 

Selecting the right material, shape and manufacturing process

Objective

The aim of this short paper is to demonstrate to you the benefit of using a systematic method for selecting the best material, shape and manufacturing process of a part.

Contents

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Introduction

I was taught early on in my career that a poor solution to the correct problem is infinitely more useful than a clever solution to the wrong problem. I have found that design in many ways really is a process of *problem finding* followed by the job of *problem solving*.

So to help you understand how I set up and solve a mechanical design problem we need to start by considering three key factors…

Three Key Factors

All of the chairs below are different. Why?

The answer is that the designer of each chair has made different decisions with respect to three factors:

(a) the **materials** that have been used for each part of the chair

(b) the **shape** of the individual parts that make up the chair

(c) the **manufacturing processes** by which the parts have been formed, finished and assembled

Sitting above these three key factors and driving the decision making process are the **functional requirements** for each of the chairs or for that matter any product….

Functional Requirements i.e. *finding the right problem to solve…*

At the end of the day a customer wants something done.

They want something; *enclosed*, *moved*, *separated*, *cleaned*, *heated*, *cooled* or whatever it might be, under certain specific constraints. Essentially the heart of any design problem is that the customer wants a function.

Now functions can be split into two broad classes:

1. ***Use* Functions**

Conduct Current	*Transmit Torque*	*Enclose Volume*	*Raise Load*	*Insulate Voltage*	*Dampen Vibration*	*Conduct Heat*	*Preserve Food*

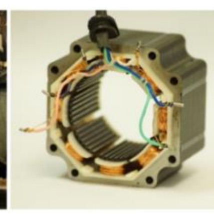
2. ***Aesthetic* Functions**

Provide Appearance	*Provide Colour*	*Reduce Noise*	*Increase Prestige*	*Provide Shape*	*Reduce Thickness*	*Generate Texture*

Many products you use in daily life require both ***Use*** and ***Aesthetic*** Functions in varying ratios:




Some products like the oil in your car or a concealed wire within a motor require only ***Use*** Functions.



In a similar way certain products require primarily ***Aesthetic*** Functions.



After we have identified and named the functions the customer wants the next two questions we must ask are:

- ***How much…?*** - which gives us a target to meet
- ***Under what conditions…?*** - which gives us the constraints and vital background to the problem

Correctly establishing the functional requirements for a product at the start sets up the design problem to be solved and stops us designing an office chair when the customer did in fact want a deck chair…

Back to the Three Key Factors

It helps to understand that any product regardless of whether it is a deck chair or a fighter jet is simply an assembly of parts.

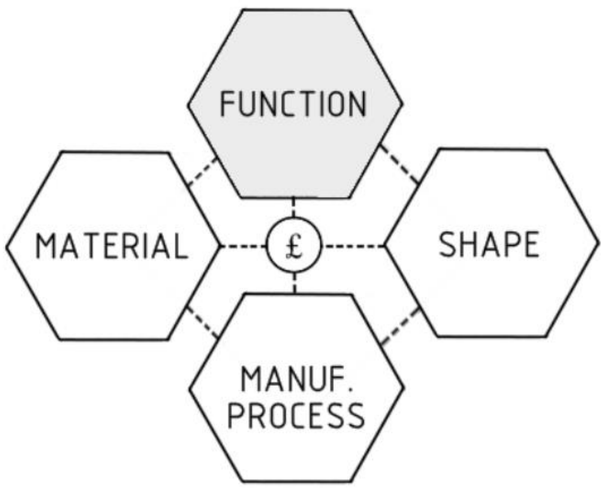
Each part within an assembly has the job of fulfilling at least one or more of the customers required functions.

Parts can be purchased directly from suppliers or we can design new ones ourselves. This important decision is made at the start of the mechanical design process and is typically known as "*Make or Buy*".

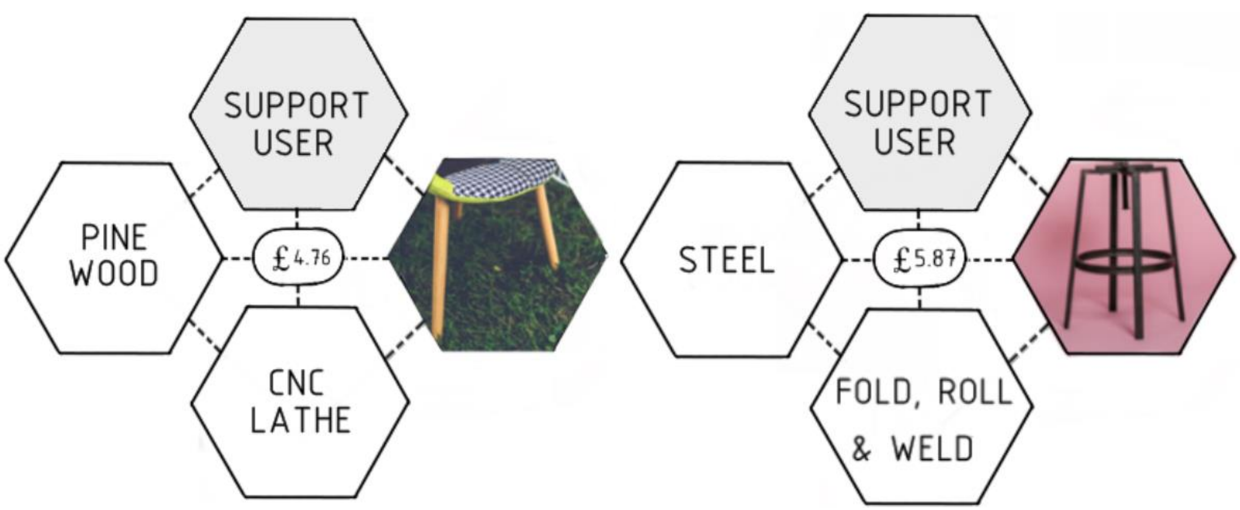
If we need to design a new part then regardless of its complexity I must first define the function and then:

1. Pick a Material
2. Create a Shape
3. Select a Manufacturing Process to convert the Material into the required Shape

The relationship between these tasks is given by the following network:

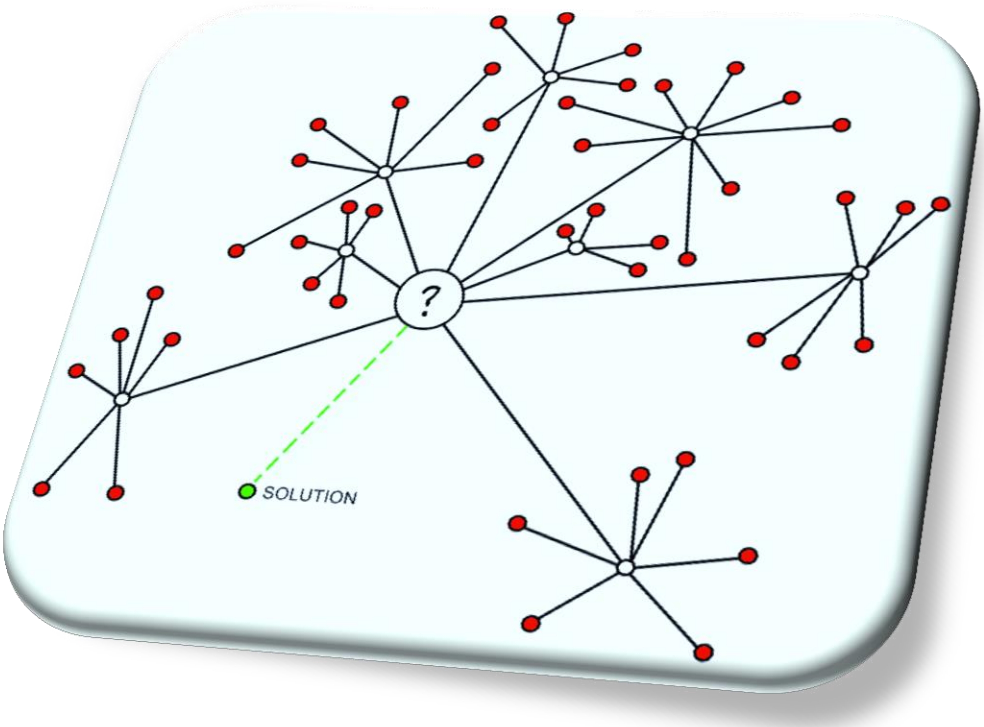


The decisions I make as I move around this interrelated network will result in different mechanical designs and ultimately what you will be most interested in; the cost for fulfilling the function.



The big problem is that we have 100,000+ commercially available materials to pick from, dozens of manufacturing processes, an infinite range of shapes and the fact that our decisions on the three key factors are interdependent.

The risk is that if we design any part with a trial-and-error approach then we can only ever really hope to hit upon a good solution by making repeated trial-and-error searches.



Good results, consistently in any sphere of man's activities arise from the use of a good system. Our goal is to get to a good solution as quickly and efficiently as possible...

Using a Systematic Approach

On the basis that experience and good luck can only take you so far I follow a systematic design approach that has been developed by Professor M. Ashby of Cambridge University.

Because Ashby's approach considers practically all of the engineering materials and manufacturing processes that are commercially available[1] it often throws up a solution that would not be immediately obvious.

To demonstrate the technique I have created a number of worked examples that illustrate in detail how I navigate around the design network from a set of functional requirements to a final design solution…

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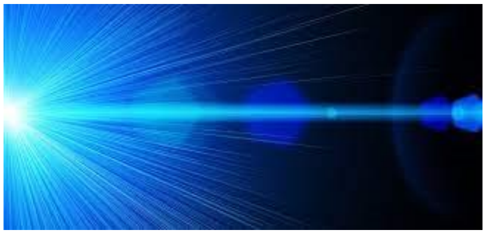
1. My primary reference material is the hard to find but highly recommended exhaustive three volume Elsevier Material Selector reference set by Ashby and Waterman. ISBN 0849377900

Material Selection Example

A laser is to be used to supply the requisite power for keeping a drone in the air for an indefinite length of time. A material is needed for the window through which the beam of the high powered laser is to pass.



I picked a synthetic diamond solution. To understand why see **Appendix A**

Material and Manufacturing Process Selection Example

Both a material and a manufacturing process are needed for the design of a guitar case.

I decided that a polypropylene blow moulding was the best option. To understand why see **Appendix B**

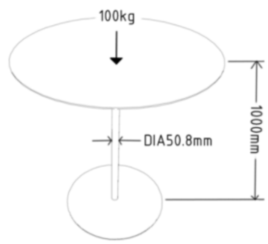
Material and Manufacturing Process Selection Example

A cylindrical tank is needed that can house 1,000 litres of kerosene oil. 1,500 units per annum are required.

I found that a roto-moulded tank made from a medium density polyethylene was the best option. To understand why see **Appendix C**

Material and Shape Selection Example

The lightest column for a display stand is required.
Five different materials have been specified for investigation by the client, namely; *aluminium*, *steel*, *copper*, *polycarbonate* and *wood*.



To find out which material-and-shape combination is best see **Appendix D**

I hope this short paper has demonstrated the benefits of using a systematic approach to mechanical design.
If you have a design problem or an idea that you would like to discuss then get in touch today:

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Appendix A

Material Selection:

Description: Laser Window

Units: Metric

Issue: A

Summary:

This report documents the material selection process for the window through which the beam of a high powered laser is to emerge.
This study recommends further investigation of a Synthetic Diamond solution.

Background to Problem:

It has been proposed that a method for keeping a drone in the air for an indefinite length of time is to use a laser to supply the requisite power.

In order to maximise the energy transfer from the ground to the drone the selection of the most suitable material for the laser window must be reviewed.

Material selection will involve considerations relating to the beam degradation caused by thermal lensing and mechanical stress induced by temperature gradients.

Problem Solving Approach:

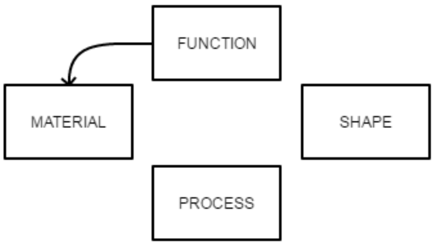

Figure 1: *Design flowchart*

As per *Figure 1* the problem solving approach is to first recognise the functional requirements and then determine suitable materials for the purpose of further review and discussion.

Recognise Functional Requirements:

Function	Laser Window
Constraints	Material must be transparent Material must have a high thermal - conductivity value Material must have a low thermal expansion coefficient
Objective	Minimise energy loss
Free variable	Material choice

Determine Optimal Material:

The material selection process was conducted on a two-step basis:

Step 1: The first step was to filter out all commercially available materials that are classed as either opaque or translucent.

Step 2: Next we recognise that we wish to have both a high thermal conductivity (λ) in combination with a low thermal expansion coefficient (α). Having the highest possible thermal conductivity value will minimise energy loss whilst a low thermal expansion coefficient will reduce the resultant thermal strain. The material index to be maximised for the remaining materials is established as:

$M_1 = \frac{\lambda}{\alpha}$ [1]

	λ $W.m.K$	α $\mu strain/\ ^{\circ}C$	£/kg	M_1
Diamond	200-400	0.8-1.2	1.5E5 – 3E5	300.00
Ti-Silicate	1-1.5	0.04-0.05	3-5	27.78
Sapphire	34.6-37.4	4.5-5.3	*1.5E3-9E3*	7.35
Alumina (Translucent)	25.9-28.1	5.4-6.7	16-24	4.46
Silica	1.4-1.5	0.48-0.52	3-5	2.90

For maximum performance irrespective of cost it is recommended that a synthetic diamond based solution be investigated.

If the resultant cost becomes problematic then the use of either a Ti-Silicate or Synthetic Sapphire based solution will need to be reviewed.

Reference:

1. Elsevier Material Selector Volume 1 - *Waterman & Ashby*
2. Materials & Processes in Manufacturing - *Black & Kosher*
3. Materials Handbook - *Cardarelli*
4. Engineering Materials - *Budinski*
5. High temperature materials and mechanisms - *Bar-Cohen*
6. Encyclopaedia of Materials, Parts, and Finishes - *Schwartz*
7. Material Handbook - *Brady*

Conclusion:

Synthetic Diamond is the optimal material in this instance as it will minimise the degradation of the laser beam quality. From a cursory review of the market a solution of this nature is commercially available and could be factored into any further system feasibility calculations.

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Appendix B

Material and Process Selection:
Description: Guitar case material and process selection
Units: Metric
Issue: A

Summary:

This report documents the selection of both a material and a corresponding manufacturing process for a guitar case.

A blow moulded Polypropylene design approach is recommended. It should be noted that the decision over which specific grade of Polypropylene is to be nominated requires both further information and research.

Background to problem:

The design requirements supplied for the guitar case are listed below verbatim:

- *'Must be lightweight and inexpensive'*
- *'Should be both wear resistant and tough'*
- *'Must not be flammable'*
- *'Must be mouldable'*
- *'Must be waterproof'*
- *'The guitar case must be black'*
- *'Size is approximately 1000 x 500 x 50mm'*
- *'Production quantity is unconfirmed, use 1,000, 5,000 and 10,000 per/year'*

Problem solving approach:

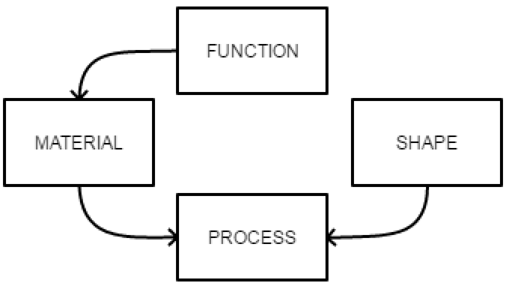

Figure 1: *Design flowchart*

As per *Figure 1* the problem solving approach taken by the author is:

1. recognise functional requirements
2. determine optimal material
3. recognise shape constraints
4. determine optimal manufacturing method

Recognise Functional Requirements:

Function	Guitar case
Constraints	Client requests that material must be moulded to meet specific aesthetic design requirements Material must be resistant to fresh water Material must be resistant to salt water Material must be '*tough*' Material must be lightweight High flammability resistance Must be coloured black
Objective	Low cost
Free variables	Material and manufacturing process

Determine Optimal Material

The material selection was conducted on a six step basis. Only materials that passed each successive step have been considered.

Step 1: For toughness we assign an arbitrary fracture toughness limit of ≥ 15 MPa.m$^{1/2}$

Step 2: Materials are then refined on the basis of suitability for moulding as a primary forming process

Step 3: Filtering is then performed on the basis of those which have a "*very good*" resistance to both fresh water and salt water.

Step 4: The three remaining materials are ranked on the basis of price versus density:

- Polypropylene (PP)
- Polyamide (PA)
- Polyurethane (PU)

We find that Polypropylene (PP) is both the cheapest and lightest option.

Step 5: Checking the flammability of Polypropylene we find quite quickly that flame retardant grades are indeed commonly available from manufacturers.

For reference typical uses of Polypropylene include;

Buckets and bowls
Artificial sports surfaces
Bottle crates
Battery cases
Toys
Washing machine drums
General mechanical parts
Pipes
Car bumpers
Fibres for carpeting

Step 6: Further detailed research is required to ascertain the specific grade of Polypropylene alongside the associated Pantone colour specification.

Reference:

1. Elsevier Material Selector - *Waterman and Ashby*
2. The Plastics Compendium Vol 2 – *Hough, Allan and Dolbey*
3. Handbook of plastic technologies – *Harper*
4. Plastics fabrication and recycling – *Chanda and Roy*
5. Plastics - *Belofsky*

Recognise Shape Constraints

Function	Guitar case
Constraints	Polypropylene to be used (*Grade unconfirmed*) Client requests that material must be moulded to meet specific aesthetic design requirements. Design is likely to have negative draft and a moderately complex surface Estimated size = 1000 x 500 x 50mm Projected QTY per annum either 1,000, 5,000 or 10,000
Objective	Low manufacturing cost
Free variables	Manufacturing process

Determine optimal manufacturing method:

The manufacturing process selection was conducted on a five step basis.

Step 1: All major manufacturing processes that are compatible with Polypropylene are to be listed:

Cutting
Drilling
Expanded foam moulding
Blow moulding
Injection moulding
Machining
Polymer extrusion
Rotational moulding
Thermoforming

Step 2: The list from the previous step is to be refined on the basis of the moulding constraint, hence:

Expanded foam moulding
Blow moulding
Injection moulding
Rotational moulding
Thermoforming

Step 3: Expanded foam moulding was discounted due to the size of the guitar case. Hence this leaves:

Blow moulding
Injection moulding
Rotational moulding
Thermoforming

Step 4: The decision over which manufacturing process is to be recommended is to be based upon the predicted complexity of the design. The client has indicated that the design is likely to have negative draft and a moderately complex surface hence this means that thermoforming is removed from our list of options which leaves:

Blow moulding
Injection moulding
Rotational moulding

Step 5: Considering a viable economic batch size then we find for low volume production rotational moulding should be selected whilst for high volume production injection moulding is the best choice. To summarise:

QTY	
1,000	Rotational moulding Blow moulding
5,000	Rotational moulding Blow moulding
10,000	Injection moulding Blow moulding

Note that the selection of blow moulding offers a degree of flexibility which can accommodate the uncertainty over potential production volumes.

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Appendix C

Process and Material Selection:
Description: Kerosene Fuel Tank
Units: Metric
Issue: A

Summary:

Tasked with designing a kerosene oil storage tank this study finds that under the constraints imposed a roto-moulded tank made from a medium density polyethylene is to be recommended.

Background to Problem:

The client has requested a cylindrical tank able to safely house 1000 litres of kerosene oil. The base of the storage tank must be flat in order to negate the use of a frame.

A production estimation of 1,500 units per annum has been made but this is potentially subject to review.

Problem solving approach:

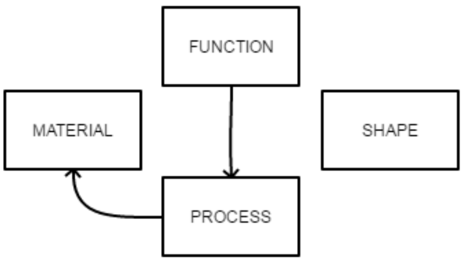

Figure 1: *Design flowchart*

As per *Figure 1* the problem solving approach taken by the author is:

1. Recognise the functional requirements
2. Determine the optimal manufacturing process
3. Determine a suitable material

Recognise Functional requirements

Function	Store kerosene
Constraints	1,500 per annum Volume = 1,000 litres Cylindrical shape Kerosene heating oil Non-metallic
Objective	Minimise cost
Free variables	Process & material

Determine Primary Shaping Process:

The process selection was conducted on a four step basis. Only manufacturing processes that passed each successive step have been considered.

Step 1: The main shape of the tank will dictate the manufacturing process. We know that a cylindrical form is required hence the first filter is to screen out all processes incapable of forming a hollow 3D shape.

Step 2: Whilst we do not know the final dimensions of the tank we can use an arbitrary minimum 1m diameter by 1m height to filter out any process incapable of creating components of this magnitude.

Step 3: Any process associated with the material families '*ceramics and glasses*' and/or '*metals*' was excluded

Step 4: An arbitrary minimum section thickness of 2mm was specified.

The resulting manufacturing processes derived are:

(a) Blow moulding
(b) Filament winding
(c) Resin transfer moulding
(d) Rotational moulding

Blow moulded tanks are viable but for the manufacturing quantity considered and the control we wish to have over the tanks wall thickness it is not considered appropriate.

Filament wound tanks are traditionally used for highly corrosive substances, a concern not found in this present application.

Resin transfer moulding is possible at this volume but because of the desired shape of the tank it would require two separate mouldings. The two halves would then need to be joined together in a separate manufacturing process to form the final tank.

This leads us to the conclusion that on the basis of simplicity and cost rotational moulding is to be considered the favoured approach.

Determine Optimal Material:

The material selection was conducted on a five step basis.

Step 1: Materials must be compatible with rotational moulding.

Step 2: Materials must not suffer degradation upon contact with a hydrocarbon based fuel hence a filter on the basis of chemical resistance is required.

Step 3: The tank must be robust to avoid accidental fracture hence we wish to filter on the basis of wear resistance.

Step 4: Flammability of the selected material must be at a minimum poor.

Step 5: Materials are to be ranked with respect to price.

Only materials that passed each of the successive steps were considered for further analysis.

The four resultant materials are tabulated below ranked on the basis of cost.

	Cost (£/kg)
PET (Polyethylene Terephthalate)	0.98 – 1.08
PE (Polyethylene)	2.46-2.72
PS (High impact polystyrene)	3.04 – 3.36
PP (Polypropylene)	5.2 -5.74

Reference:

PET is used for the blow moulding of small bottles and in the creation of packaging film

PE is commonly found within bowls, buckets, milk crates, tanks and various types of containers

PS is used for toys, cutlery and general household appliances

PP is used for buckets, bowls and general mechanical parts

PE is the cheapest viable solution and is the most widely used polymer in roto-moulding.

PE is traditionally subdivided into one of three categories depending upon its density:

Material	**Density** (kg/m^3)
Low density PE	915-929
Medium density PE	930-939
High density PE	940-965

The relationship between the material properties and the density of PE is illustrated below in *Figure 2*.

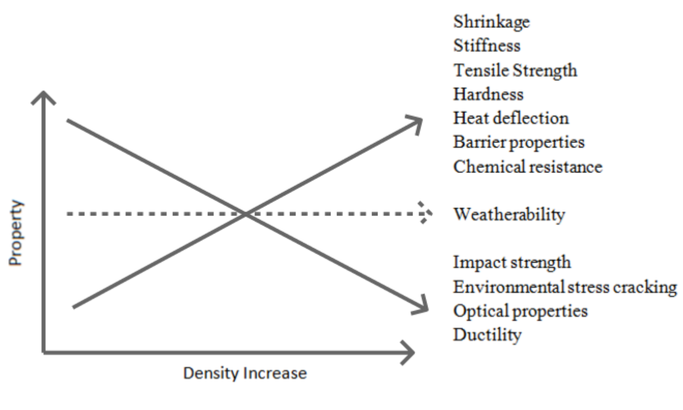

Figure 2: *Effect of density change on properties*

It can be seen that a sensible compromise is to select a medium density PE as the provisional material choice.

It should also be noted that whilst it is found that as standard polyethylene has a poor UV resistance, UV stabilised medium density PE variants are commercially available.

Reference:

1. Elsevier Material Selector - *Waterman and Ashby*
2. Manufacturing Engineers Reference Book - *Koshal*
3. Rotational Moulding of Plastics - *Crawford*

Conclusion:

A roto-moulded medium density polyethylene tank has been proposed.

If this approach is to be selected then a quick standards review shows that the tank must conform to legislation.

It is recommended that both BS EN ISO 13341 and CEN 266 are reviewed in full.

Confirmation on the precise grade of polyethylene required should be made in accordance with the manufacturer's advice.

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Appendix D

Shape-and-Material Selection

Description: Display Stand

Units: Metric

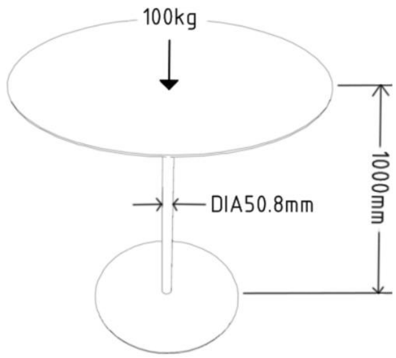
Issue: A

Summary:

This report documents the material and shape selection for a lightweight display stand and recommends the use of 50.8 OD X 1.6mm THK Aluminium 6082 tubing.

Background to Problem:

The lightest column for a display stand is required.



The column must support a load of 100kg placed on the upper surface of the table.

An aesthetic specification dictates that the outside diameter of the column should be as close to 50.8mm as possible.

Five different materials have been specified for investigation by the client, namely; *aluminium*, *steel*, *copper*, *polycarbonate* and *wood*.

Functional Requirements:

	Description
Function	Lightweight column
Constraints	Specified buckling load Height specified
Objective	Minimum mass
Free Variables	Choice of material Choice of shape

Problem Solving Nomenclature:

	Description	Units
A	Area	m^2
b	Breadth	m
E	Modulus of elasticity	GPa
F_c	Critical load	N
h	Height	m
I	Moment of inertia	m^4
L	Length	m
m	Mass	kg
n	End condition	ul
r	Radius	mm
t	Wall thickness	mm
$\emptyset_B^e$	Elastic-bending shape factor	ul
ρ	Density	$\mathrm{kg/m}^3$

Selection of Material and Shape:

The mass of the column is given by:

$$m = AL\rho \quad [1]$$

A column loaded in compression buckles elastically when the load exceeds the critical load. This load is also known as the Euler load:

$$F_c = \frac{n^2\pi^2 EI}{L^2} \quad [2]$$

A shape factor (ϕ) is a dimensionless number which tells us how efficiently the material is being used in a particular mode of loading. Using a square section as the neutral shape to which we will reference our design the moment of inertia is:

$$I_o = \frac{bh^3}{12} = \frac{b_o^4}{12} \quad [3]$$

Because $A = b^2$ we can write:

$$I_o = \frac{A^2}{12} \quad [4]$$

Our shape factor is thus a comparison between the new moment of inertia and the original:

$$\emptyset_B^e = \frac{I}{I_O} = \frac{I}{\left(\frac{A^2}{12}\right)} = \frac{12I}{A^2} \quad [5]$$

Rearranging for the moment of inertia:

$$I = \frac{\emptyset_B^e A^2}{12} \text{ [6]}$$

If we swap **[6]** into **[2]** then:

$$F_c = \frac{n^2\pi^2 E\left[\frac{\emptyset_B^e A^2}{12}\right]}{L^2} = \frac{L^2 n^2 \pi^2 E \emptyset_B^e A^2}{12} \text{ [7]}$$

$$A = \sqrt{\frac{12F_c}{L^2 n^2 \pi^2 E \emptyset_B^e}} \text{ [8]}$$

Moving **[8]** into **[1]** gives:

$$m = [A]l\rho = \sqrt{\frac{12F_c}{L^2 n^2 \pi^2 E \emptyset_B^e}}\, l\rho \text{ [9]}$$

Grouping material terms we arrive at:

$$m = \sqrt{\frac{12F_c}{L^2 n^2 \pi^2}}\, l \left[\frac{\rho}{(E\emptyset_B^e)^{0.5}}\right] \text{ [10]}$$

We want to achieve the minimum possible mass for the column therefore we must maximise the inverse of the bracketed terms which gives us our material-and-shape index:

$$\uparrow M_1 = \frac{(E\emptyset_B^e)^{0.5}}{\rho} \text{ [11]}$$

Note that the macro shape factor for elastic bending for a tubular profile is given by:

$$\emptyset_B^e = \frac{3}{\pi}\left(\frac{r}{t}\right) \text{ [12]}$$

Whilst the macro shape factor for elastic bending for a solid circular profile is given by:

$$\emptyset_B^e = \frac{3}{\pi} = 0.955 \text{ [13]}$$

A constraint imposed upon the selection is that for safety the column must be able to support a 100kg load, hence:

$$F_c = \frac{n^2\pi^2 EI_{min}}{L^2} = \frac{0.5^2\pi^2 EI_{min}}{1^2} = 0.617EI_{min} \text{ [14]}$$

$$980.6 = 0.617EI_{min} \text{ [15]}$$

$$\therefore \phi_1 = EI \geq 1589.8 \text{ N.m}^2 \text{ [16]}$$

<u>Evaluation</u>:

The five materials proposed for the column were evaluated based on both the material-and-shape-index and the buckling constraint.

Note that the shape selected for each material is based on maximising the macro shape factor from the range of stock profiles that were found to be commercially available.

Material	E	r	t	ρ	$\emptyset_B^e$	M_1	ϕ_1
Aluminium (6082)	69	25.4	1.6	2,700	15.2	378.8	5,166
Steel (304)	193	25.4	2	7,900	12.1	193.7	17,656
Copper (C106)	117	25.4	1.6	8,920	15.2	149.3	8,760
Polycarbonate (PC)	2.2	25.4	3.175	1,200	7.6	108.0	297
Wood (Beech)	11.9	25.4	-	750	0.9	136.6	3,594

With the outside diameter constraint imposed we find that that the best choice based upon the material-and-shape index is to use Aluminium tubing for the column.

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