GREEN AVIATION MANUFACTURING: Addressing Environmental Impacts with MDO Methodologies

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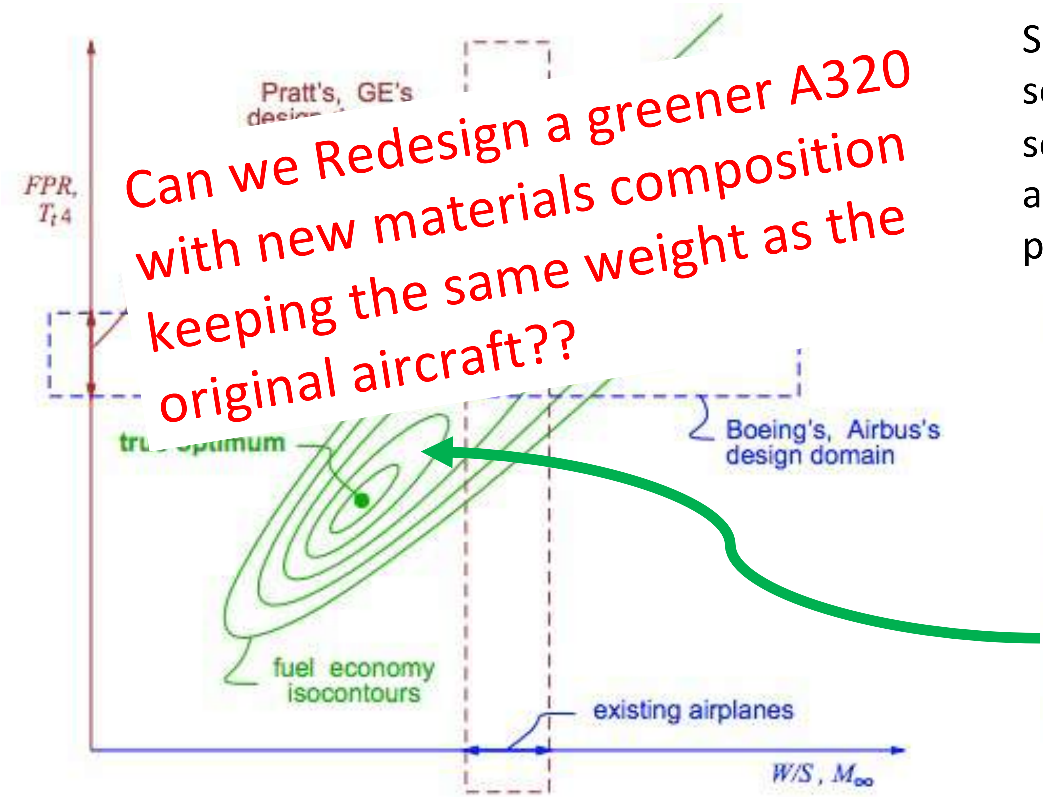
AeroBest 2025

Sustainable Aviation (SA)

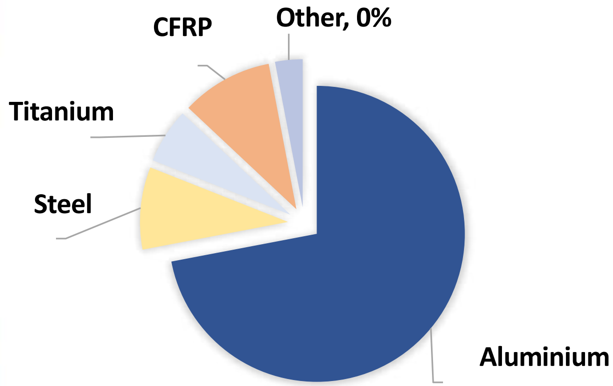
https://aero.engin.umich.edu/research/research-areas/sustainable-aviation/

Sustainable aviation is a multi-disciplinary field that seeks solutions to improve the environmental and societal impacts of air transportation. It aims to reduce aviation's contribution to climate change through new practices and radical innovation

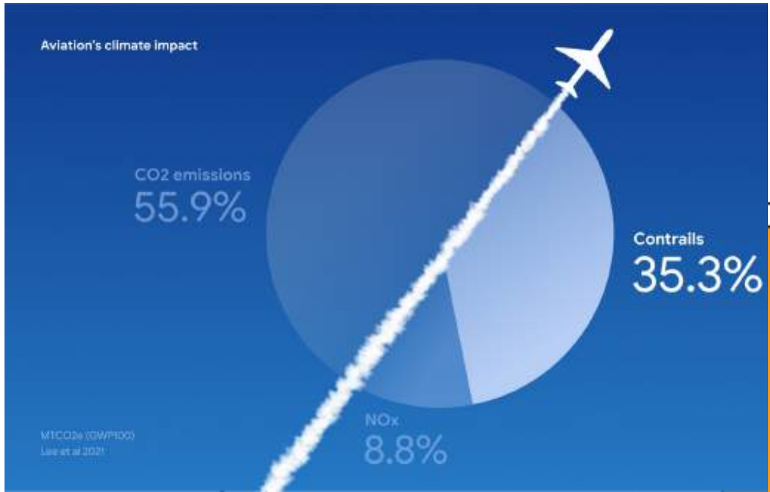
Can we Redesign a greener A320 with new materials composition keeping the same weight as the original aircraft??

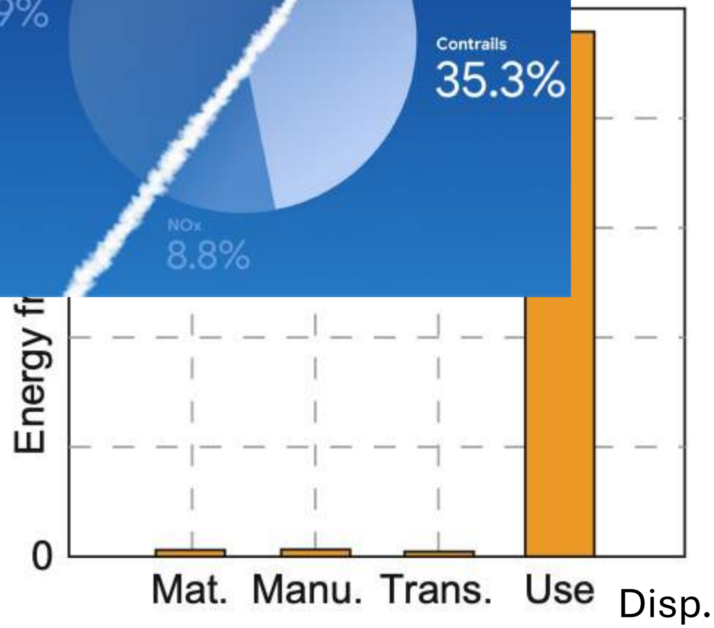


Low-Order Modeling for Conceptual Aircraft Design and Development of the D8 Transport Concept
Mark Drela MIT Aero & Astro



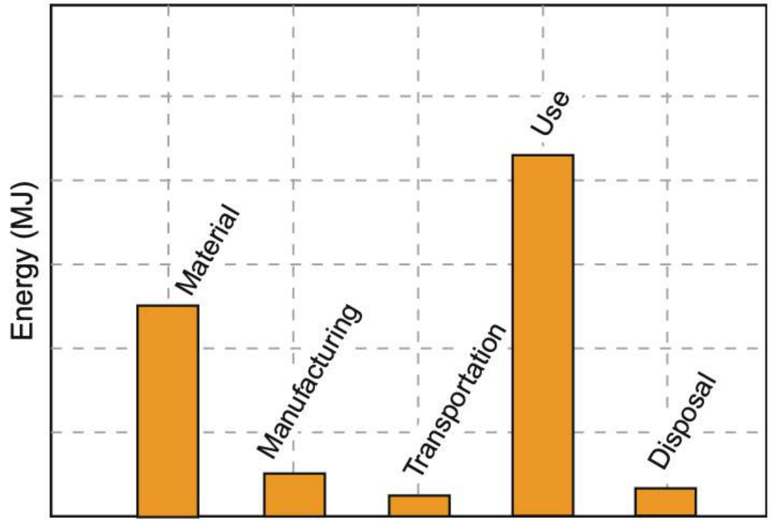
Energy $\propto$ CO_2 footprint





CES Edupack
Prof. Ashby

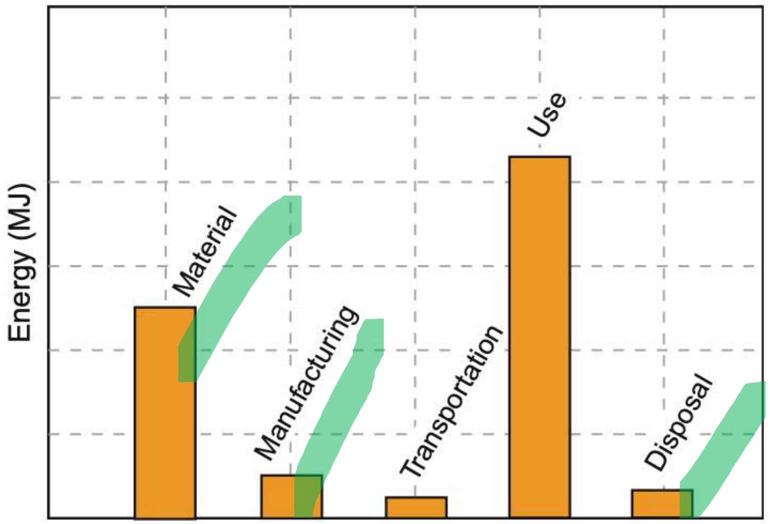
Future Sustainable Air vehicule



Breakdown of energy into that associated with each life phase

Hydrogen, SAF, Electric/Hybrid Propulsion...

Our idea is to define a Material-based approach for OAD (without physical simulations)



Breakdown of energy into that associated with each life phase

Summary

1. Eco-design, LCA & MDAO
2. Environmental assessment of aircraft manufacturing and production
3. A material-based approach in AD
4. Use-case scenario of methodology

Summary

1. **Eco-design, LCA & MDAO**
2. Environmental assessment of aircraft manufacturing and production
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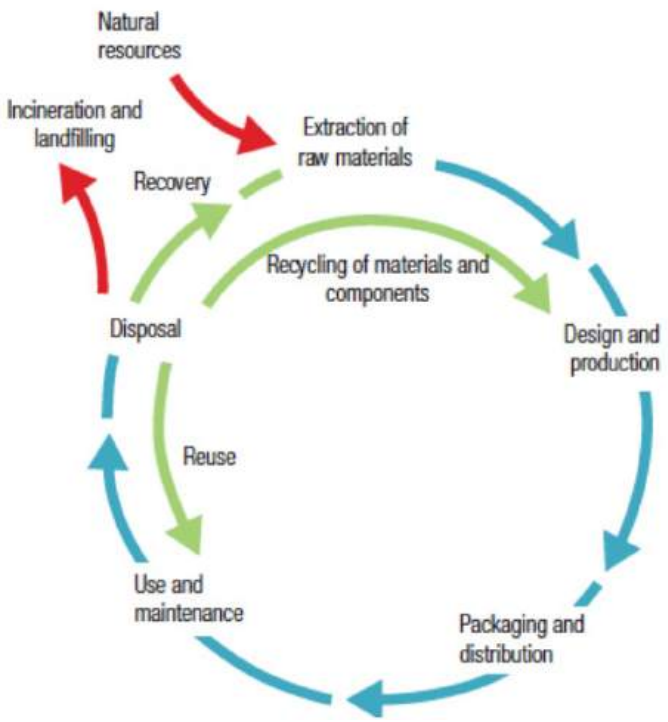
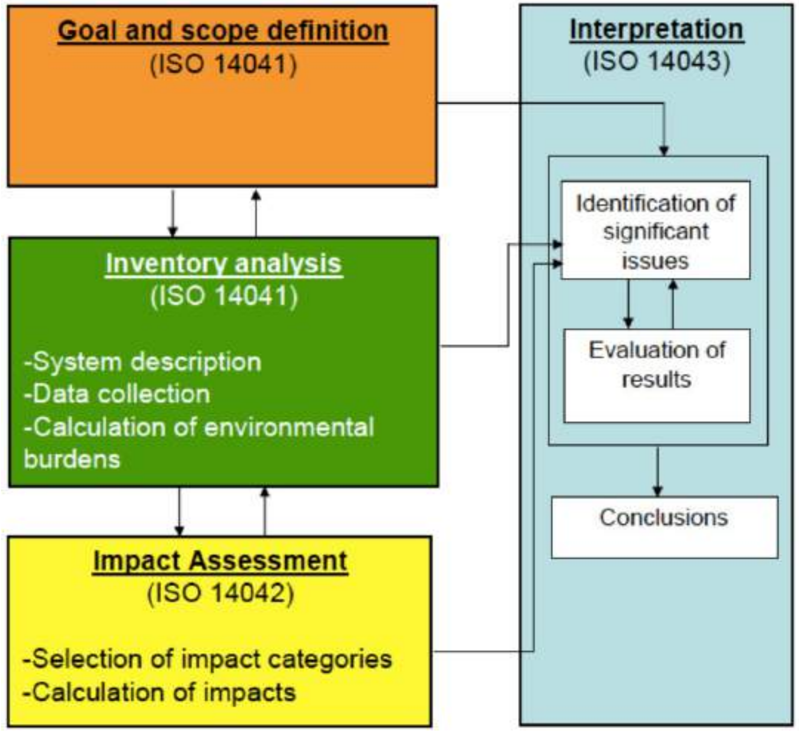
Life Cycle Assessment

ISO norm:
- Proper goal and scope definition, including functional unit
- Inventory analysis and the database problem
- Selection of impacts, and difference between raw flux, midpoint, and endpoint impacts





Eco-design and MDAO

MDAO

- Custom code or software
- Many simulations on low amounts of variables
- Engineering teams

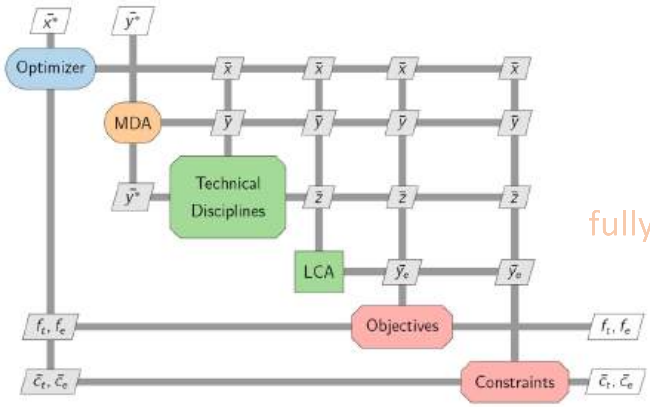
Life Cycle Assessment (LCA)

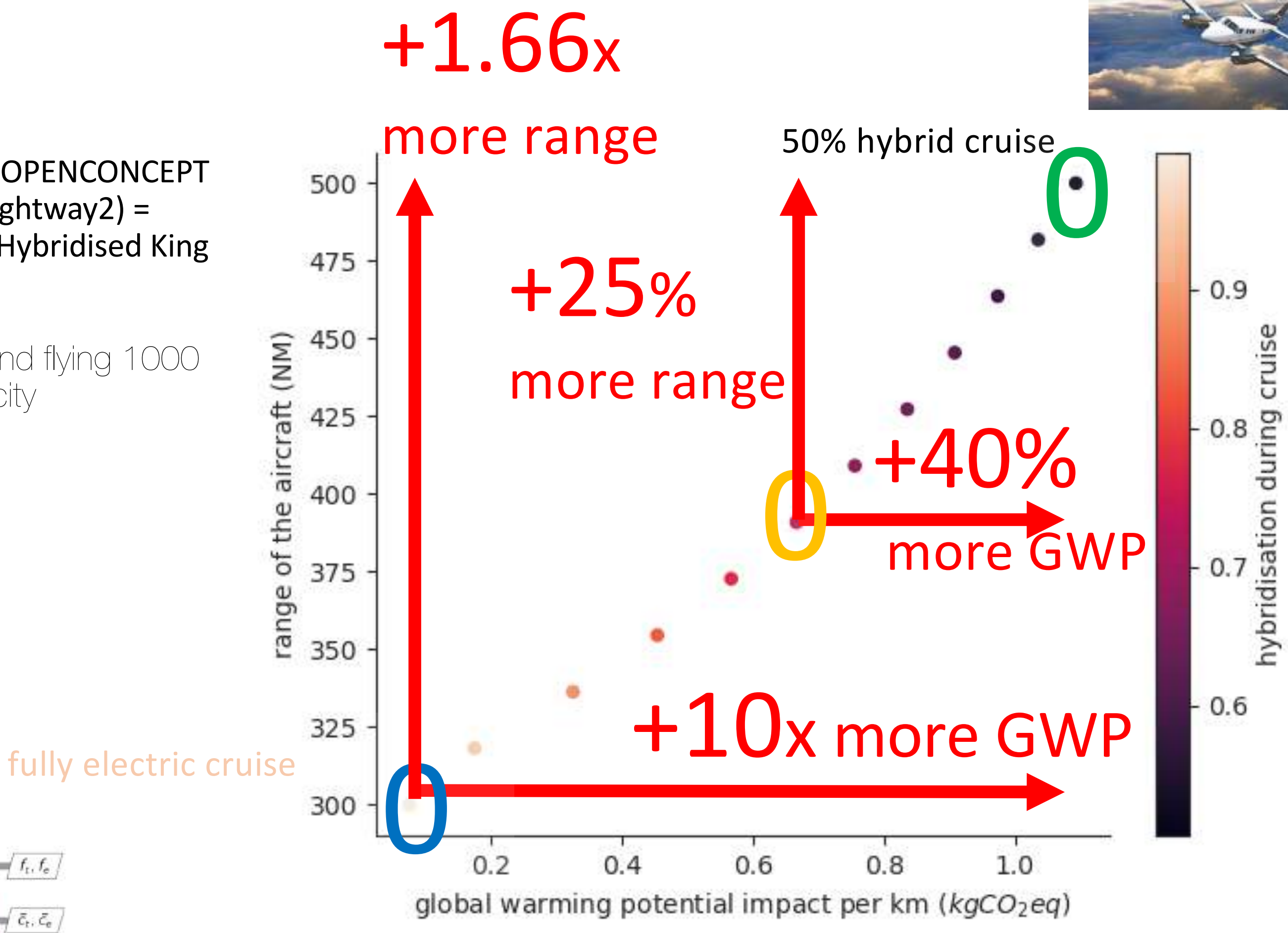
- Independent software (*OpenLCA*, *Simapro*, etc…)
- Single calls on large external databases (*Ecoinvent*, *ILCD*, etc…)
- Dedicated teams or consultancies

LCA4MDO ;)

- Aerobest 2023 : (build **PYMOO + OPENCONCEPT (OpenMDAO) + LCA4MDO (Ecoinvent+Brightway2) = Automatic Tradeoff Range / GWP for the Hybridised King Air C90GT electric aircraft**

  LCA scope include building the aircraft and flying 1000 cycles at max range with fuel and electricity
- Functional unit is a kilometre flown

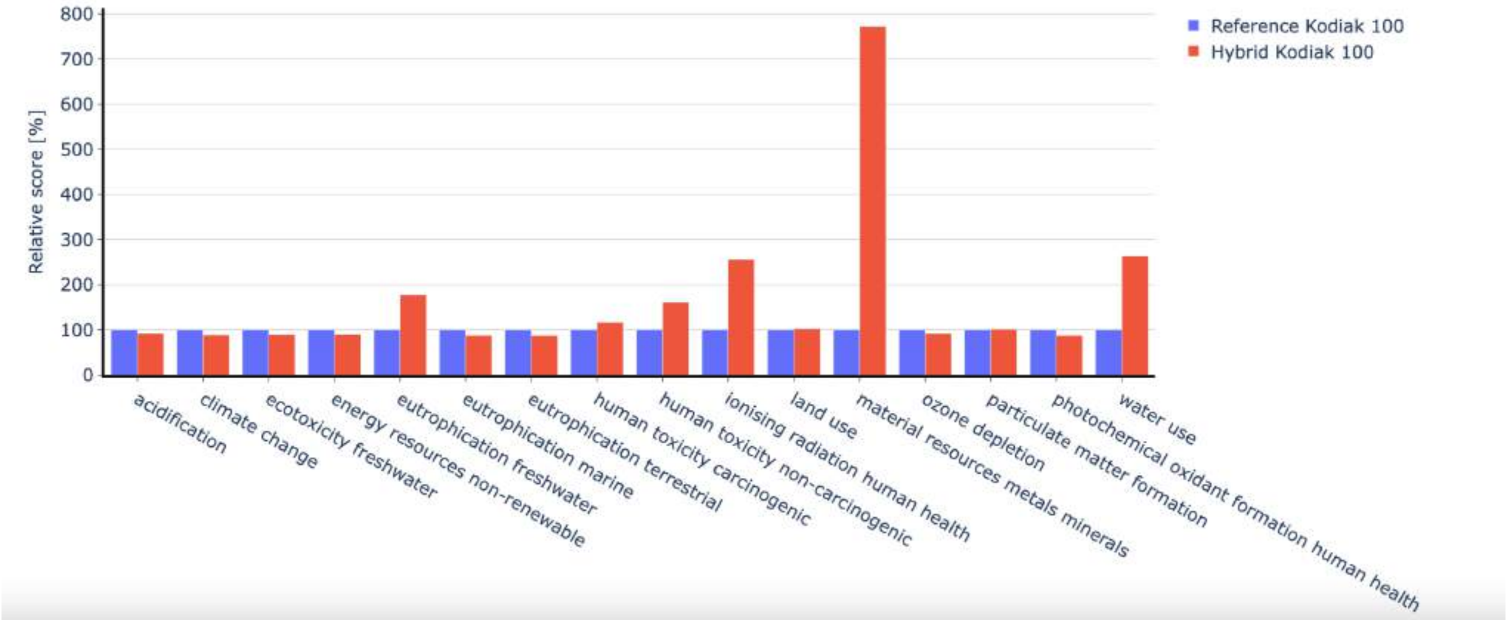




https://github.com/mid2SUPAERO/LCA4MDAO

LCA and OAD

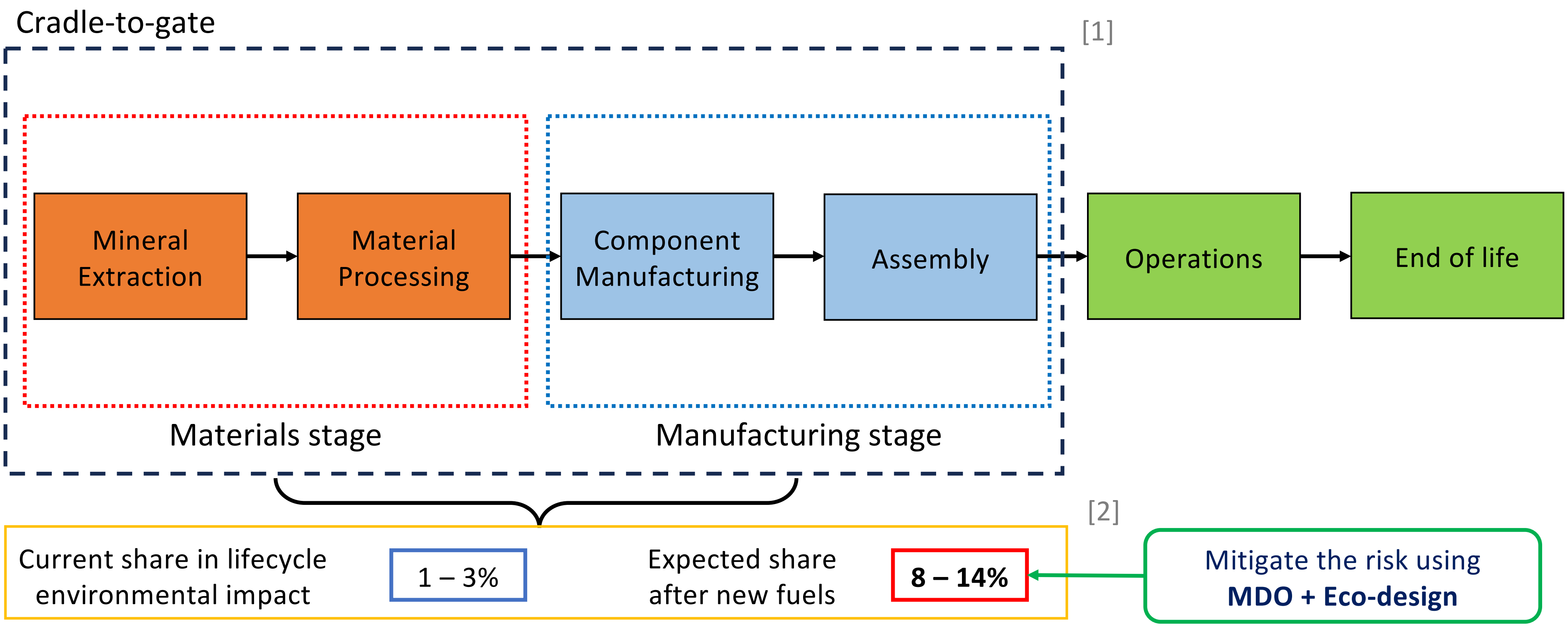
- Pollet, F., Lutz, F., Planès, T., Delbecq, S., & Budinger, M. A Comprehensive and Generic Life Cycle Assessment Tool for Overall Aircraft Design. *Available at SSRN 5211853*.



Summary

1. Eco-design, LCA & MDAO
2. **Environmental assessment of aircraft manufacturing and production**
3. A material based approach in AD
4. Use-case scenario of methodology

System boundaries

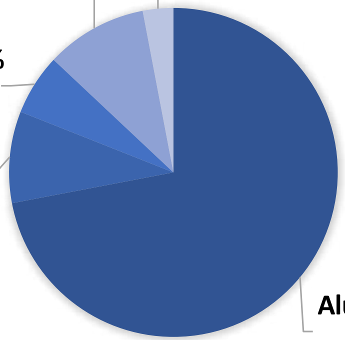


[1] E. Pierrat et al. Global environmental mapping of the aeronautics manufacturing sector. Journal of Cleaner Production, 2021.
[2] N. Thonemann et al. Towards sustainable regional aviation: Environmental potential of hybrid-electric aircraft and alternative fuels. Sustainable Production and Consumption, 2024.

Material Composition of Airframe

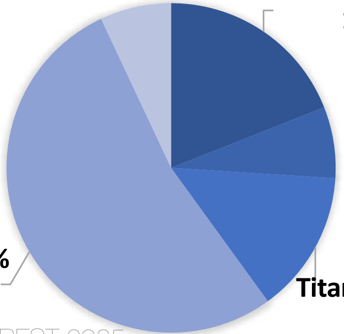
Metal airframe: e.g. a320

Source: planespotters.net



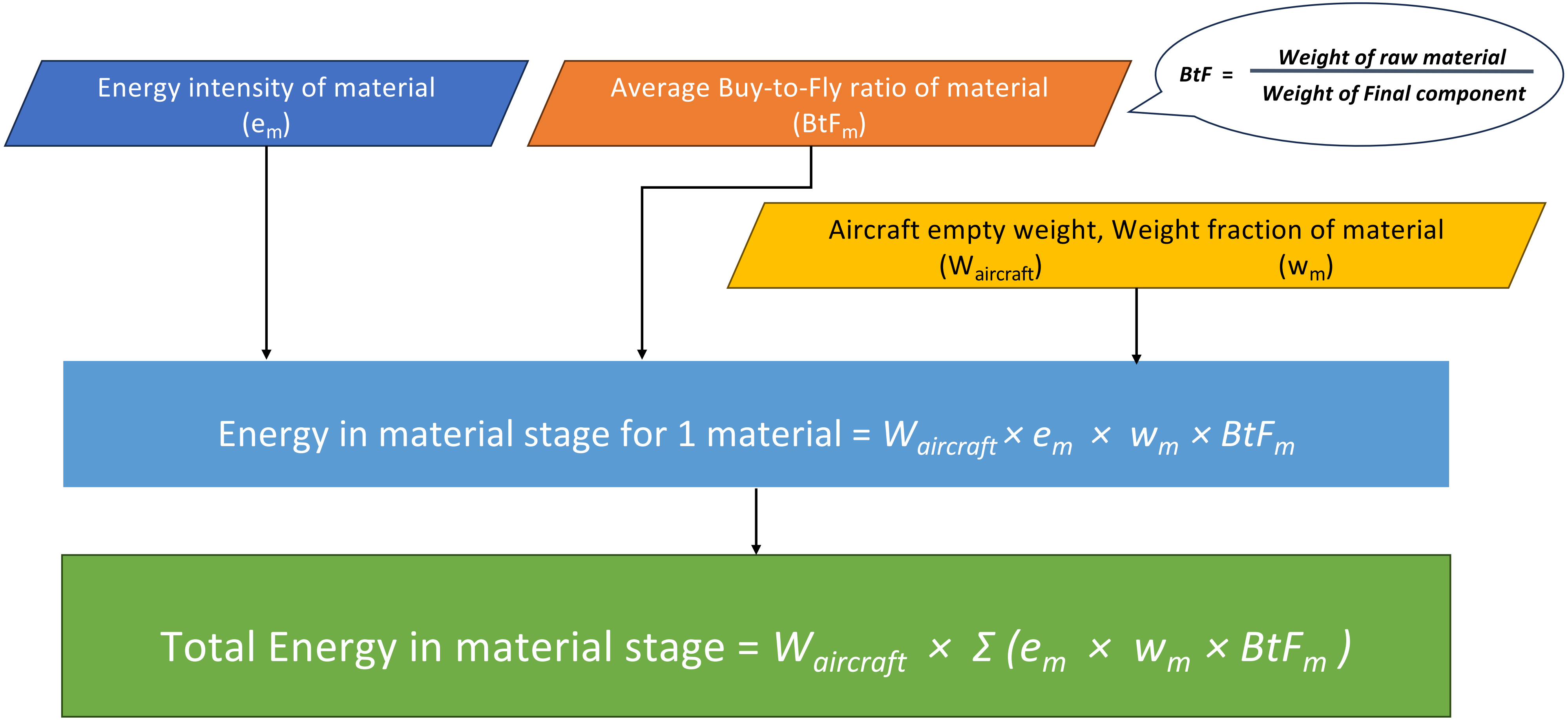
Carbon fiber airframe: e.g. a350

Source: www.airliners.net

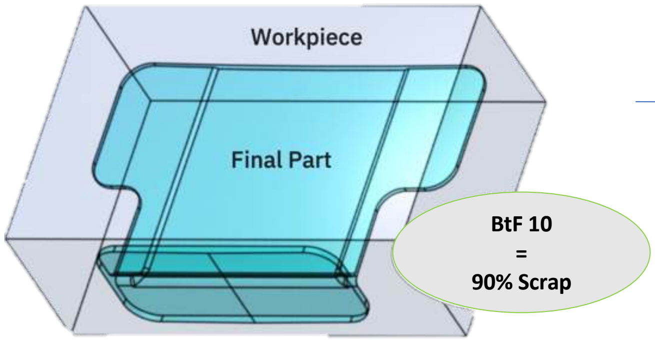


4 Main materials:
- Aluminium
- Titanium
- Steel
- CFRP

Environmental Assessment: Bottom-up approach



Environmental Assessment: Bottom-up approach



$$\textit{BtF} = \frac{\textit{Weight of raw material}}{\textit{Weight of Final component}}$$

Final part (w)

Total Waste = $w \times (BtF_m - 1)$)

Recyclable

Non-Recyclable

Non-Recyclable Waste = $w \times (BtF_m - 1) \times \mathbf{nrw_m}$)

nrw = 5% - Aluminium, Steel
15% - Titanium
100% - CFRP

Environmental Assessment: Bottom-up approach

Average Buy-to-Fly ratio of material (BtF_m)

Aircraft empty weight, Weight fraction of material ($W_{aircraft}$) (w_m)

Mfg waste in manufacturing stage for 1 material = $W_{aircraft} \times (w_m \times (BtF_m - 1))$

Total waste in manufacturing stage = $W_{aircraft} \times \Sigma (w_m \times (BtF_m - 1))$

Non-Recyclable waste in manufacturing stage = $W_{aircraft} \times \Sigma (w_m \times (BtF_m - 1) \times nrw_m)$

Environmental Assessment: Input data

[1]

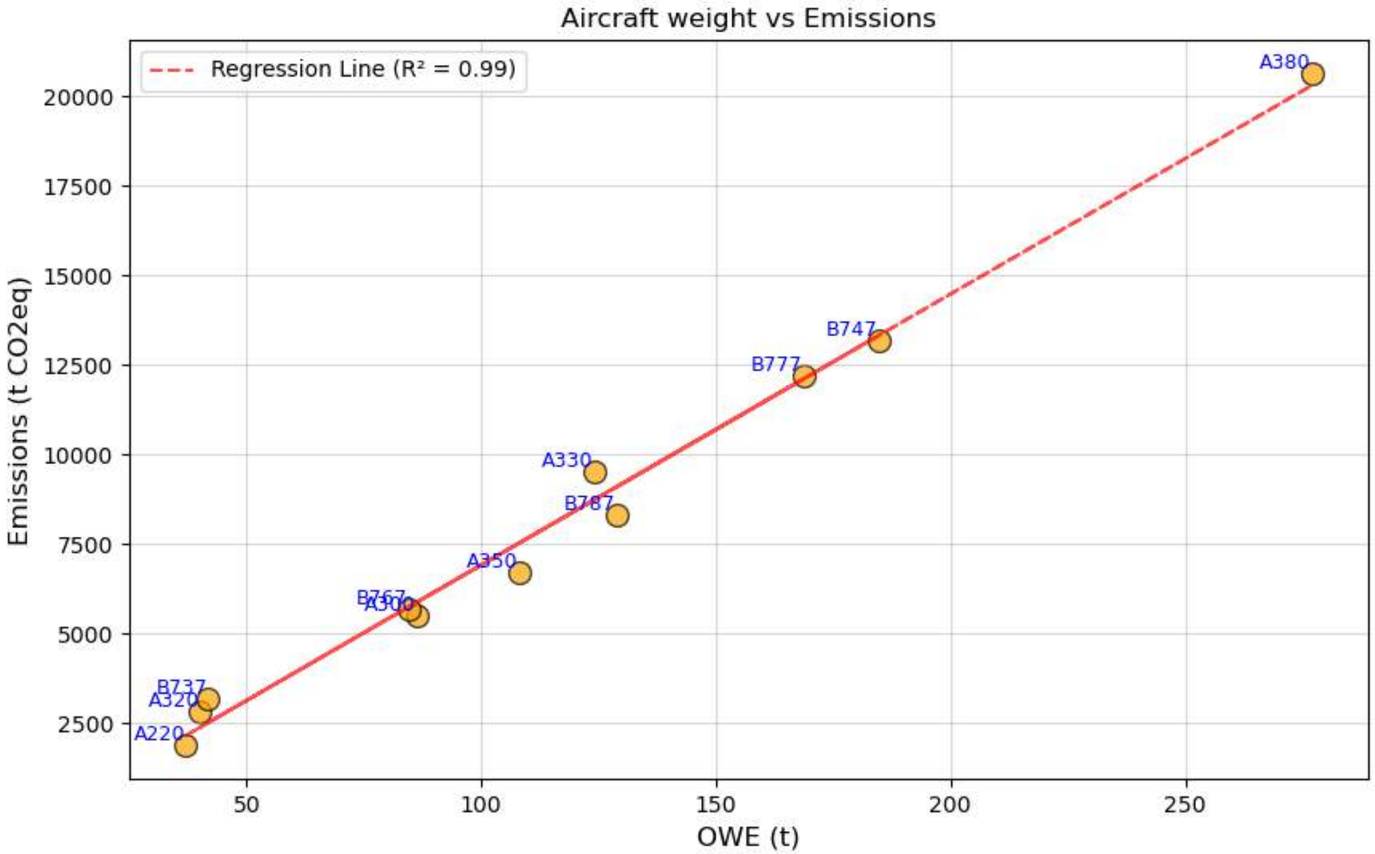
Property	Unit	Aluminium	Steel	Titanium	CFRP
BtF	kg/kg	5	6	10	1.5
Energy	MJ/kg	163	20	536	514

Energy intensive materials

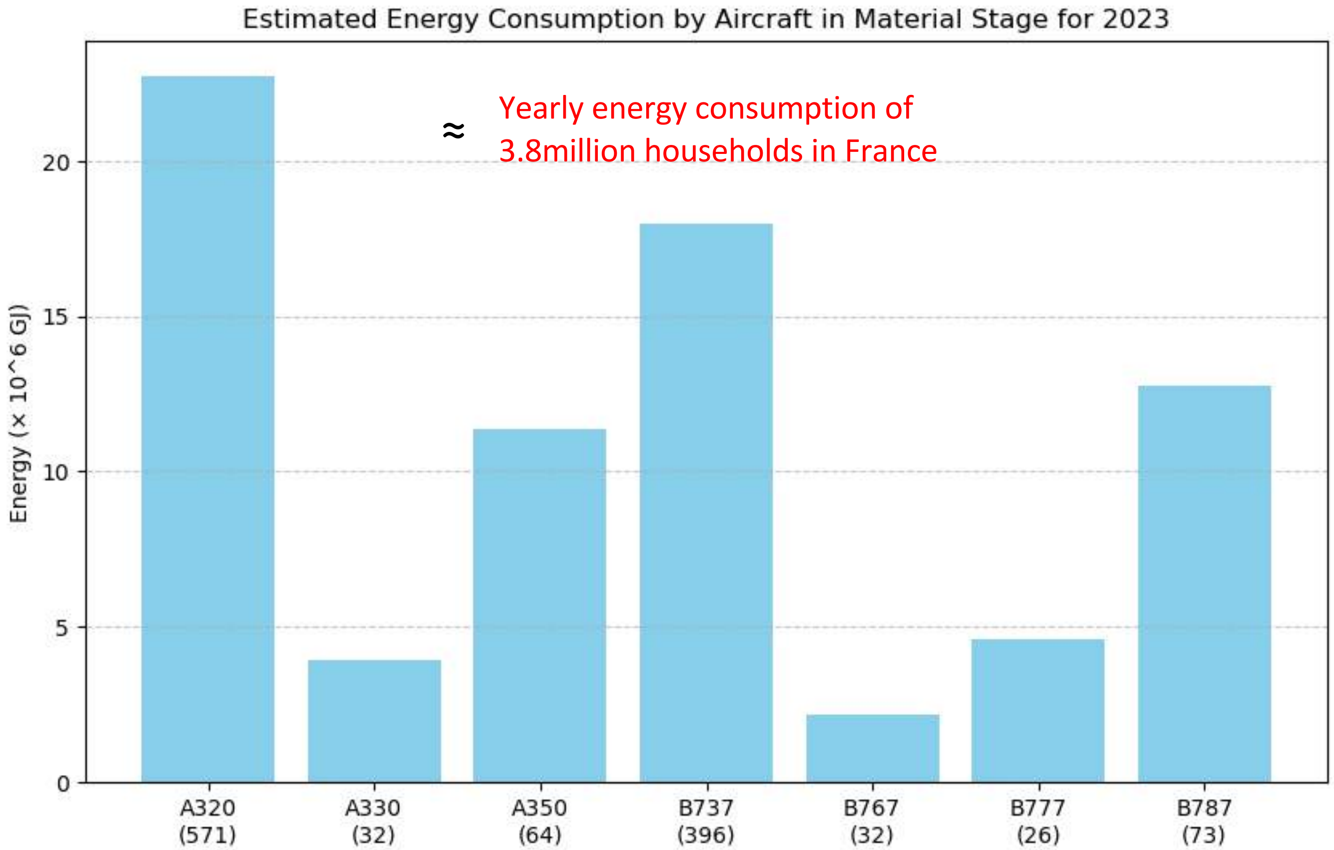
- Metals have high BtF - subtractive manufacturing
- CFRP has low BtF – Formative manufacturing

[1] Average values taken from literature. Dataset available on: github.com/mid2SUPAERO/pLCA-MDO/blob/main/Environmental_Impact_Manufacturing_Calculations.xlsx.

Environmental Assessment: Results – 1 Aircraft level



Environmental Assessment: Results – year 2023



Numbers in the bracket are aircraft deliveries in 2023

- Single aisle aircraft have highest share in energy consumption – **potential for including ecodesign approach**
- Scope for material composition selection that would **MINIMIZE energy consumption in materials**
- **Same trend for CO_2 PP**

Environmental Assessment: Results – year 2023

Numbers in the bracket are aircraft deliveries in 2023

- Despite the big difference in deliveries, **Non-recyclable waste from Single-aisle and A350/B787 is almost same**
- Scope for material composition selection that would **MINIMIZE non-recyclable waste**

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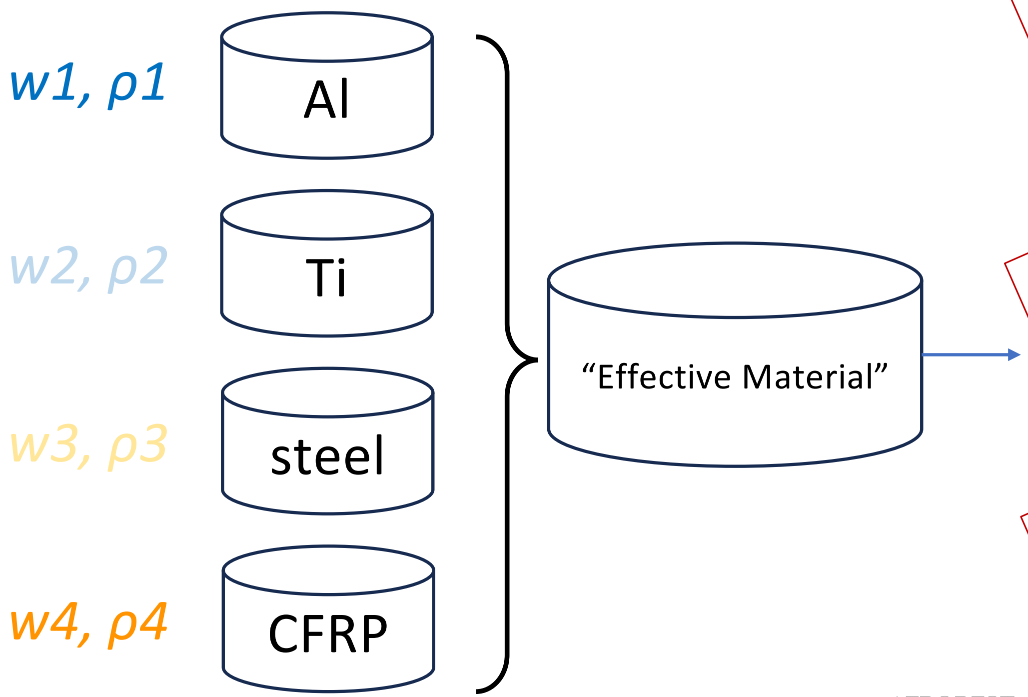
Multiobjective Optimization (discrete) problem

Conceptualize the material system as “effective material”



weight

$$\rho_{eff} = \sum(v_m\, \rho_m)$$

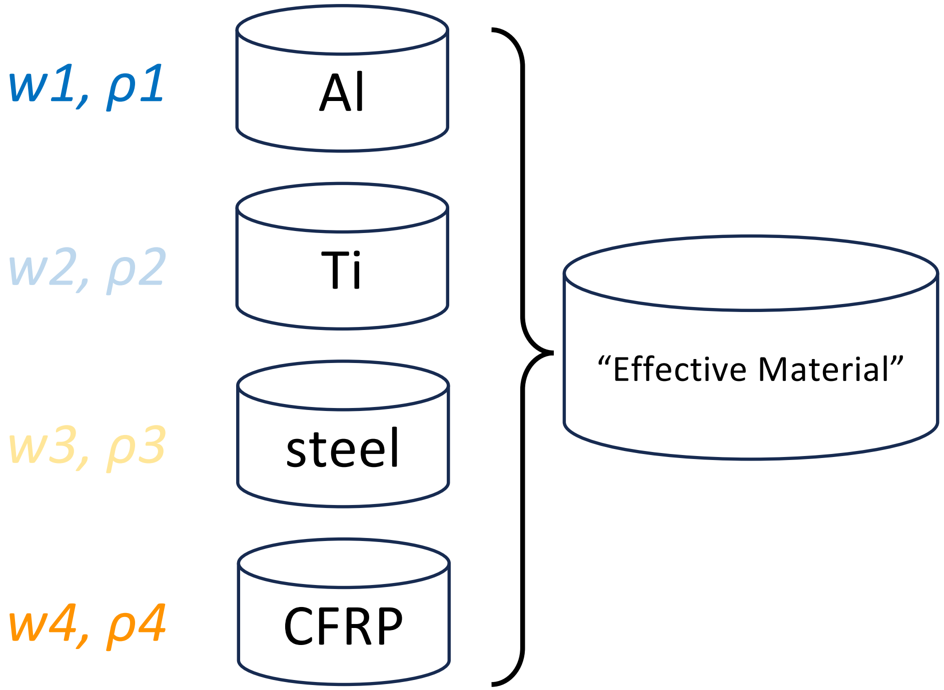
cost/energy

$$c_{eff} = \sum(w_m * BtF_m * c_m)$$

waste (nr)

$$n_{eff} = \sum(w_m(BtF_m - 1) * nrw_m)$$

Multiobjective Optimization problem



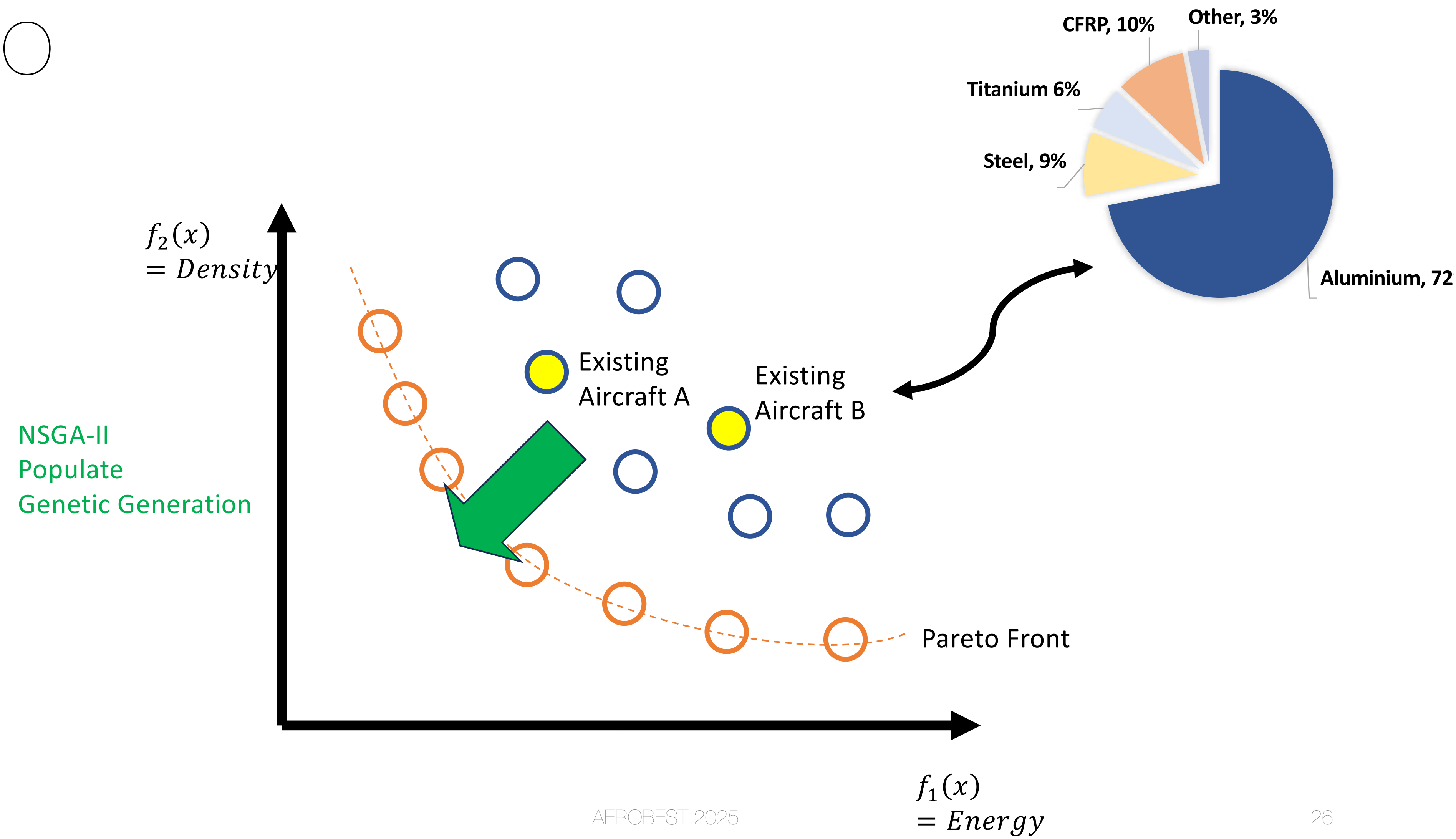
Find optimal weight fractions for minimum:

- Effective density
- Energy consumption
- Cost
- Non recyclable waste

Constraints:

- Sum of weight fractions = 100%
- Minimum quantity of materials
  (min value from aircraft compositions)
- Titanium ≥ 25% as that of CFRP
  (Literature + observation)

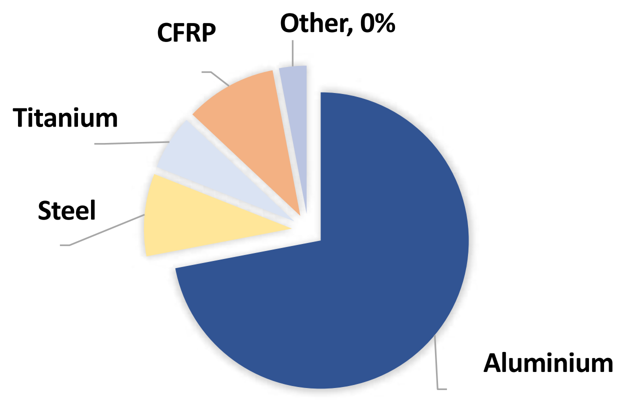
MOO

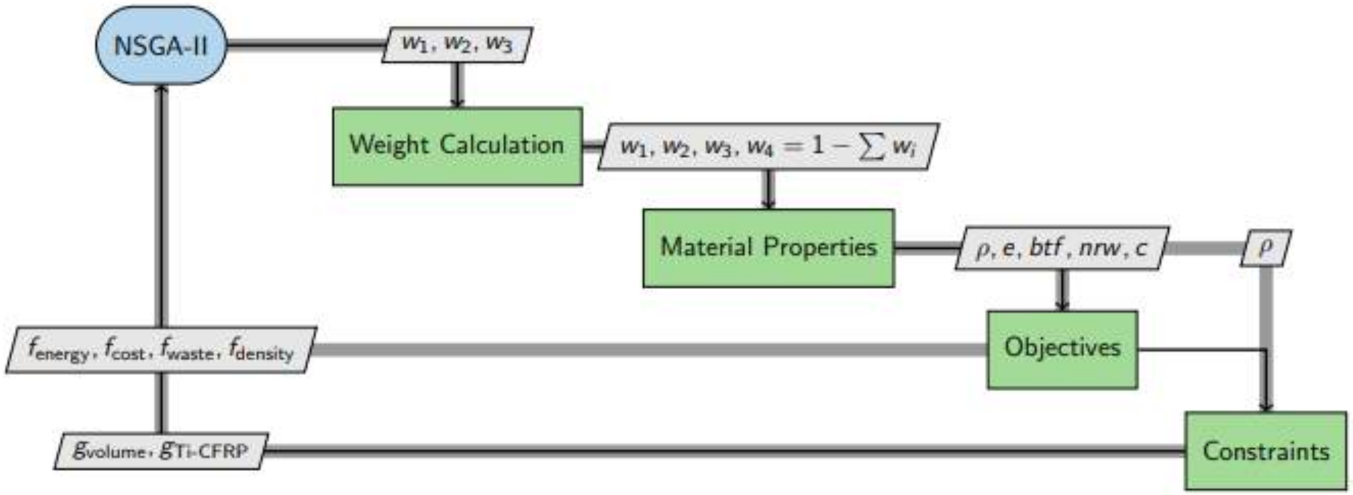


CFRP, 10%
Other, 3%
Titanium 6%
Steel, 9%
Aluminium, 72
$f_2(x)$
$= Density$
Existing
Aircraft A
Existing
Aircraft B
NSGA-II
Populate
Genetic Generation
Pareto Front
$f_1(x)$
$= Energy$

MOO for estimating

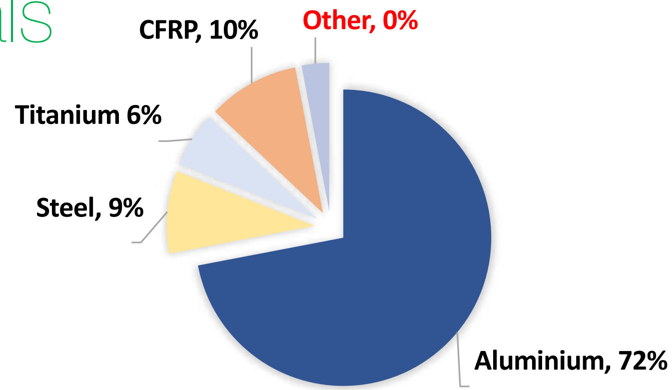
best material composition for Aircraft
. . . from 4 materials only

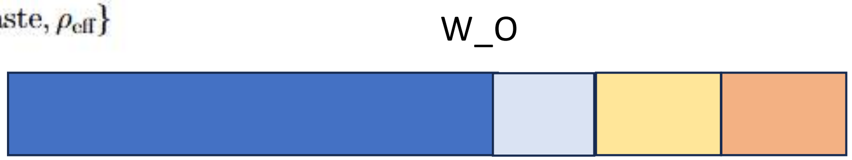




MOO with 4 objectives /4DV := 4 materials

https://pymoo.org





$$\min_{\mathbf{w}} \quad \{\text{Cost}, \text{Energy}, \text{Waste}, \rho_{\text{eff}}\}$$

subject to:

$$\sum_{i=1}^{4} w_i = 1$$

$$w_1 > 0.15, \quad w_2 > 0.01, \quad w_3 > 0.01, \quad w_4 > 0.01$$

$$w_3 > 0.25 \times w_4$$

$$\text{Energy}_m = w_m \times e_m \times BtF_m$$

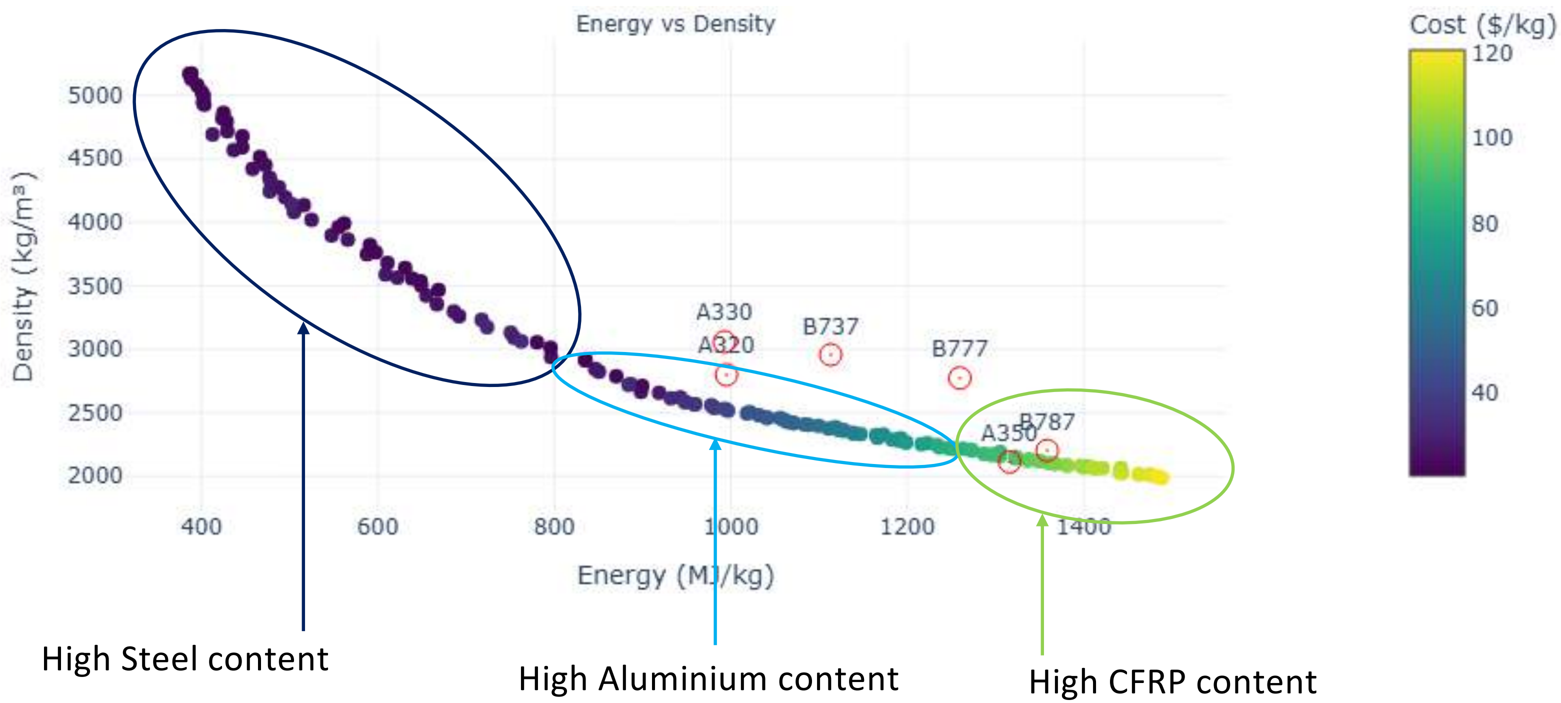
$$\text{Cost}_m = w_m \times c_m \times BtF_m$$

$$\text{Waste}_m = w_m \times (BtF_m - 1) \times nrw_m, \quad m = 1, \ldots, 4$$

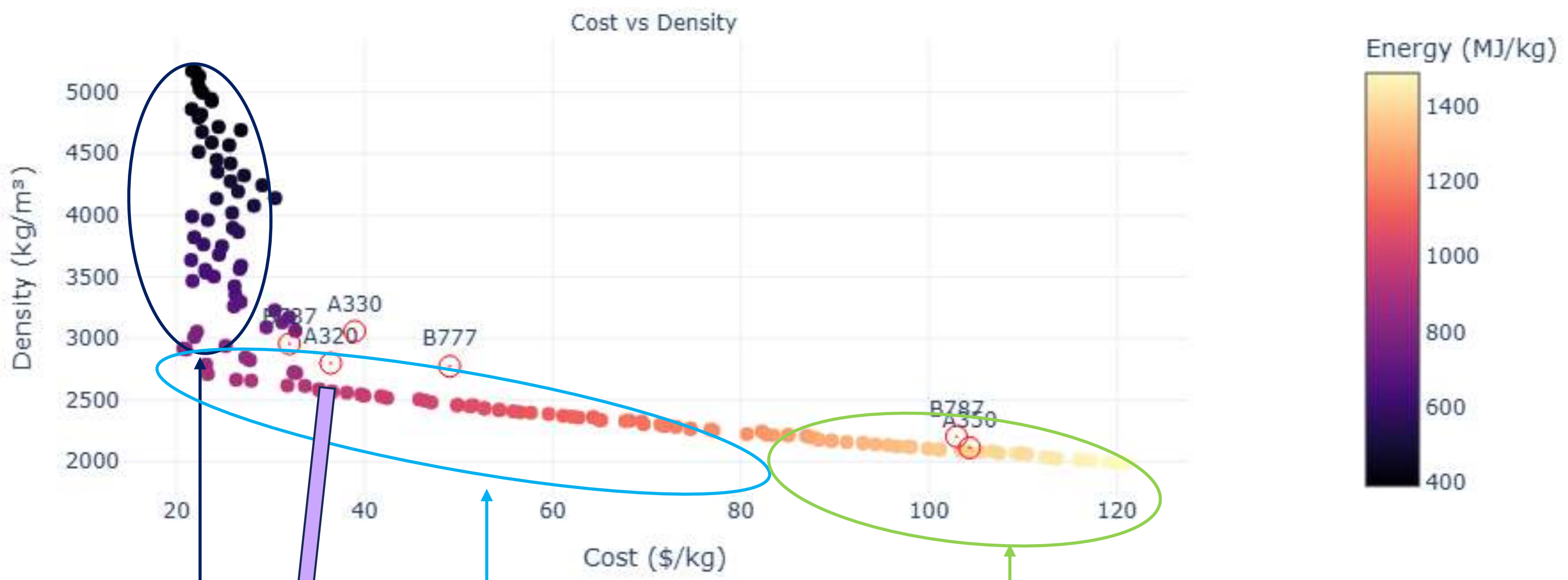
$$\text{Total impact} = \sum_{i=1}^{4} Parameter_i \quad Parameter = \{Energy, Cost, Waste\}$$:= 4 materials

$$\rho_{\text{eff}} = \sum_{i=1}^{4} x_i \rho_i$$

MOO results: Density versus Energy (+Cost)



MOO results: Density versus Cost (+Energy)



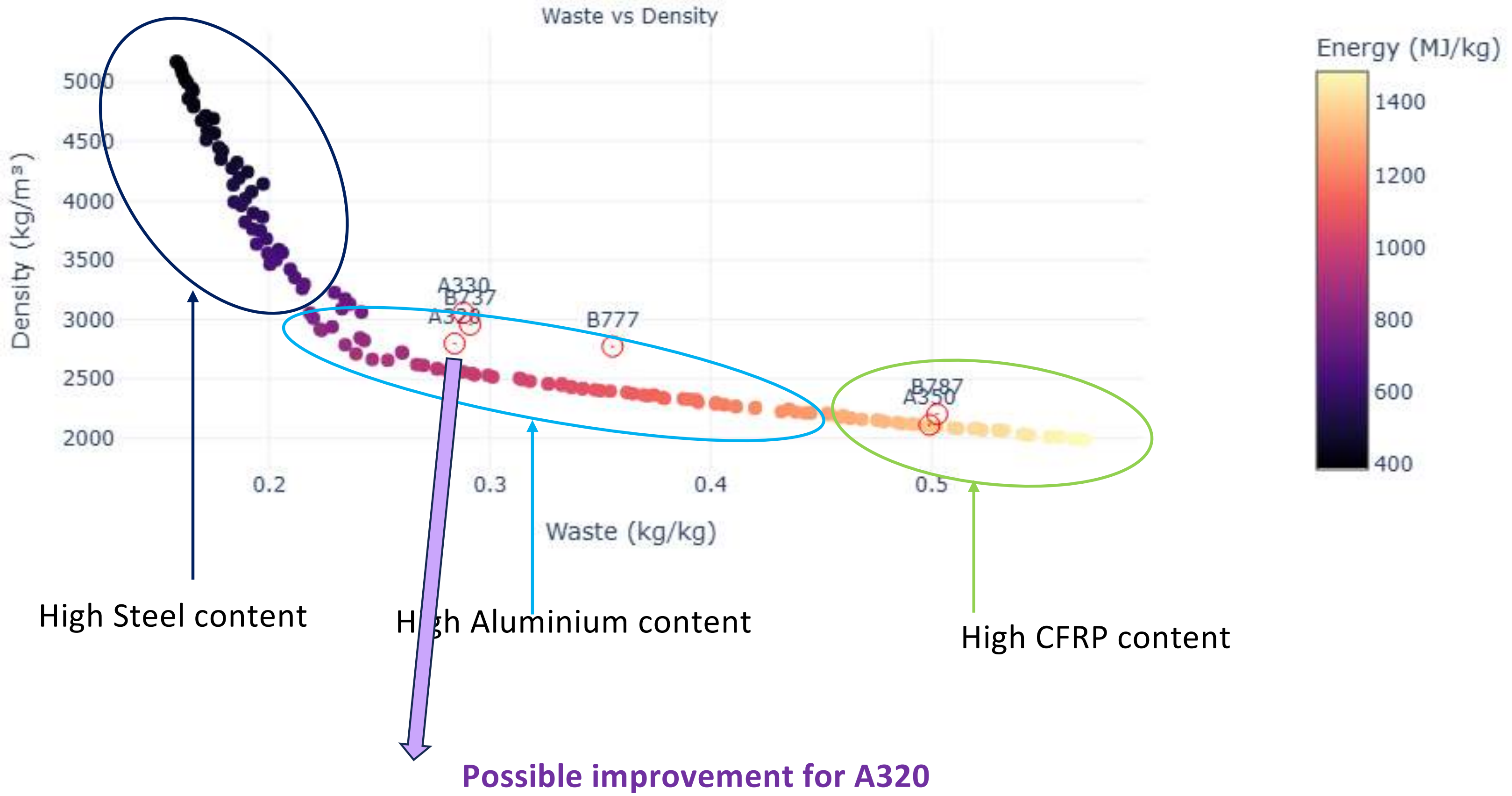
High Steel content

High Aluminium content

High CFRP content

Lower cost, possible improvement energy and density

MOO results: Density versus Waste (+Energy)



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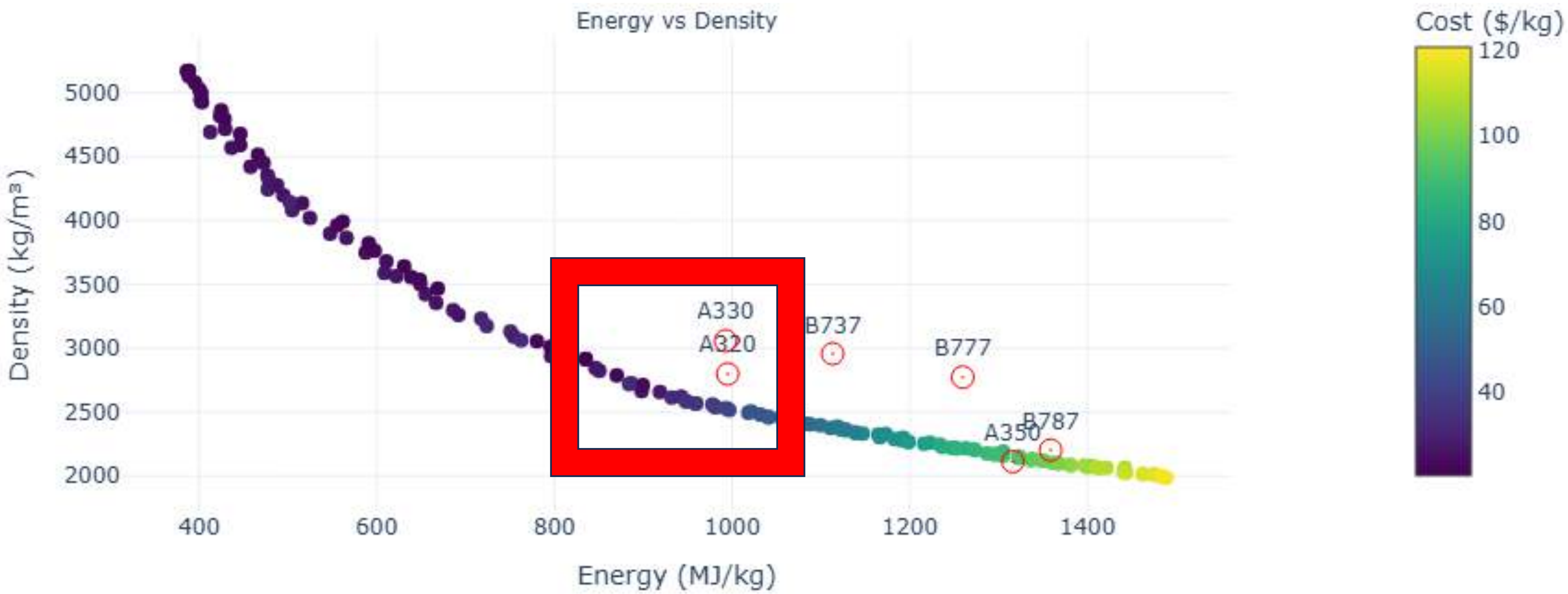
Industrial use case

- Redesign A320 with a new composition on pareto front keeping same weight as original aircraft

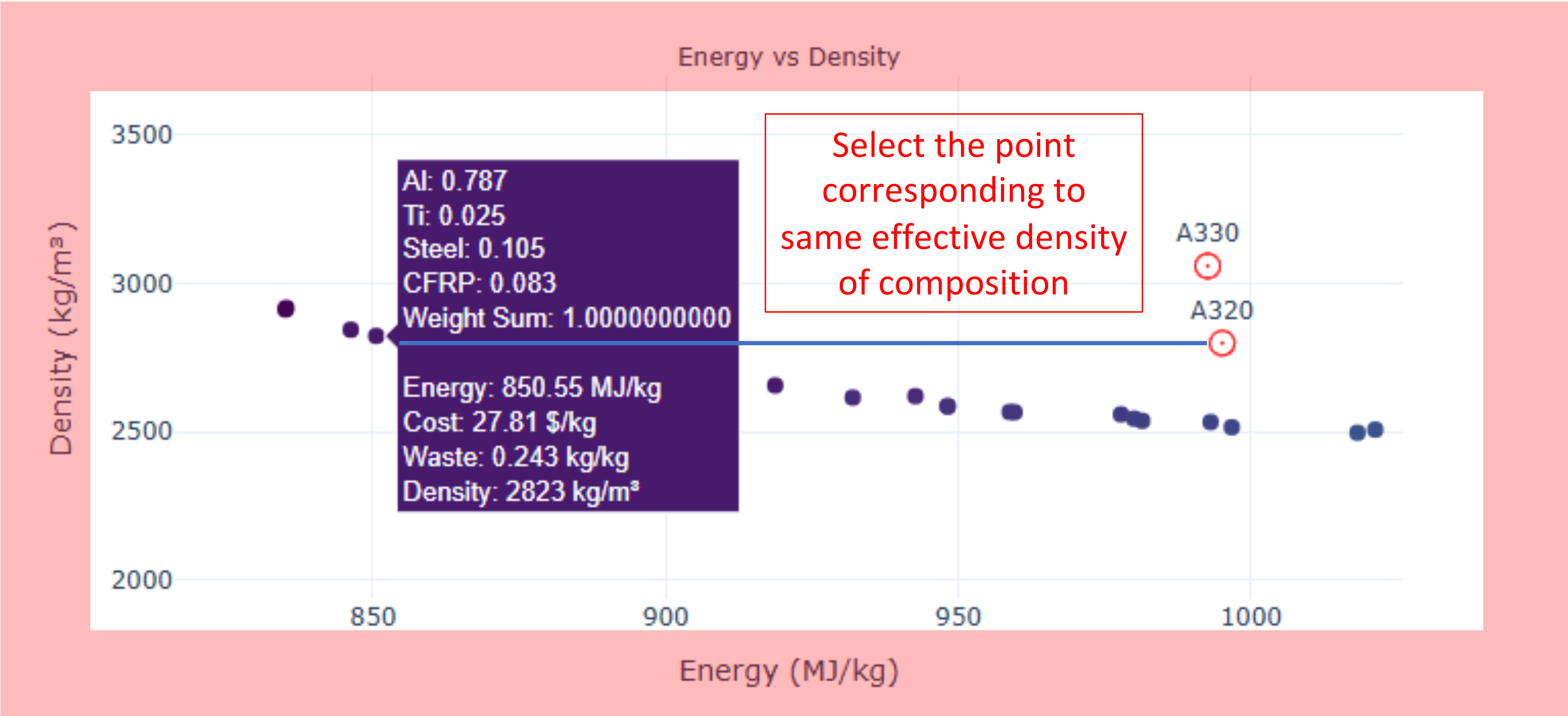
Use-case scenario (Let's zoom IN)

Redesign A320 with a new composition on pareto front keeping same weight as original aircraft



Use-case scenario

Redesign A320 with a new composition on pareto front keeping same weight as original aircraft



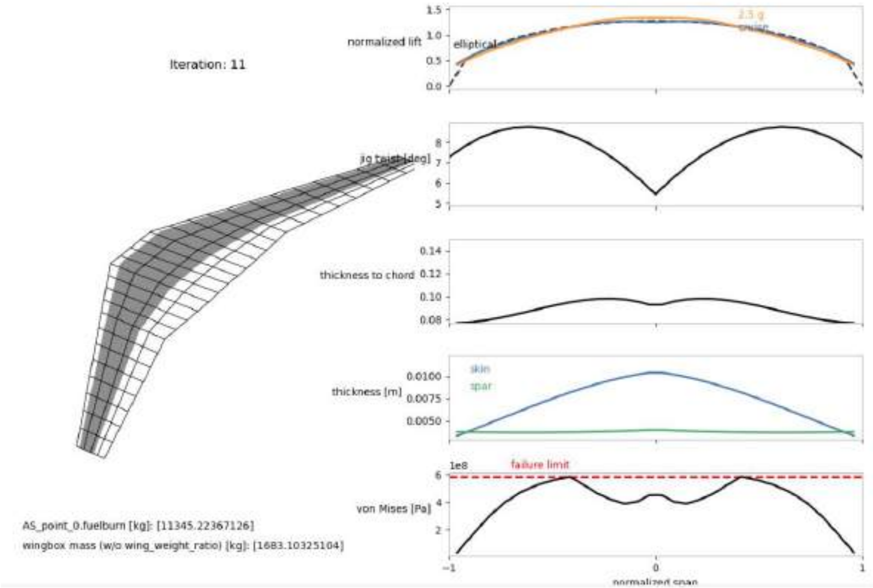
Use-case scenario A320 new: results

Less CFRP, Less Titanium, more Aluminium and Steel

Parameter	Unit	Existing composition	New Composition	% Change
Aluminium	%	72	78.7	+9%
Titanium	%	6	2.5	-58%
Steel	%	9	10.5	+17%
CFRP	%	10	8.3	-17%
Energy	GJ	39804	34040	-14%
Waste(NR)	ton	11.4	9.73	-14%
Cost	M$	1.46	1.11	-24%

Lower energy, waste and COST !!!!

Link With MDO using OAS (A320 type)



Short-Medium Range aircraft	Unit		
Material		Aluminium	CFRP
Fuel Burn	kg	9809	8996
Mass of Wingbox	kg	5086	1748
Cost of fuel	$/kg	0.85	0.85
CO_2 / flight	kg	35901	32925
Number of flights in lifetime		70000	70000
CO_2 operations	kg	2513087833	2304723960
Fuel cost operations	$	583640617	535250100

Jasa, J. P., Hwang, J. T., & Martins, J. R. (2018). Open-source coupled aerostructural optimization using Python. *Structural and Multidisciplinary Optimization*, *57*, 1815-1827.
Chauhan, S. S., & Martins, J. R. (2018, September). Low-fidelity aerostructural optimization of aircraft wings with a simplified wingbox model using OpenAeroStruct. In *International conference on engineering optimization* (pp. 418-431). Cham: Springer International Publishing.
Jasa, J. P., Chauhan, S. S., Gray, J. S., & Martins, J. R. (2019). How Certain Physical Considerations Impact Aerostructural Wing Optimization. In *AIAA Aviation 2019 Forum* (p. 3242).

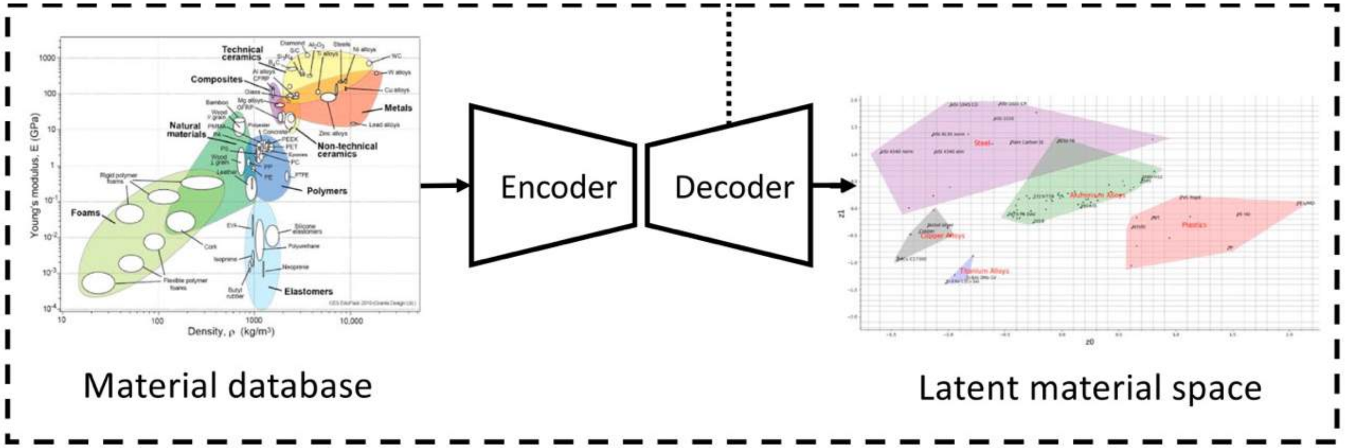
Conclusions

- Single aisle aircraft have a larger environmental impact because of their huge volumes need an optimized composition to reduce their environmental impact in early phase.
- LCA data specific to aerospace grade materials should be taken for better quality of results
- Current MDO results are limited to wingbox
- The current methodology simplifies material selection by not accounting for example strength properties etc…needed by MDO tools

Future Works in MDO

- Add more physics from AD https://github.com/fast-aircraft-design/FAST-OAD

with VAE for continuous material representation



Llorente et al. (2024). A hybrid machine learning and evolutionary approach to material selection and design optimization for eco-friendly structures. *Structural and Multidisciplinary Optimization*, *67*(5), 69.

Thank you for your attention!