COSTING COMPOSITE COMPONENTS

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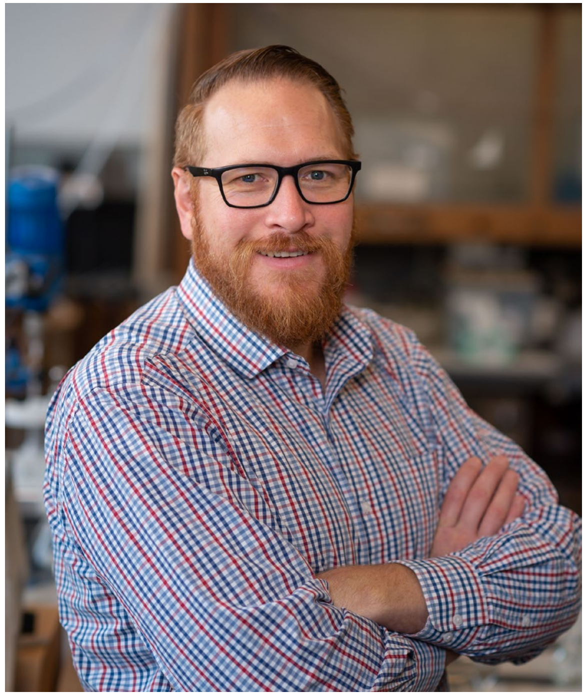
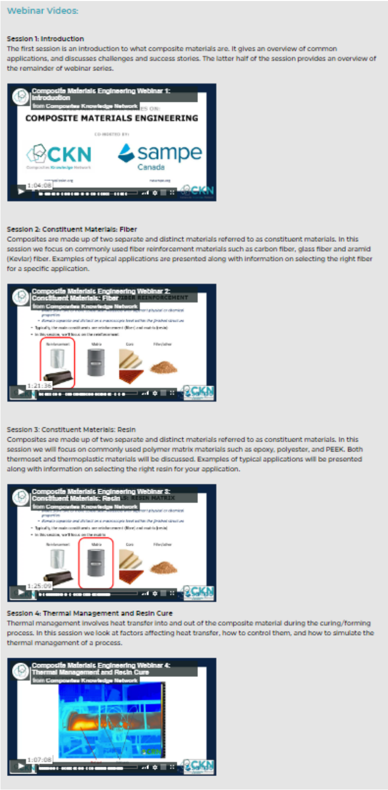


Casey Keulen, Ph.D, P.Eng.
Assistant Professor of Teaching, University of British Columbia
Co-Director of Advanced Materials Manufacturing MEL Program, UBC
Lead of Continuing Professional Development, CKN

- Ph.D. and M.A.Sc. in Composite Materials Engineering
- Over 15 years experience in industry and academia working on polymer matrix composites in aerospace, automotive, marine, energy, recreation and others
- Experience working with over 150 companies from SME to major international corporations
- Expertise in liquid composite moulding and thermal management

PAST WEBINAR RECORDINGS AVAILABLE

compositeskn.org



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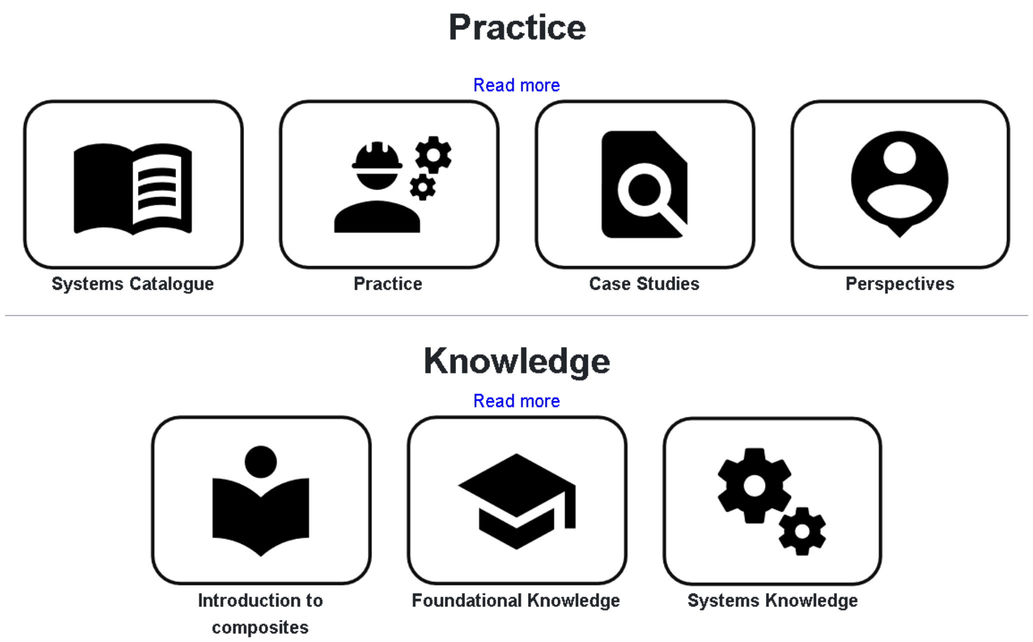
CKN KNOWLEDGE IN PRACTICE CENTRE

- Coming soon…
- A freely available online resource for composites engineers
- Focus on practice, guided by foundational knowledge and a systems-based approach to thinking about composites manufacturing



UPCOMING AIM EVENTS

- **Parameters for Structural Analysis of Composites**
  - February 10 @ 9:00 PT
  - Register via the eventbrite link at https://compositeskn.org/aimevents/
  - Focus will be on the elastic material properties necessary for structural analysis, and the different methods for obtaining them:
    - Experimental
      - Handbook/database values
      - Commissioning your own testing
    - Theoretical
      - Micromechanics
      - Laminate plate theory
- **Ongoing series/mini-series' on composites processing**
  - Focus on case studies and content within the Knowledge in Practice Centre
  - Will provide further depth on some topics covered in our previous 12-part series
- **For more information on dates and times visit:**

  https://compositeskn.org/aimevents/

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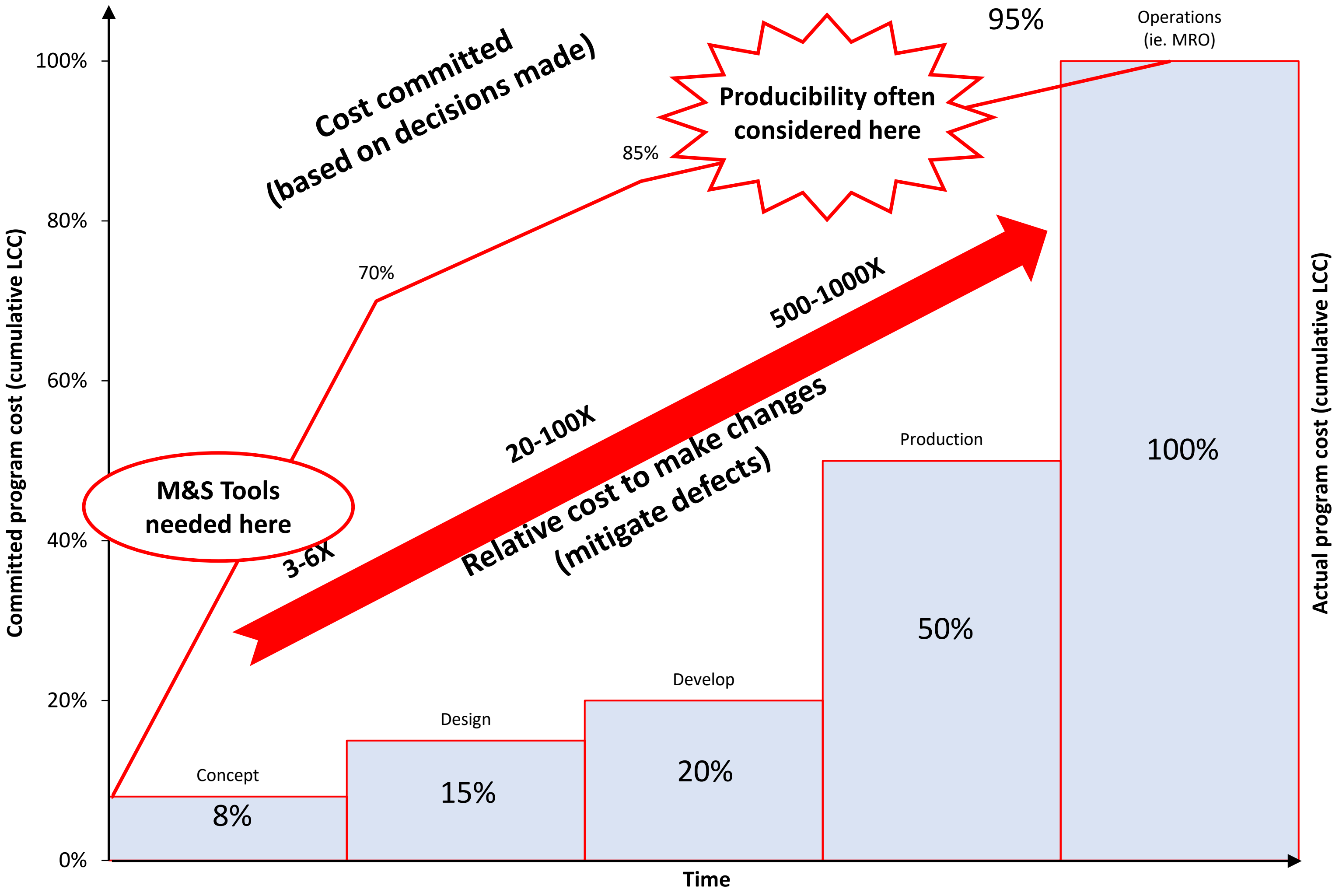
OUTLINE

- Introduction, learning objectives
- Cost commitment
- Manufacturing cost
  - How does the cost of manufacturing with composites compare to other materials?
- Material cost
- Cost modelling options
- Example – bottom-up cost estimating

INTRODUCTION

- Learning objectives:
  - Understand the timelines for cost commitment & product development
  - Understand risks associated with cost commitment
  - Understand material costs and manufacturing costs
  - Understand the composites supply chain
  - Understand the cost breakdown of a component
  - Understand the importance of cost analysis as a decision-making tool
  - Be able to produce cost models of your components

COST COMMITMENT



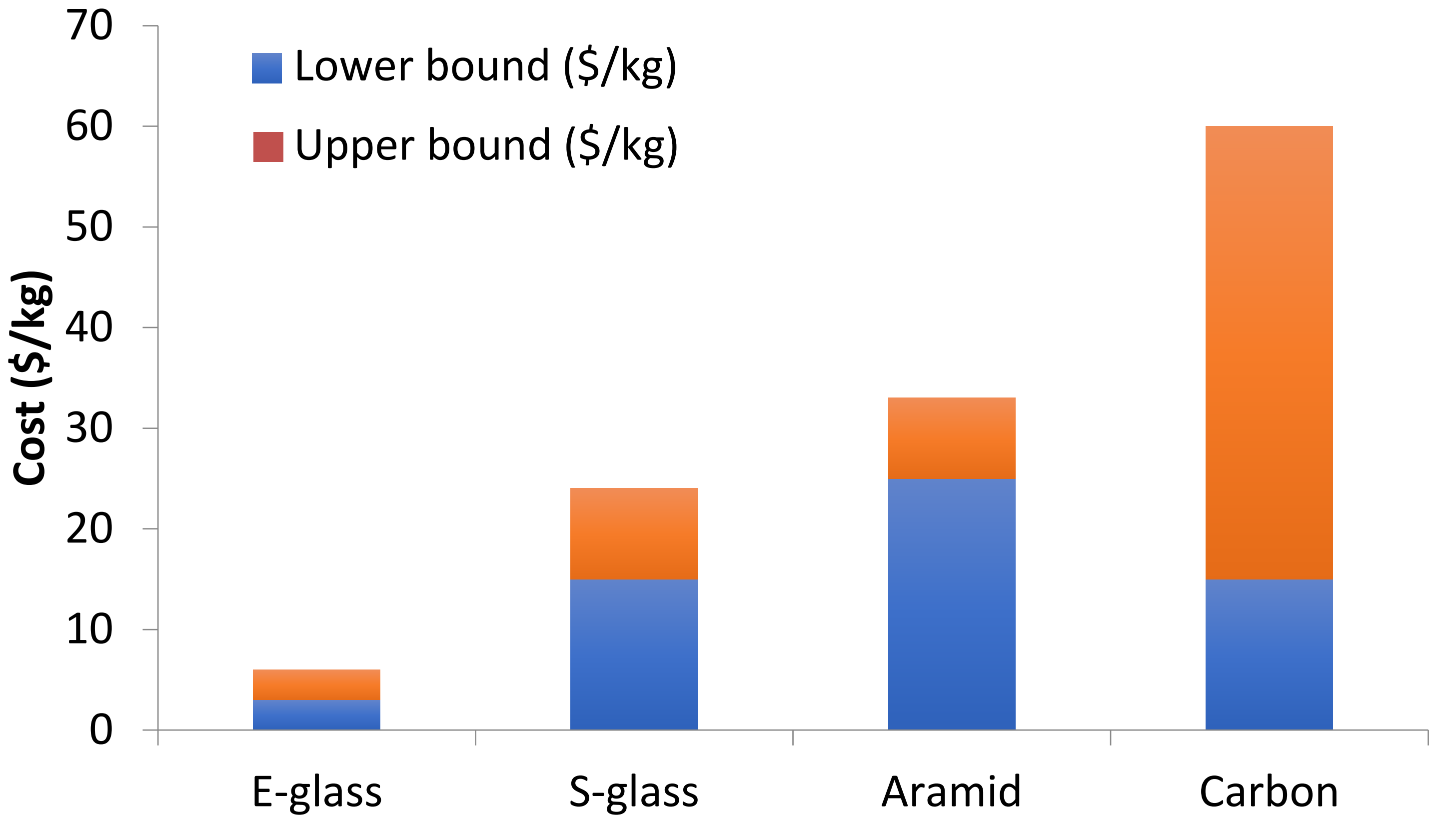
NDIA Manufacturing Division White Paper, "21st Century Manufacturing Modelling & Simulation Research and Investment Needs" (2011)
INCOSE Systems Engineerings HDBK (2006).

MATERIAL COST

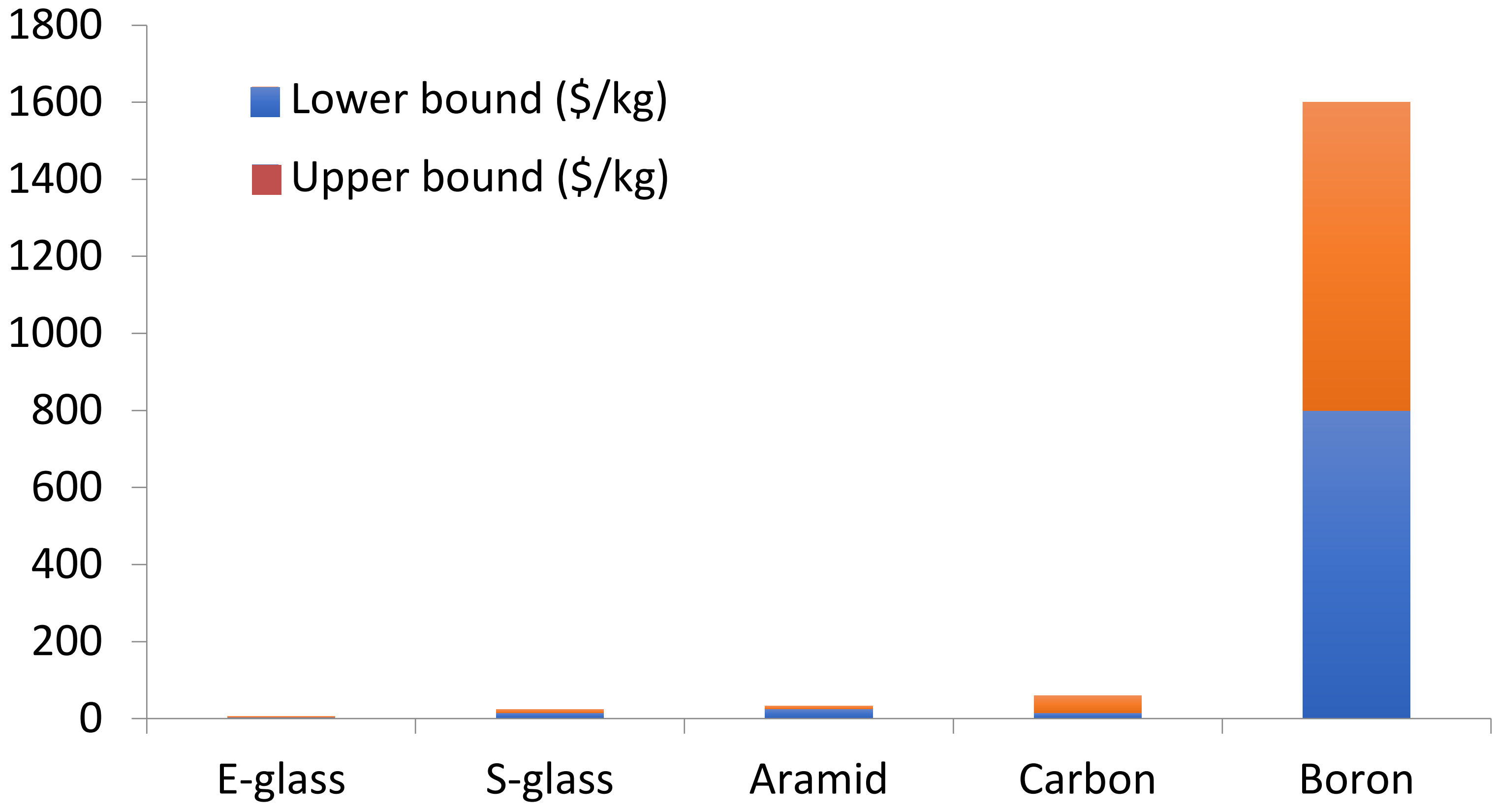
- Carbon fibre currently costs ~$15-60 USD/kg ($7-27 USD/lb)[1,2], while steel is less than ~$2.2 USD/kg ($1 USD/lb)
- Automotive industry has been waiting for $11 USD/kg ($5 USD/lb) carbon fibre before committing to it[3]
- Quote: "Ford did assert in 2009 at the Composites World Expo that it would not consider increased carbon fibre use unless the cost for the material dropped to $5 USD/lb"[4]

[1] http://auto.howstuffworks.com/fuel-efficiency/fuel-economy/carbon-fiber-oil-crisis2.htm
[2] http://www.rmi.org/RFGraph-carbonfiber_vs_steel_manufacturing
[3] http://www.compositesworld.com/columns/waiting-for-5lb-carbon-fiber%284%29
[4] http://www.compositesworld.com/articles/auto-composites-quest-one-minute-cycle-time

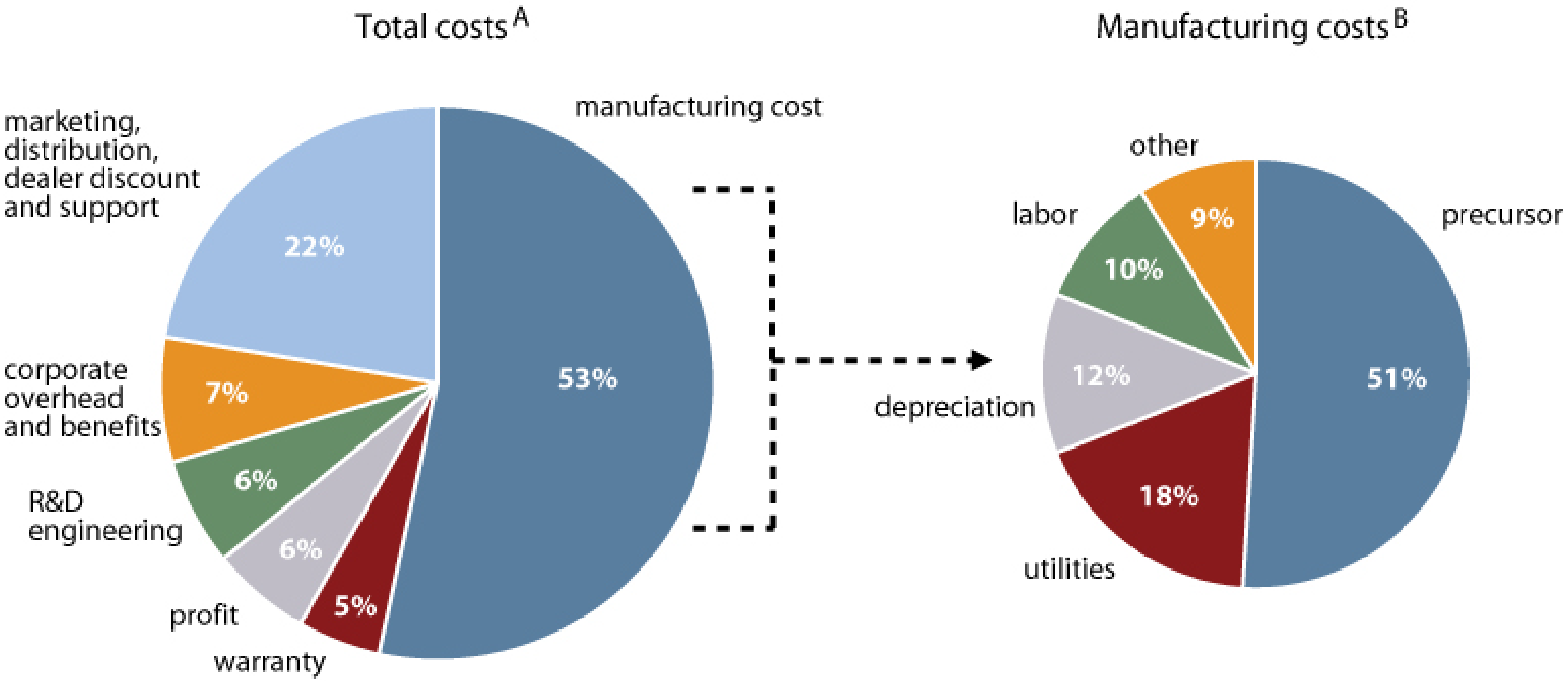
FIBRE MATERIAL: COSTS



FIBRE MATERIAL: COSTS



CARBON FIBRE COST

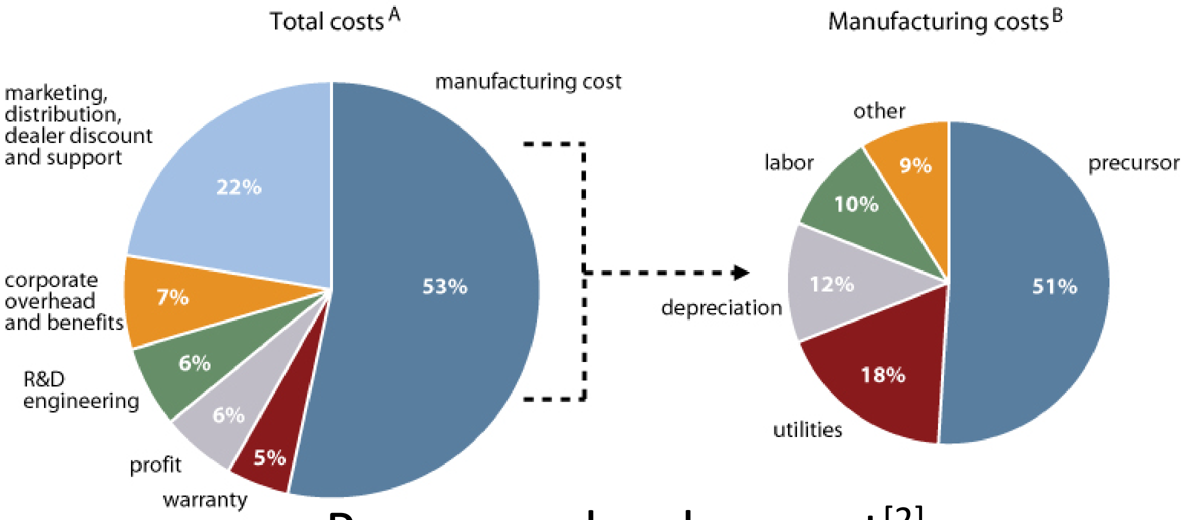


Carbon fibre cost breakdown[1]

[1] http://www.rmi.org/RFGraph-carbon_fiber_cost_breakdown
[2] Elmarakbi, A., Advanced composite materials for automotive applications, Wiley, 2014

CARBON FIBRE COST

Carbon fibre cost breakdown[1]



Precursor development[2]

- Conventional PAN precursor ~$11 USD/kg
- Commodity grade PAN textile
  - ~$4.4-6.6 USD/kg
  - Zoltex's Panex 35 fibre manufactured from textile grade PAN
- Polyolefin
  - ~$2.2-4.4 USD/kg
- Lignin
  - Byproduct from wood pulping process, cheap, abundant, renewable
  - Many challenges still to be addressed

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[1] http://www.rmi.org/RFGraph-carbon_fiber_cost_breakdown
[2] Elmarakbi, A., Advanced composite materials for automotive applications, Wiley, 2014

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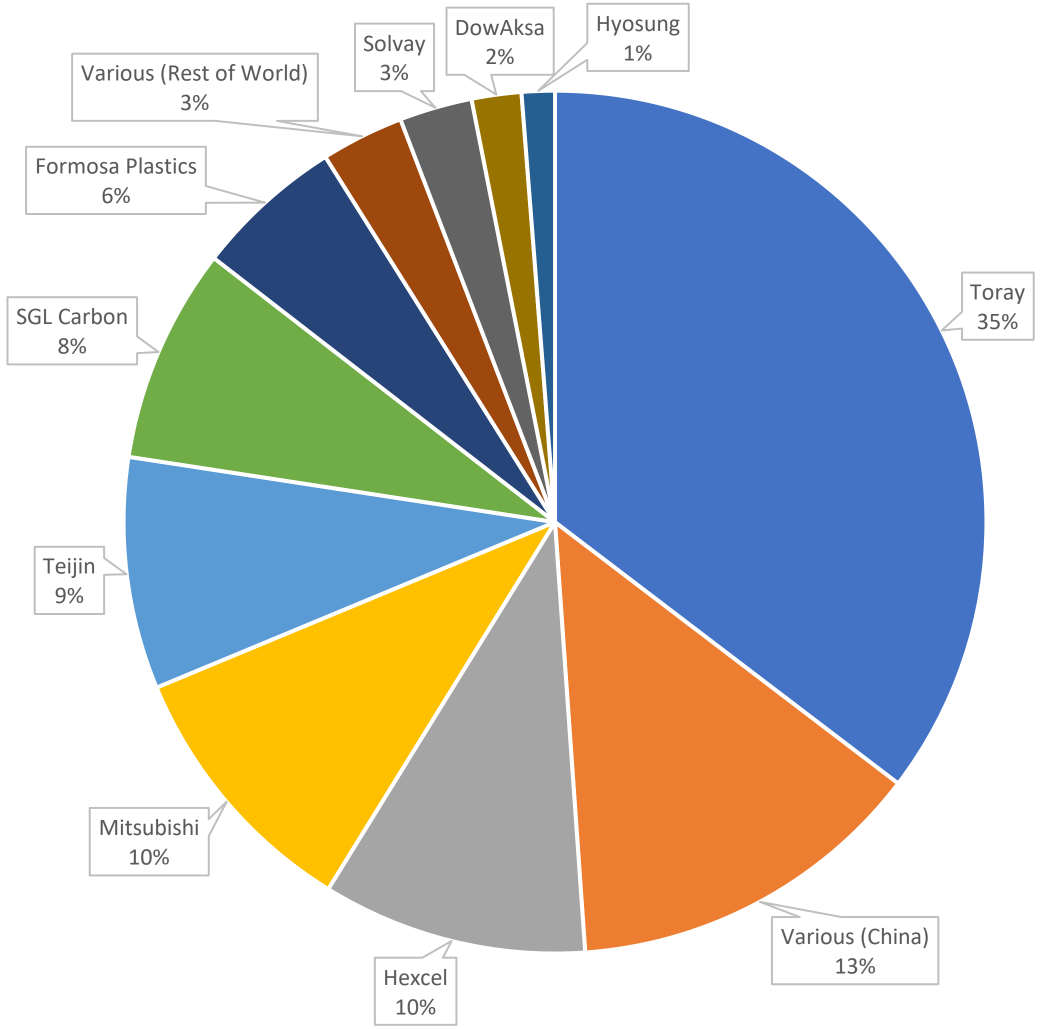
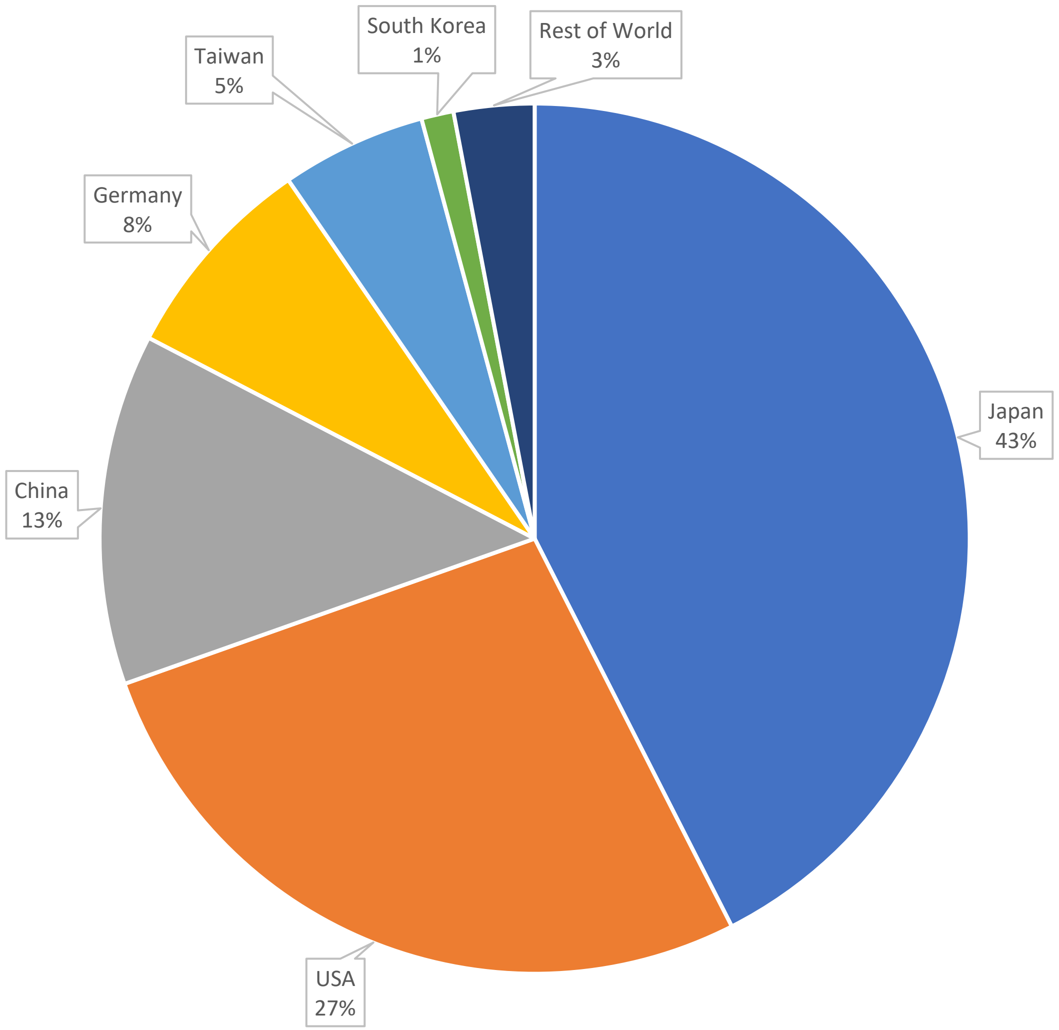
CARBON FIBRE MARKET SHARE



Source: Anthony Roberts/AJR Consulting , printed in https://cw.mydigitalpublication.com/publication/?m=59263&i=660367&p=32 (June 2020)

CARBON FIBRE MARKET SHARE



Source: Anthony Roberts/AJR Consulting , printed in https://cw.mydigitalpublication.com/publication/?m=59263&i=660367&p=32 (June 2020)

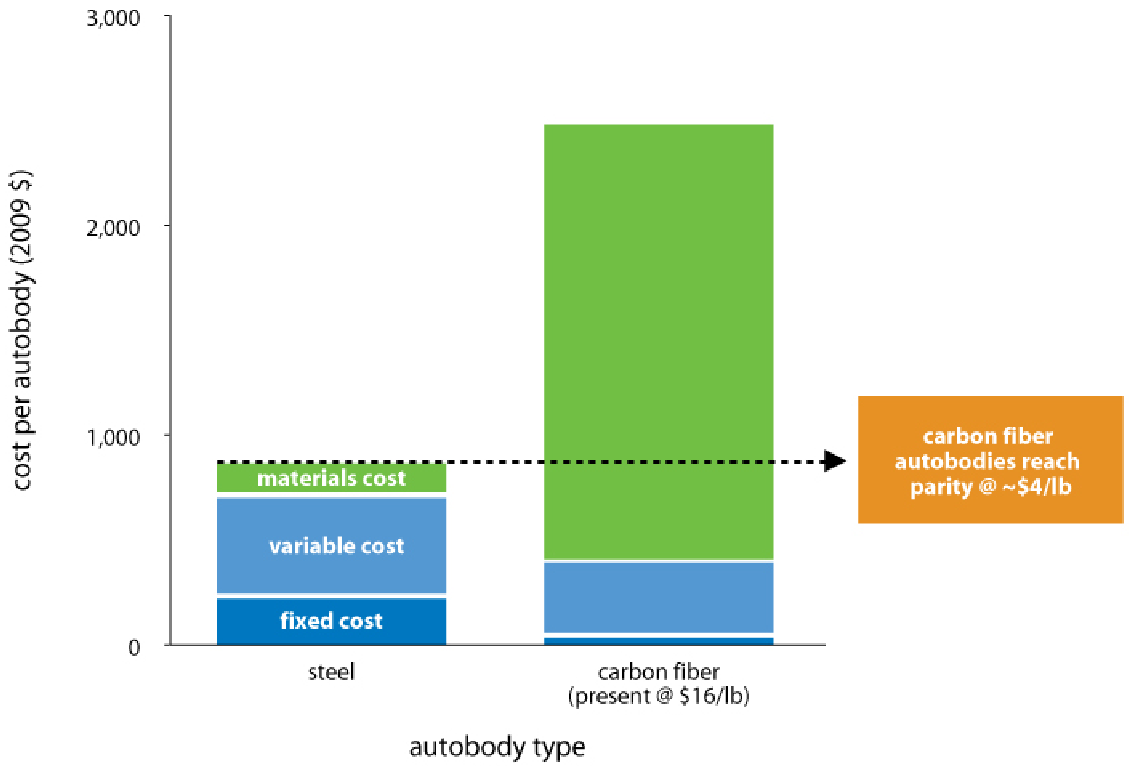
RESIN COST

EPOXY COST > VINYL ESTER COST > POLYESTER COST

MANUFACTURING COST

- Actual manufacturing costs can be less than steel manufacturing in automotive applications, but material cost increases total cost

Comparison of carbon fiber vs. steel manufacturing costs [1]



[1] http://www.rmi.org/RFGraph-carbonfiber_vs_steel_manufacturing

COMPOSITES SUPPLY CHAIN

[2]

Challenges include:

- Difficulty getting small quantities of material
- Difficulty in switching material systems (single source)
  - Proprietary material systems are not equivalent across companies
- Even the big guys have problems with it
  - John Byrne (VP aircraft materials and structures, Boeing) stated that the relative immaturity of the composites industry made up-front capital costs a substantial barrier[1]
- Lack of standardization (very different from metals industry)

- Despite this, Airbus developed the composite A350, Bombardier the C-Series (now A220) and Boeing the 777X (composite wings)

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[1] https://www.compositesworld.com/articles/despite-787-boeing-not-sold-on-composites
[2] Boeing image gallery, https://boeing.mediaroom.com/image-gallery

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HOW CAN COMPOSITES BE COST COMPETITIVE?

- *Reduced Part Count!*

Boeing 747-400

Boeing 787

- Final assembly time is significantly decreased:
  Boeing 767 – 30 days

  Boeing 787 – 3 days

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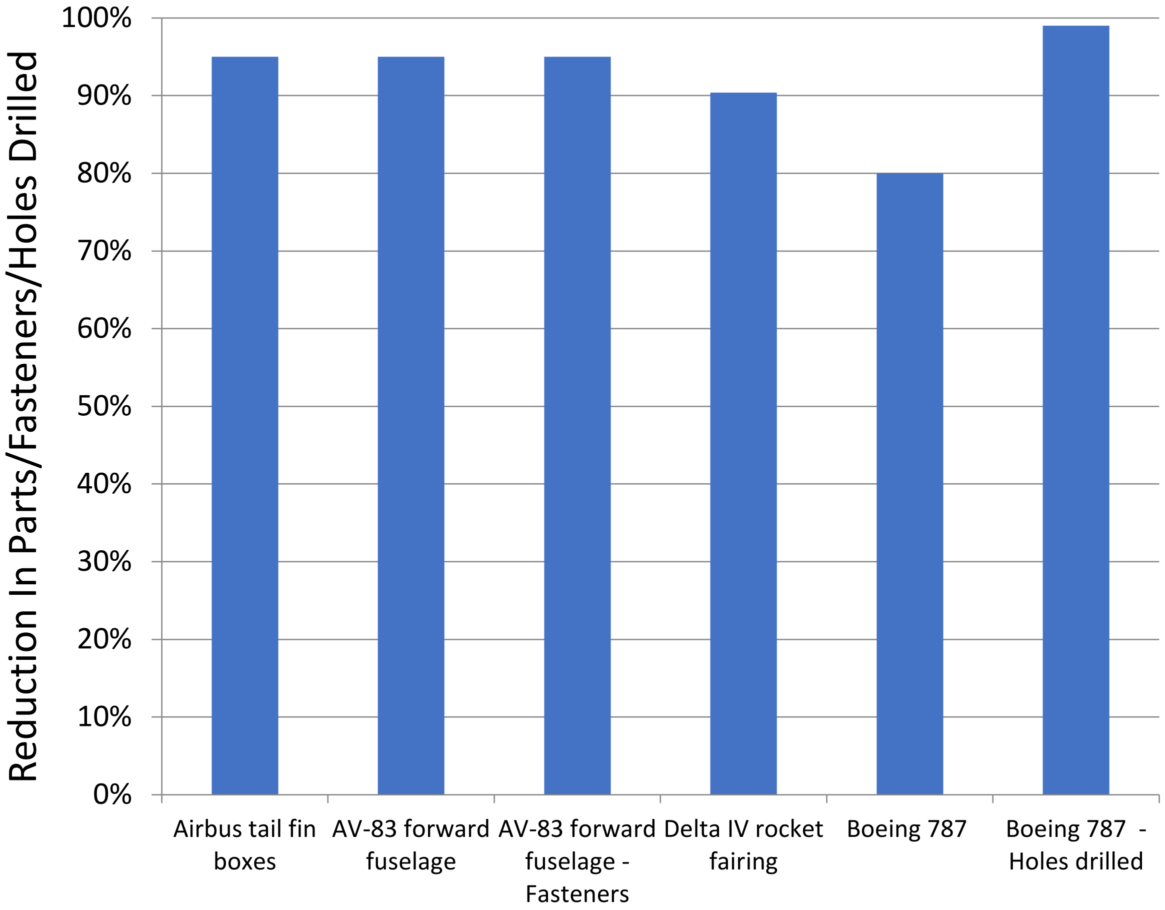
HOW CAN COMPOSITES BE COST COMPETITIVE?

- *Reduced Part Count!*



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Case Study: BMW & Composites

- In 2011, SGL Automotive Carbon Fibers (a BMW group and SGL group joint venture) completed construction on a new carbon fibre plant in Moses Lake, Washington[1]
- Started at 3000 tonnes/year, expanded to 6000 tonnes in 2013 & 9000 tonnes in 2015 [2]
- Material used to build the first generation of mass-production, composites intensive vehicles: the i3 and i8
- BMW had planned to need 10% of the world’s carbon fibre manufacturing capacity[3]
- BMW exited this joint venture in 2017[4]
- BMW is moving further away from composites in 2020 and the iX SUV will not rely as much on composites[4]

[2]

"IAA 2013: BMW i3" by motorblog [CC BY 2.0]

"BMW i8" by Loco Steve [CC BY-SA 2.0]

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[1] https://www.materialstoday.com/carbon-fiber/news/sgl-automotive-carbon-fibers-completes-us-facility/
[2] http://www.bmwcoop.com/wp-content/images/2014/03/bmw-carbon-fiber-factory.jpg
[3] https://www.youtube.com/watch?v=la4Eq8_FBPc
[4] https://www.bloomberg.com/news/articles/2020-11-12/bmw-backed-carbon-fiber-maker-cutting-500-jobs-in-restructuring

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COMPOSITES COST MODELLING OPTIONS

[1]

MODEL CATEGORY	DESCRIPTION	ADVANTAGES	LIMITATIONS
Guessing	Off-the-cuff estimates	Quick	No basis or substantiation. No Process. Usually wrong.
Analogy	Compare project with similar projects from the past.	Estimates are based on actual experience.	Truly similar projects must exist.
Expert judgment	Consult one or more experts.	Little or no historical data is needed; good for new or unique projects.	Experts tend to be biased; knowledge level is sometimes questionable; may not be consistent.
Top-down estimation	A hierarchical decomposition of the system into progressively smaller components.	Provides an estimate linked to requirements.	Needs valid requirements. Engineering bias may lead to underestimation.
Bottom-up estimation	Divides the problem into the lowest items. Estimate each item... sum the parts.	Complete work breakdown structures (WBS) can be estimated.	Costs can occur in items that are not considered in the WBS.
Design to cost	Uses expert judgment to determine how much functionality can be provided for given budget.	Estimate always lower than given budget.	Little or no engineering basis. Only valid in combination with another model.
Simple Cost estimation relationships (CERs)	Equation with one or more unknowns that provides cost estimates.	Cost based on actual data.	Simple relationships may not tell the whole story. Historical data may not tell the whole story.
Comprehensive parametric models	Perform overall estimate using design parameters and mathematical algorithms.	Models are usually fast and easy to use, and useful early in a program; they are also objective and repeatable.	Models can be inaccurate if not properly calibrated and validated; historical data may not be relevant to new programs; optimism in parameters may lead to underestimation.

[1] http://www.sirris.be/sites/default/files/content/composites-whitepaper-6-cost-estimation.pdf

COST MODELLING – TOP-DOWN ESTIMATION

- Appropriate for the beginning of the design stage as a decision-making tool for evaluating the economic feasibility of various design concepts
  - i.e. Used to guide the selection of materials and processes

1. Begin with an estimate of the maximum sales price
2. Deduct the desired profit per part to determine the allowable cost of manufacture per unit
3. Deduct an estimate of general/administrative overhead per part
   - Company specific and dependent on the percentage of total production that this part represents & the production rate
4. Deduct the estimated material cost per part (accounting for scrap/rework and non-composite components) and the estimated tooling cost per part (cost of tools divided by the total number of parts manufactured with the tools)

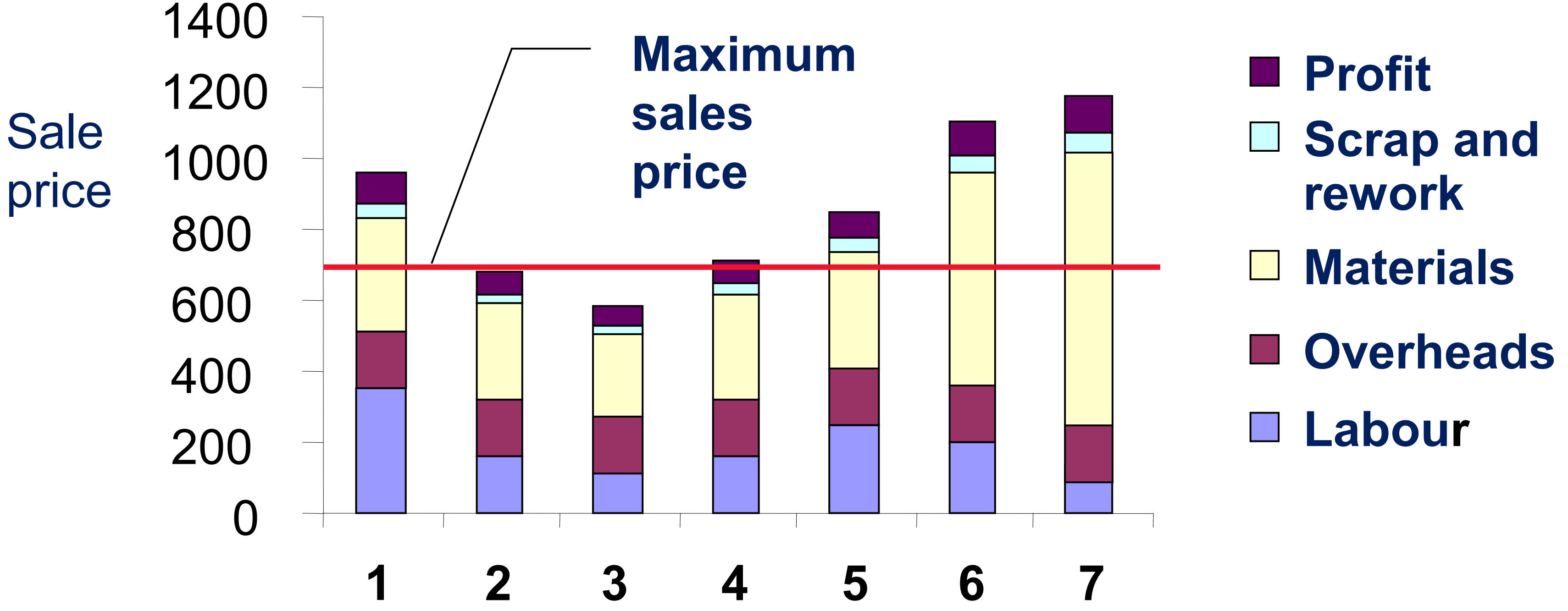
- The remainder is the maximum possible burdened labour content

5. Divide by the hourly burdened labour rate to determine the maximum production time and evaluate for feasibility

- This is a crude approach, but is useful to estimate if a design solution has the potential to be economically feasible or should be rejected

Reference: Potter, K., An Introduction to Composite Products – Design, development and manufacture, Chapman & Hall, 1997

COST MODELLING – TOP-DOWN ESTIMATION



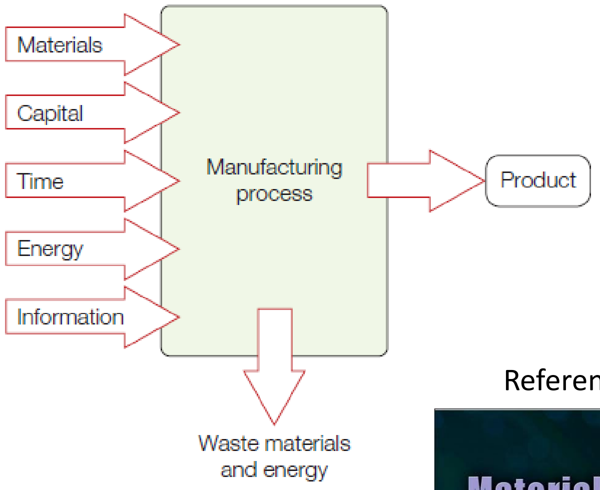
- Trying to avoid design solutions where the cost is well above the maximum sales price
- Top-down costing for seven different design solutions of the same product is shown, several of the design solutions can be quickly rejected based on cost
- This frees up resources to more thoroughly investigate the most economically feasible design solutions
- Design solutions close to the maximum sales price shouldn't be rejected or pursued outright, but will require more detailed bottom-up costing to estimate economic feasibility

Reference: Potter, K., Course notes on "Costing and Decision Making". University of Bristol/Advanced Composites Collaboration for Innovation & Science, 2018

COST MODELLING – BOTTOM-UP ESTIMATION

- "The manufacture of a component consumes resources (Table 13.5), each of which has an associated cost. The final cost is the sum of expenses of all of the resources is consumes"

$$C = C_1 + C_2 + C_3 + C_4$$



Reference: Ch. 13

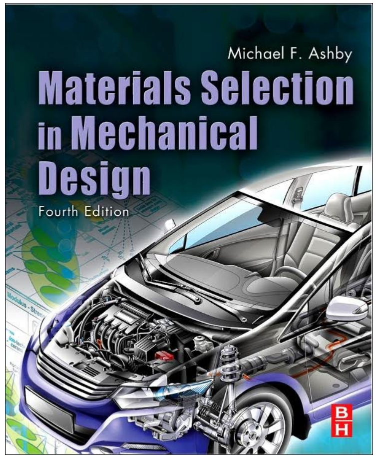


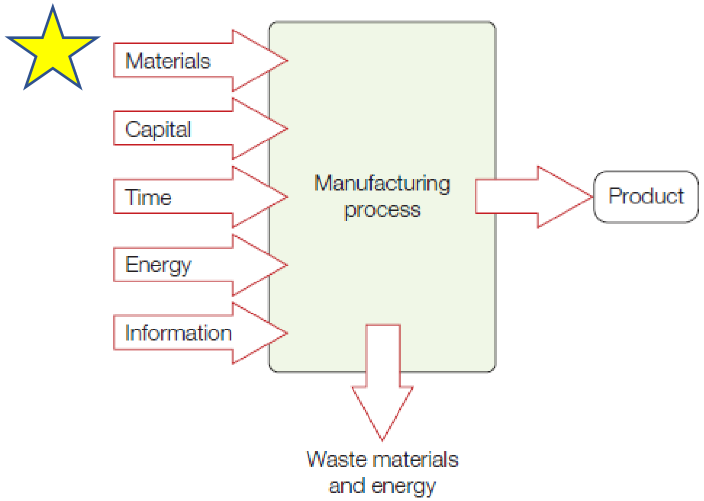
Table 13.5 Symbols, Definitions, and Units

Resource	Symbol	Unit
Materials: including consumables	C_m	\$/kg
Capital: cost of tooling	C_t	\$
cost of equipment	C_c	\$
Time: overhead rate, including labor, administration, rent …	$\dot{C}_{oh}$	\$/hr
Energy: cost of energy	$\dot{C}_e$	\$/hr
Information: R & D or royalty payments	$\dot{C}_i$	\$/year

Reference: Ashby, M.F., Materials Selection in Mechanical Design, Elsevier, 2011

COST MODELLING – BOTTOM-UP ESTIMATION

- Materials cost: $$C_1 = \frac{mC_m}{(1-f)}$$



- Where: m = mass (kg)

  C_m = material cost ($/kg)

  f = scrap rate

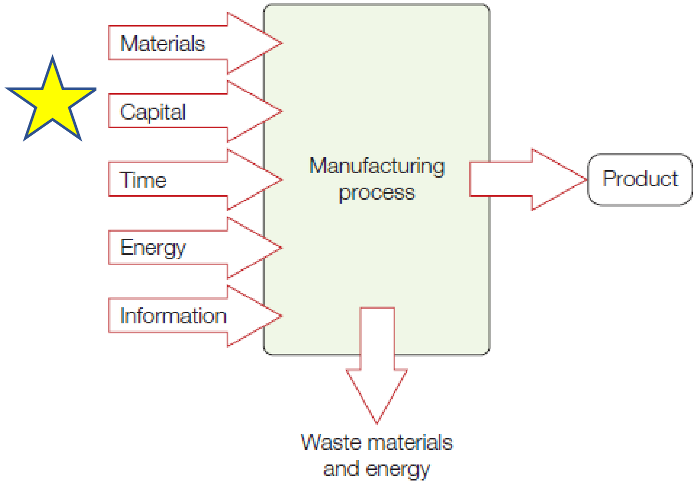
Note: scrap rate depends on process, part shape, etc.; however, a reasonable first order estimate is f = 25%.

Reference: Ashby, M.F., Materials Selection in Mechanical Design, Elsevier, 2011

COST MODELLING – BOTTOM-UP ESTIMATION

- Tooling cost (dedicated cost):

$$C_2 = \frac{C_t}{n}\left\{ceiling\left(\frac{n}{n_t}\right)\right\}$$



- Where: C_t = tooling cost ($)

  n = production run size

  n_t = number of parts per tool

Note: ceiling() is a function that rounds to the next highest integer. This increments the cost of tooling every time the life of a tool is exceeded

COST MODELLING – BOTTOM-UP ESTIMATION

- Capital equipment cost (non-dedicated):

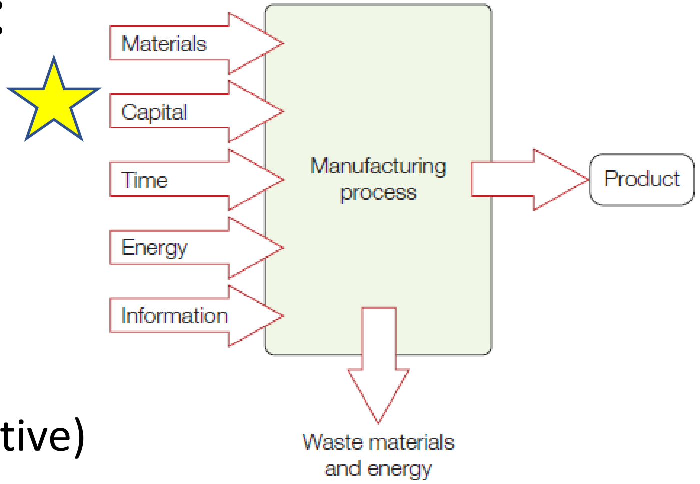
$$C_3 = \frac{1}{\dot{n}}\left(\frac{C_c}{Lt_{wo}}\right)$$

- Where: C_c = equipment cost ($)

  L = load factor (fraction of time equipment is productive)

  t_{wo} = capital write-off time

Note: typical capital write-off time could be ~5 years

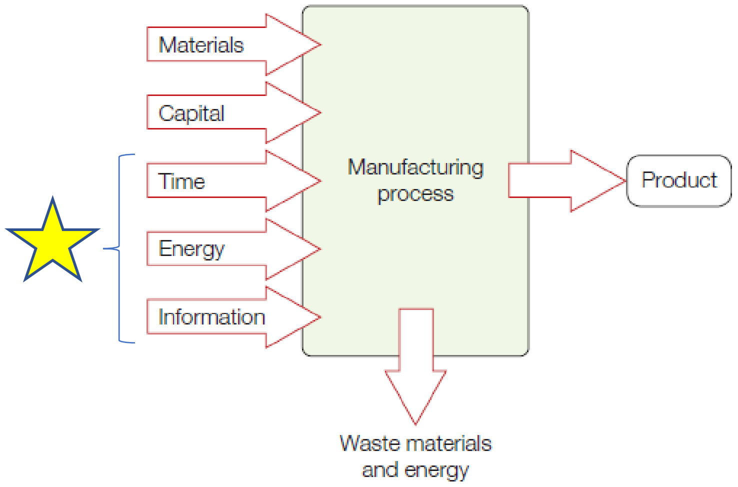


Reference: Ashby, M.F., Materials Selection in Mechanical Design, Elsevier, 2011

COST MODELLING – BOTTOM-UP ESTIMATION

- Overhead cost:

$$C_4 = \frac{\dot{C}_{oh}}{\dot{n}}$$



- Where: $\dot{C}_{oh}$ = overhead rate ($/hr)

Note: the overhead rate includes a variety of overhead sources like labor, energy, rent, marketing, sales, etc.

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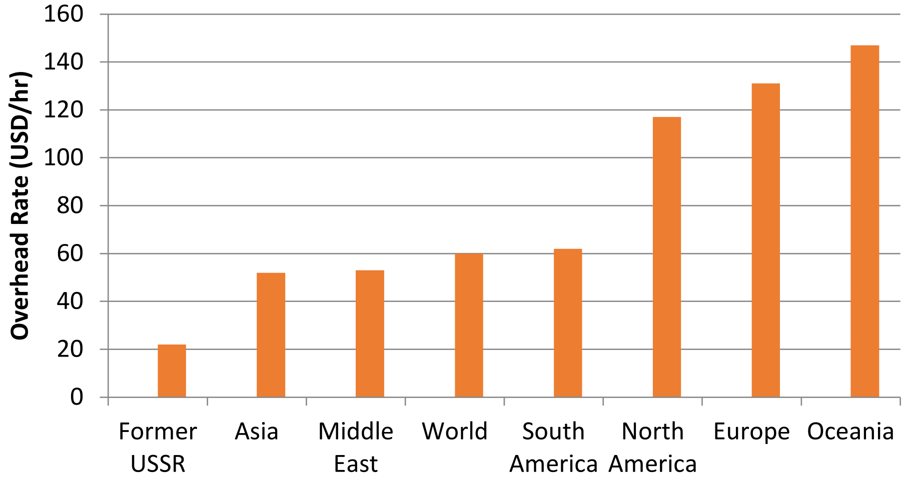
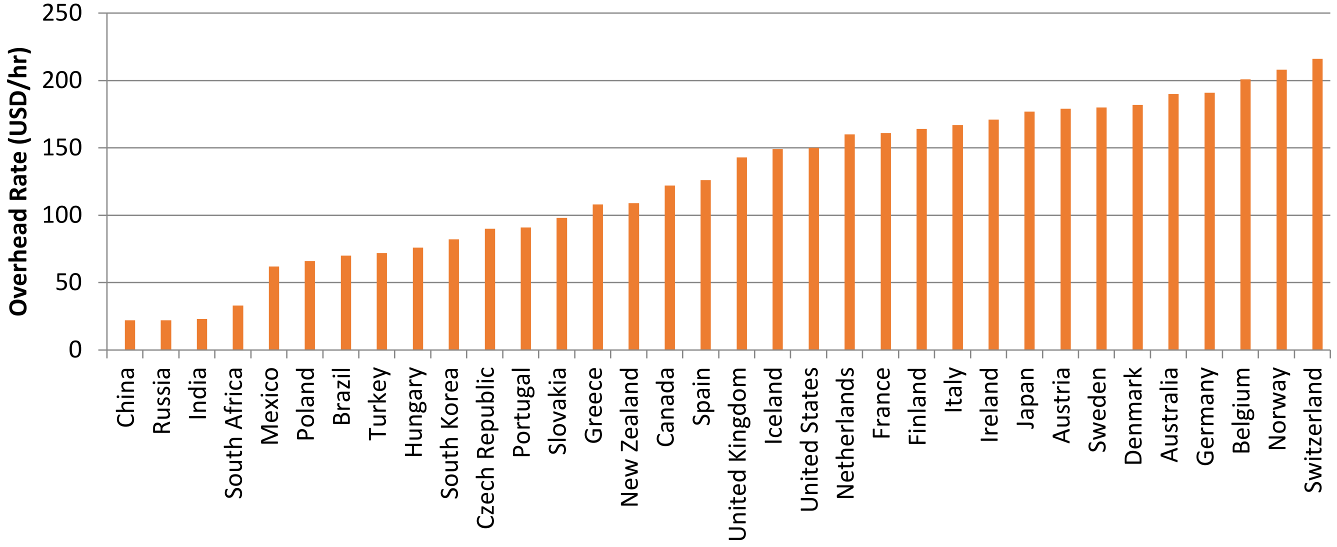
COST MODELLING – BOTTOM-UP ESTIMATION

- Overhead rates (2017):





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Reference: Granta CES Selector 2017, help manual

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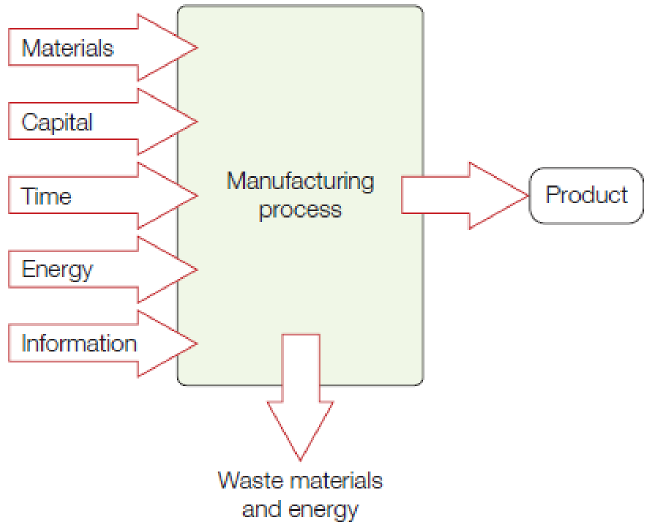
COST MODELLING – BOTTOM-UP ESTIMATION

- Total cost: $C = \frac{mC_m}{(1-f)} + \frac{C_t}{n}\left\{ceiling\left(\frac{n}{n_t}\right)\right\} + \frac{1}{\dot{n}}\left(\frac{C_c}{Lt_{wo}} + \dot{C}_{oh}\right)$



Reference: Ashby, M.F., Materials Selection in Mechanical Design, Elsevier, 2011

EXAMPLE

- Let's use the cost model that was just presented in the following example
- A company is proposing to make a carbon fibre automotive wheel and is considering two processes:
  - Prepreg/autoclave processing
  - Resin transfer moulding (RTM)
- Let's compare the cost of each

Koenigsegg wheel made with prepreg/autoclave

Carbon Revolution wheel made with RTM

EXAMPLE

- Let's start with the prepreg case first
- We'll calculate the material costs first

- Here are the inputs:
  - Mass of wheel: 7.5 kg
  - Cost of prepreg: $100/kg
  - Assume a scrap rate of 10%

$$C_1 = \frac{mC_m}{(1-f)} = \frac{(7.5\,kg)(100\,\frac{\$}{kg})}{(1-0.10)} = \$833$$

EXAMPLE

- Now let's calculate the tooling (dedicated) costs

- Here are the inputs:
  - Tool: $15,000
  - Number of parts we can get out of the tool: 1000
  - Production run size: 1 (let's start with 1 then look at volume)

$$C_2 = \frac{C_t}{n}\left\{ceiling\left(\frac{n}{n_t}\right)\right\} = \frac{\$15000}{1000}\left\{ceiling\left(\frac{1}{1000}\right)\right\} = \$15{,}000$$

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EXAMPLE

- Now let's calculate the capital equipment (non-dedicated) costs

- Here are the inputs:
  - Autoclave: $250,000
  - Rate: ~4 hours per part = 0.25/hour
  - Load factor: 0.75
  - Write off time: 5 years

$$C_3 = \frac{1}{\dot{n}}\left(\frac{C_c}{Lt_{wo}}\right) = \frac{1}{0.25/hr}\left(\frac{\$250000}{0.75 * (5 * 24 * 365)}\right) = \$30$$

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EXAMPLE

- Now let's calculate the overhead costs

- Here are the inputs:
  - Overhead rate: $122/hour

$$C_4 = \frac{\$122}{0.25} = \$488$$

EXAMPLE

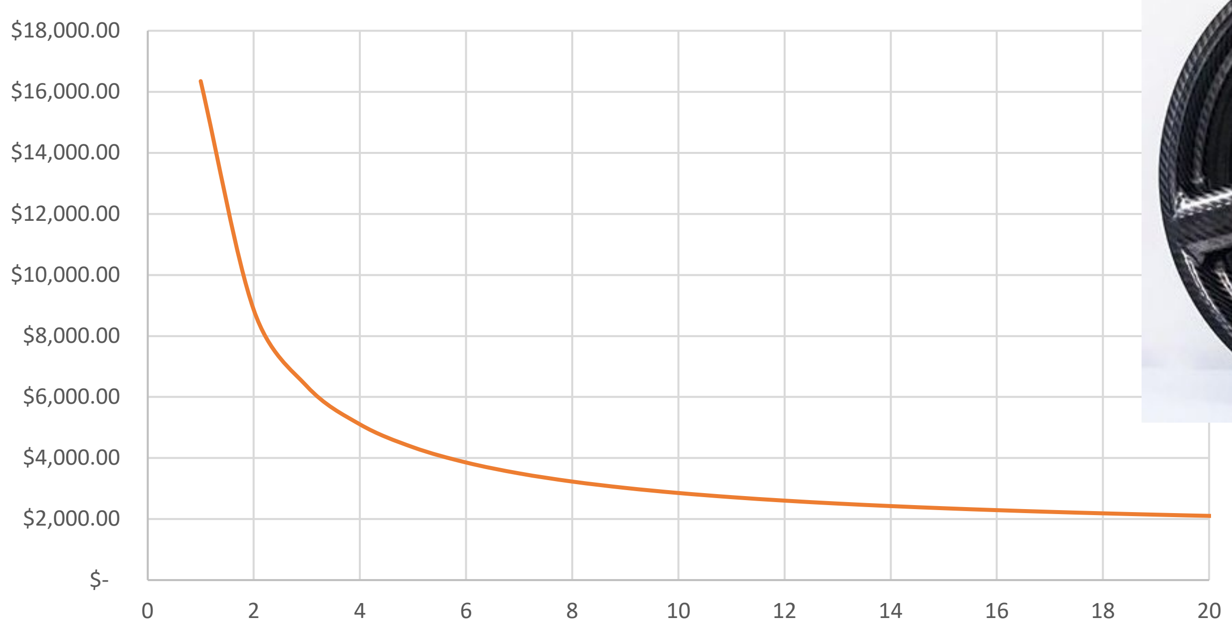
- Now sum it up to get a cost per part:

$$C = \underbrace{\$833}_{\text{Material}} + \underbrace{\$15{,}000}_{\text{Tooling}} + \underbrace{\$30}_{\text{Capital}} + \underbrace{\$488}_{\text{Overhead}} = \$16{,}352$$

- But naturally the cost per part drops significantly as the volume increases…

EXAMPLE

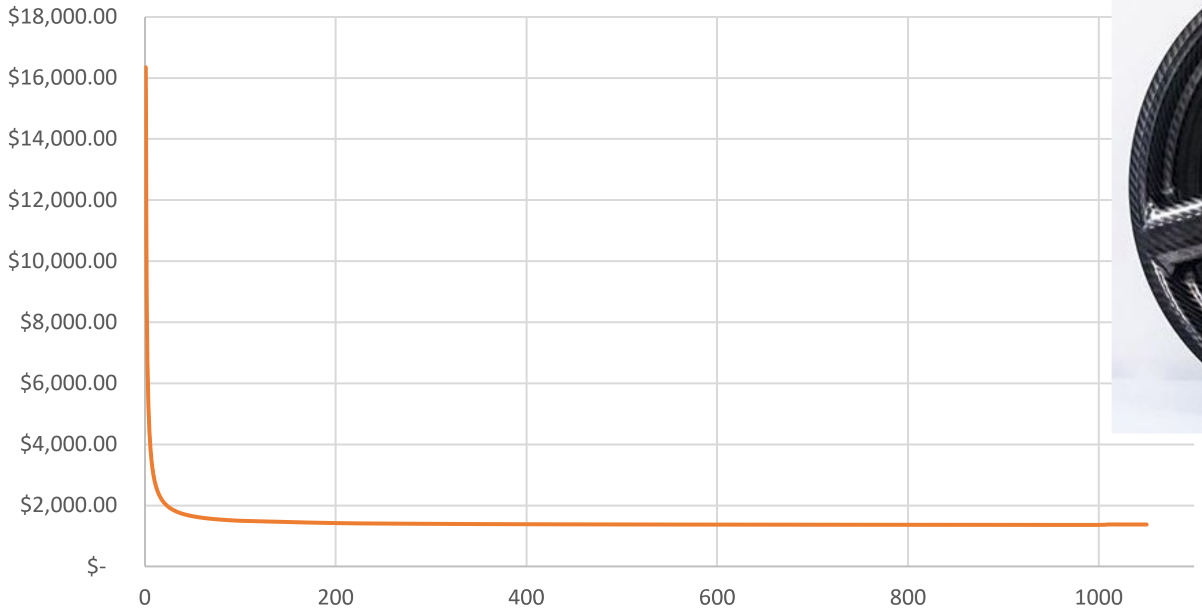
- But naturally the cost per part drops significantly as the volume increases…



- Cost drops very quickly at first, then slows down

EXAMPLE

- But naturally the cost per part drops significantly as the volume increases…



- Bottoms out around $1370/part

EXAMPLE

- Now let's look at the RTM case
- Inputs are same as previous case, aside from:
  - Cost of material: \$30/kg
  - Tool: \$150,000
  - Press: \$100,000
  - Rate: 4 parts/hour

- Now sum it up to get a cost per part:

Material Tooling Capital Overhead

$$C = \$250 + \$150{,}000 + \$1 + \$31 = \$150{,}281$$

EXAMPLE

- Now let's look at the RTM case
- Inputs are same as previous case, aside from:
  - Cost of material: $30/kg
  - Tool: $150,000
  - Press: $100,000
  - Rate: 4 parts/hour

- Now sum it up to get a cost per part:

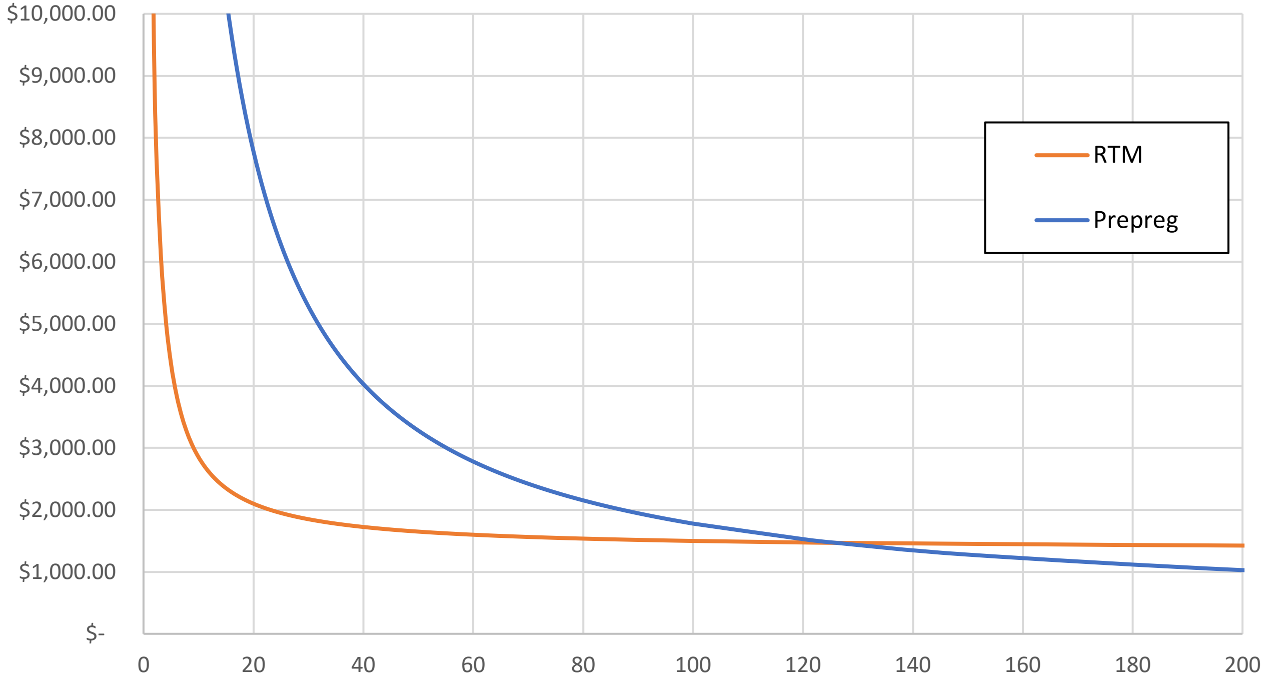
$$C = \underbrace{\$250}_{\text{Material}} + \underbrace{\$150{,}000}_{\text{Tooling}} + \underbrace{\$1}_{\text{Capital}} + \underbrace{\$31}_{\text{Overhead}} = \$150{,}281$$

- But naturally the cost per part drops significantly as the volume increases…
- Any guesses on how the two fare over time based on the numbers shown? When do they cross over?

n = 100, 500, 1000, 2500?

EXAMPLE

- Comparison over production quantity



Prepreg wheel

RTM wheel

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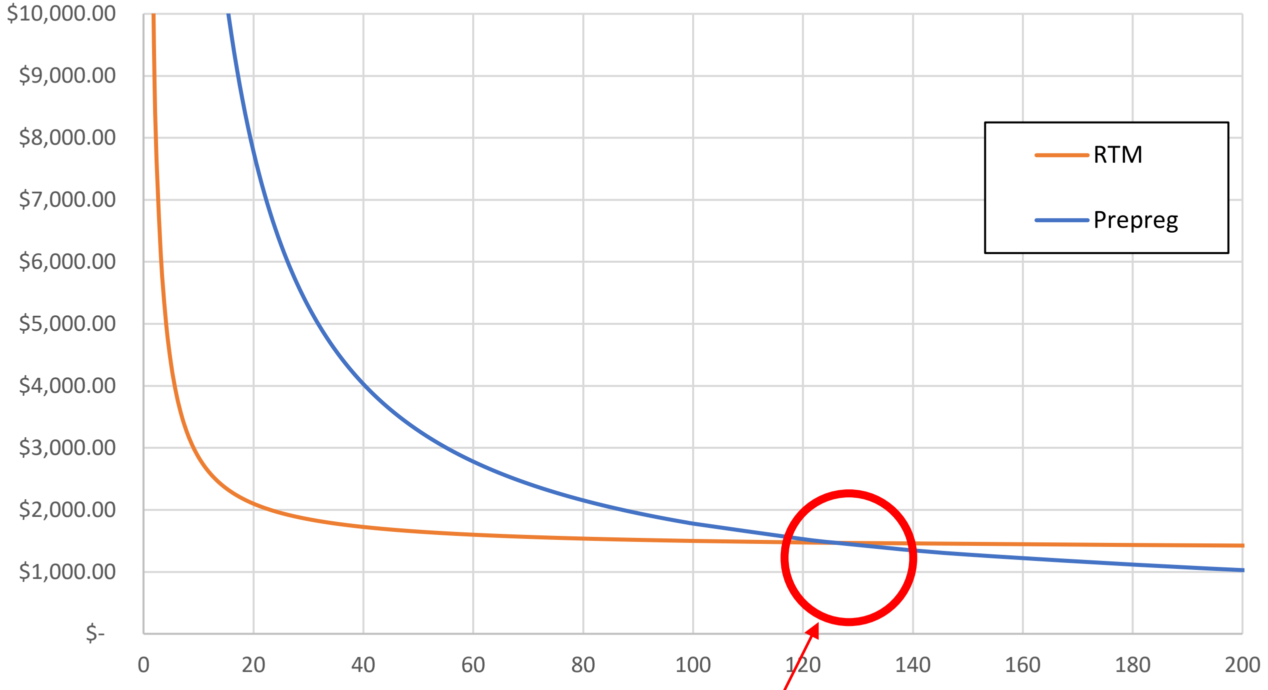
EXAMPLE

- Comparison over production quantity
- Prepreg ~$1370/part
- RTM ~$430/part



Cross over point at ~125 parts

Prepreg wheel

RTM wheel

Thank you for joining us!

The next session is:

Parameters for Structural Analysis of Composites

February 10, 2021 @ 9:00 am PT

Questions?

For more information on future dates and times visit:

compositeskn.org