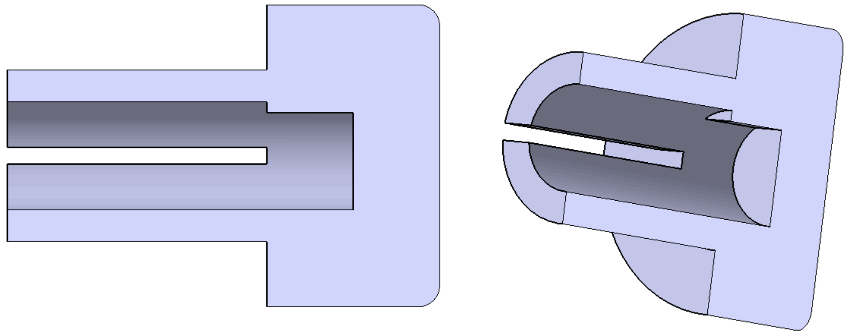


Audio knob

Customer's complain:
The knob is pulled out frequently when it is turned.

FR1: Grip the shaft tightly
FR2: Transmit the torque to the shaft

DP1: Split tubular part
DP2: Flat surface



$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & X \\ x & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Coupled design

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

Uncoupled design

Summary of Axiom 1

- The designer must always think in terms of FRs before any solution is sought. (Functional & Solution-neutral thinking)
- The functional requirements (FRs) must always be maintained independent of one another by choosing appropriate design parameters.
- The design matrix generated by the mapping process must be a diagonal or triangular matrix to make it an optimal design.

How can AD help our design process?

- Visualising the relativity of abstract concepts such as FRs and DPs
- Identifying whether the design is good or bad and filtering the bad design out quickly not to waste your time
- Identifying which element leads to a bad design quickly
- Providing the engineer with a easy guidance to evaluate your design

Summary of Axiomatic Design Procedure

1. Define functional requirements and constrains
2. Perform decomposition
3. Create design equation and check the independence of FRs (Repeat this process until you get decoupled or uncoupled designs.)
4. Choose the best one with the least information content.
5. Check if your design can meet the same FRs with fewer physical pieces (reducing the information content by physical integration)

Common mistake by designers

- Concentrating on symptoms rather than causes
- Coupling due to insufficient number of DPs
- Not recognising a decoupled design
- Having more DPs than FRs
- Not considering the robustness of a design

Comments

- Attitudes of a good designer
  - Do not accept conventional things without suspicion.
  - Be curious about everything around you, and analyse it.
  - Invest more time to think about what you want to achieve ultimately before starting the engineering design.
  - Try to do functional & solution-neutral thinking.
  - Try to obtain multidisciplinary knowledge and experience.

- All design principles must have their weaknesses because they are so conceptual. Try to find out and absorb profound insights that the authors have found in their experiences. Then adopt them to create your own principle.

Next Lecture

Week 4 – CAD & documentation

by
Richard Martin

Week 5 – Patenting your invention