Impact of corrugated tubes on multi-disciplinary optimization of charge air coolers.

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Agenda

1. Introduction
2. Motivation
3. Approach
   - Multi-disciplinary approach with vibrations.
4. Results
   - Optimization
5. Conclusions.

Introduction

- Overall goal
    - Reduce temperature of the charge air.

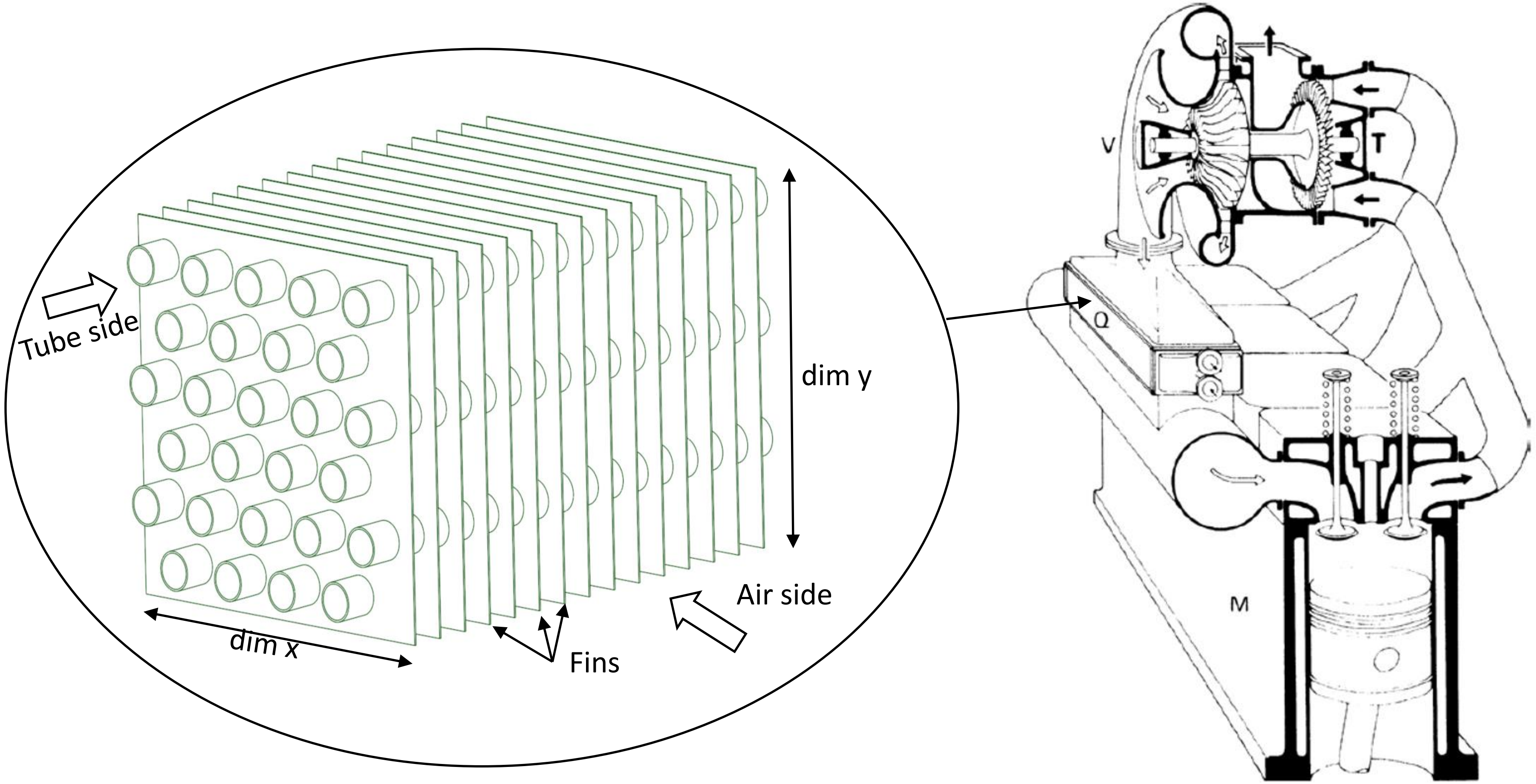


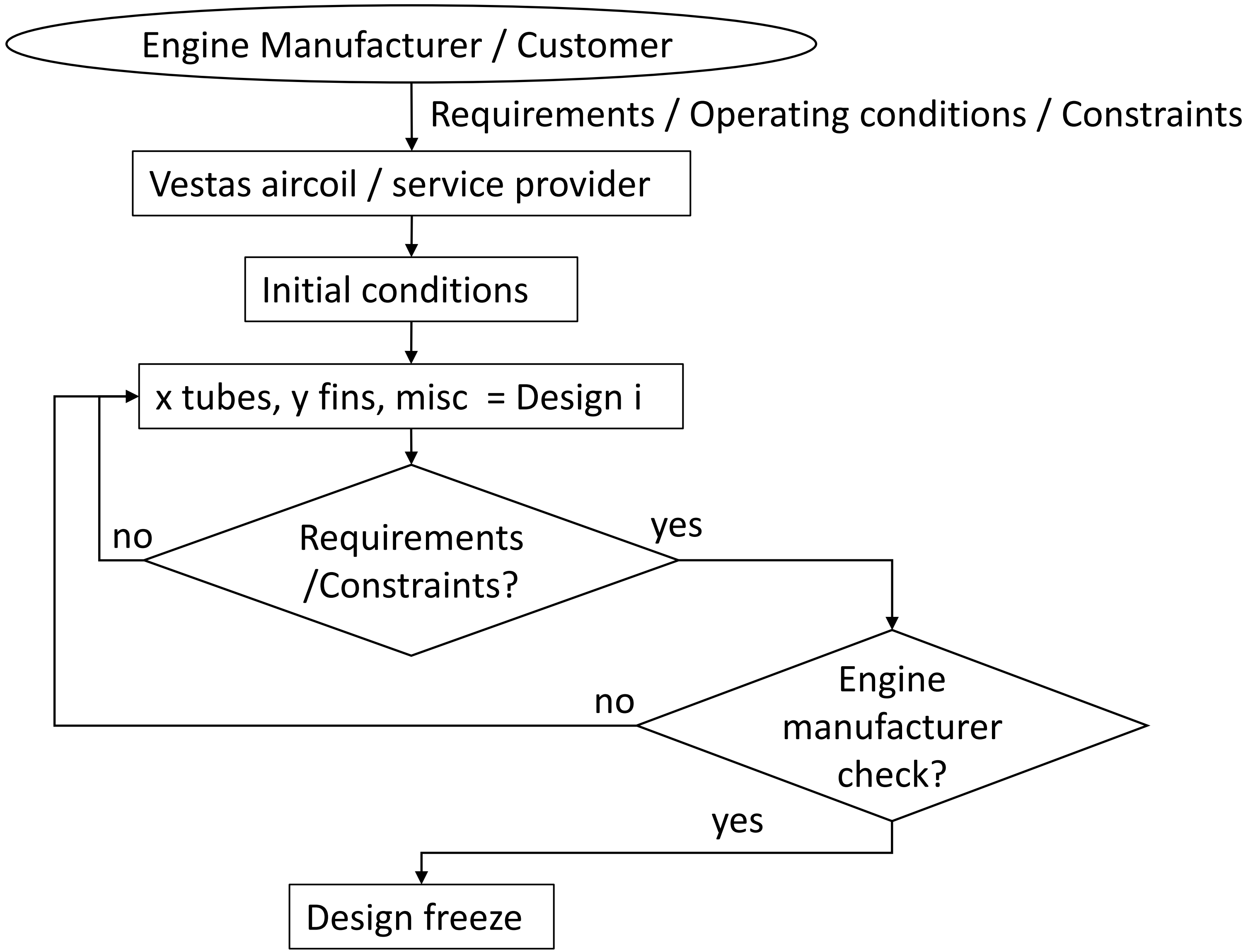
Figure 4: Inset of a schematic of a charge air cooler in an IC engine (not to scale) [10]

Introduction

Figure 1: Some heat exchangers at Vestas-aircoil

- Complex engineering systems.
- Many variables affecting performance.
- Continuous variables. (size dimensions e.g., diameters, length, heights, widths etc)
- Discrete variables. (number of tubes, number of fins, number of plates, etc)

Motivation



Engine Manufacturer / Customer
Requirements / Operating conditions / Constraints
Vestas aircoil / service provider
Initial conditions
x tubes, y fins, misc = Design i
no
Requirements /Constraints?
yes
no
Engine manufacturer check?
yes
Design freeze

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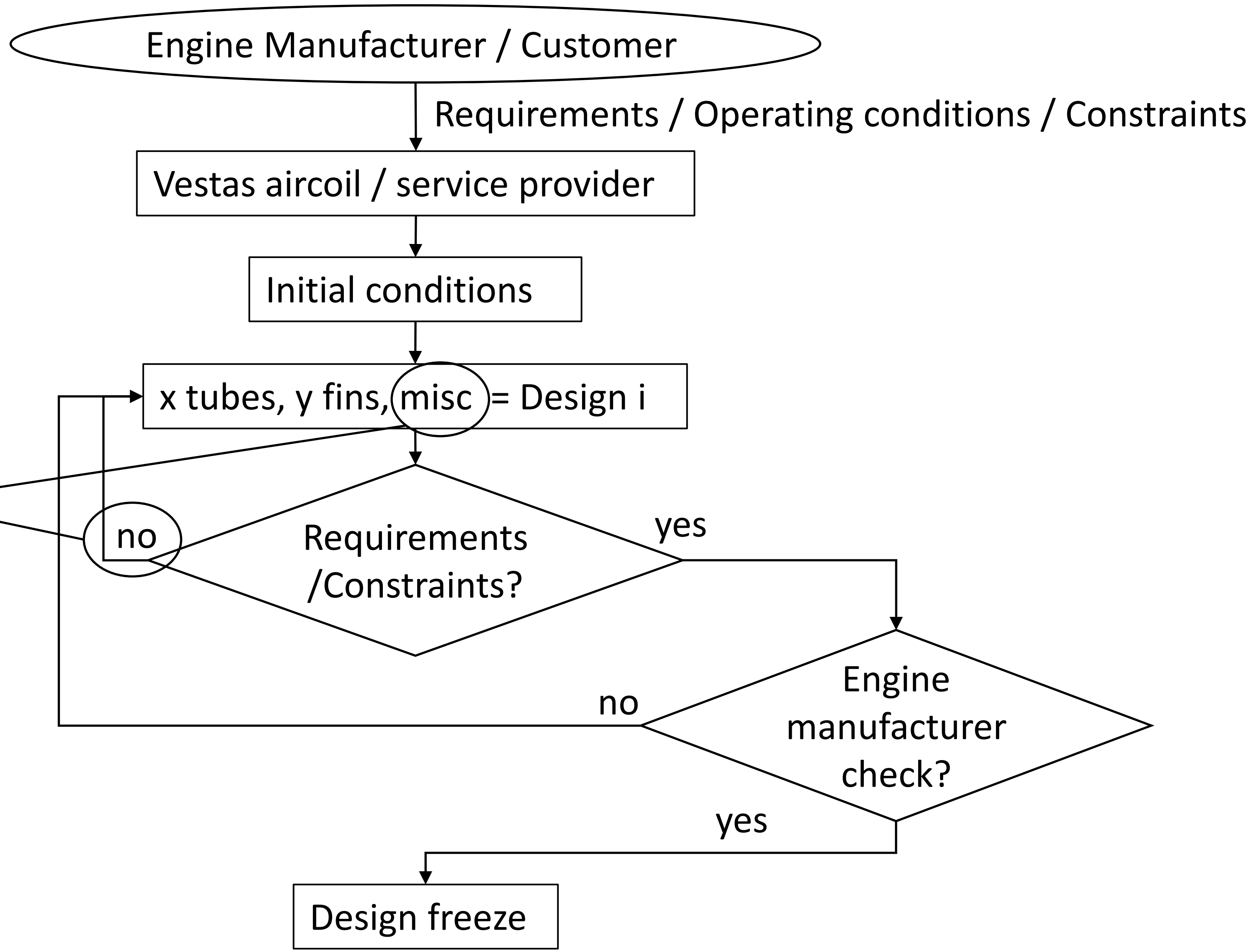
- May require hand calculation.
- Change tubes? or Fins? or both , or something else?
- May require legacy knowledge.
- Most likely require satisfying constraints from a different discipline-> Different checks.



Motivation

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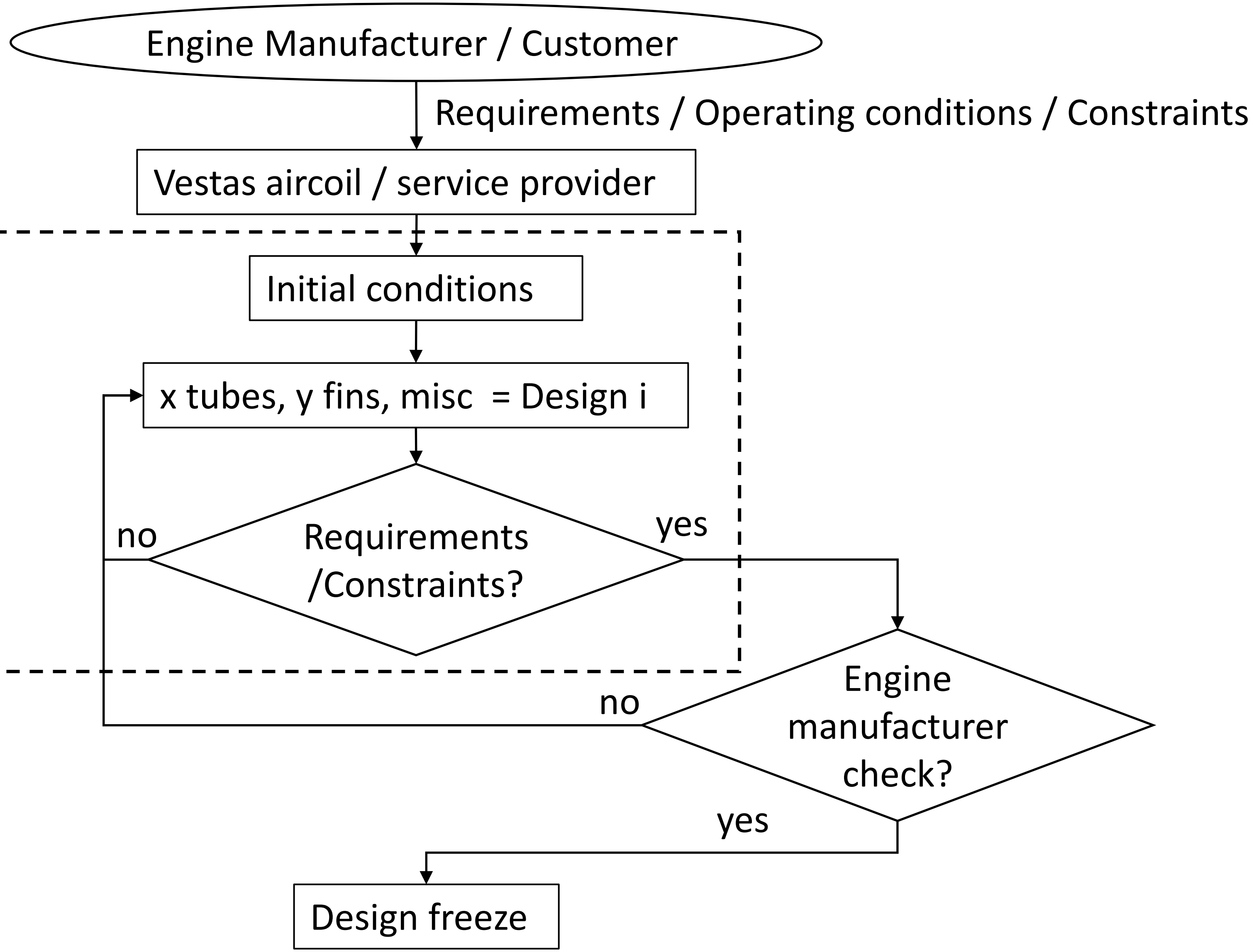
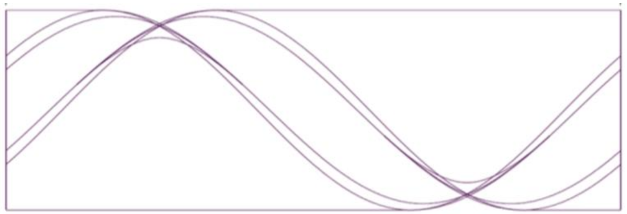
- Can a tool, help in arriving at the best candidate, **in one go**, satisfying objectives and constraints, from different disciplines?



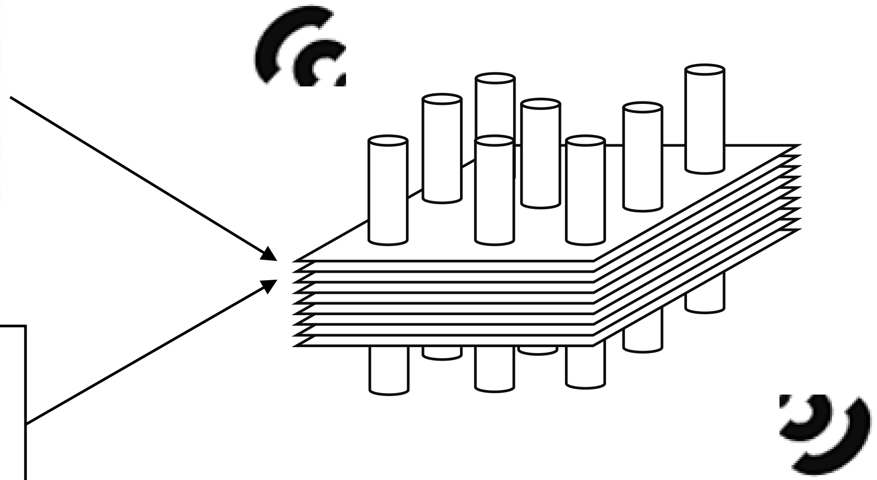
Problem statement

1. Why use corrugated tubes?
   Or are they better than smooth tubes?
2. Does including a frequency constraint make a difference?



(Corrugated tube)

(Smooth tube)



(1)

(2)

Novelties

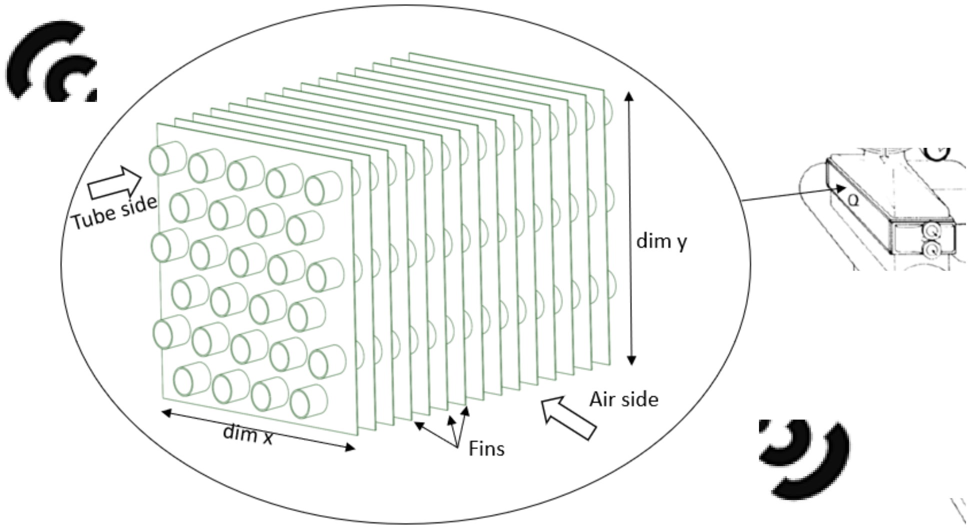
- Materials choice as design variables.

Al, Cu, SS, CuNi10

- Mixed integer problem definition.

- Corrugated tubes in the context of whole heat exchangers.

- Inclusion of vibration model.



Scope

Figure 5: A corrugated tube for heat exchanger.

- Scope
  - Only surface alterations to the tubes. (no inserts)
  - Material used for corrugated tube is same as smooth tube. (No cutting or material removal process assumed)
  - Vibration model aims to find lowest natural frequencies.

Approach

Approach

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Thermal model

- calc_thermal_model
  - Initial conditions
  - fin configurations
  - Design parameter declarations
  - Material properties
  - Derived constants for tube and fins
  - Mean temperature estimation
    - kt
    - mu_t
    - rho_water
    - rhot
    - Pra
    - ka
    - mu_a
    - rhoa
    - Cpa
    - Cp25
    - Cp44
    - Cp120
    - Cpt
    - Pr47
    - Pr120
    - Prt
    - tam
    - Ca
    - Ql
    - Ct
    - ttm
    - Ret
    - ft_4k
    - Nut_4k

- Nut_4k
- Nut_tro
- Nut_to
- Gzt
- beta_t
- Grt
- Nut_ll
- Nut_i
- Fpt
- Nut_t
- Nut
- ht
- Fin side htc
  - Rea
- Fin dimensions
  - jsw
  - jhtfs
  - ja
  - ha1
  - ma
  - Bia
  - bi
  - eta_f
  - eta_o
- Vestas fin type constants
- Vestas-quantities
  - St
  - ha1_vestas
  - A_vestas
  - Fif
  - Nfin

- Nfin
- ha_vestas
- ha
- Overall cooler performance
  - Ul
  - twi
  - twall_i
- Min capacities for NTU formulae
  - Cmin
  - Cmax
  - Rc
  - NTU
  - eumUM
  - epsilon4
  - eff
  - eff4
- charge air outlet temperature
- Pressure drops
- log mean temperature
- pressure drop through tube bundle
- Cost
- Fins cost
- Tube cost
- Plate cost
- Corrugation cost
- Objective function
- For constraints
- Return indices

Approach

Vibration model – Making the analysis multi-disciplinary.

Design variables

- Continuous variables

Length	1	2.5
Groove depth(e)	0.02	0.06
Pitch (p)	0.18	0.27

- Discrete variables

N_row	26	32
N_col	17	34
N_plates	0	4
Fins/m	373	561
Fin material	1	3
Tube material	1	3

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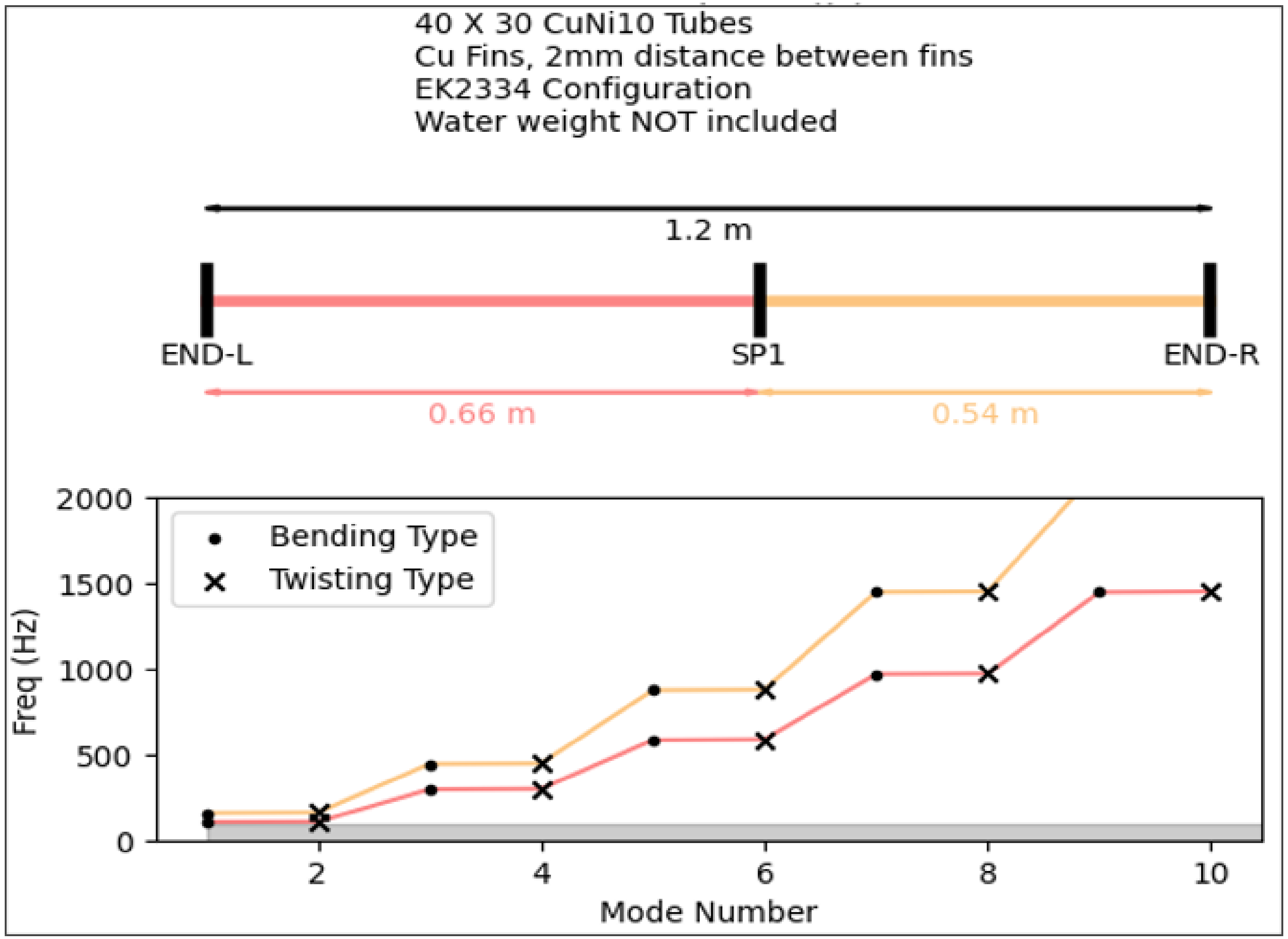
Vibration model

$$freq_{bending} = \left(\frac{1}{2\pi}\right)\sqrt{\left(\frac{E_{tube} I_{tube} B}{\mu_{tube} A + \mu_{fin} \frac{b}{L} A}\right)}$$

- E_{tube} Young's modulus (of tube material)
- I_{tube} Second moment of Area of tube
- μ_{tube} , μ_{fin} area densities
- L is length of section
- b is tube pitch
- A, B are constants.



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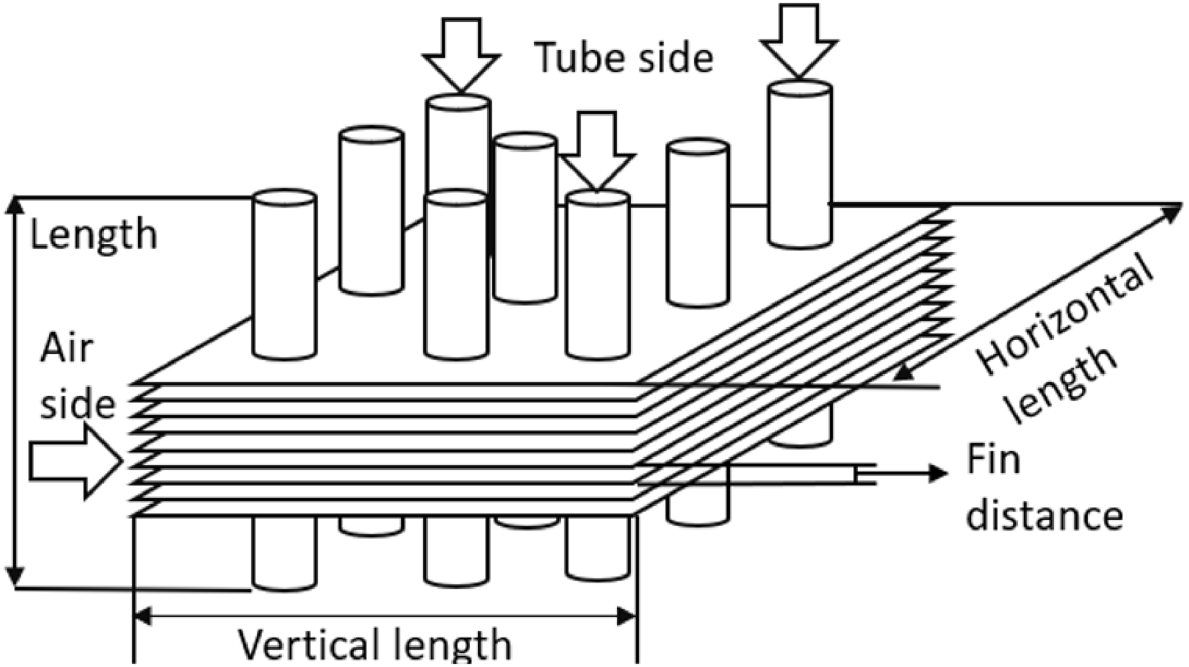
Constraints for CAC optimization problem



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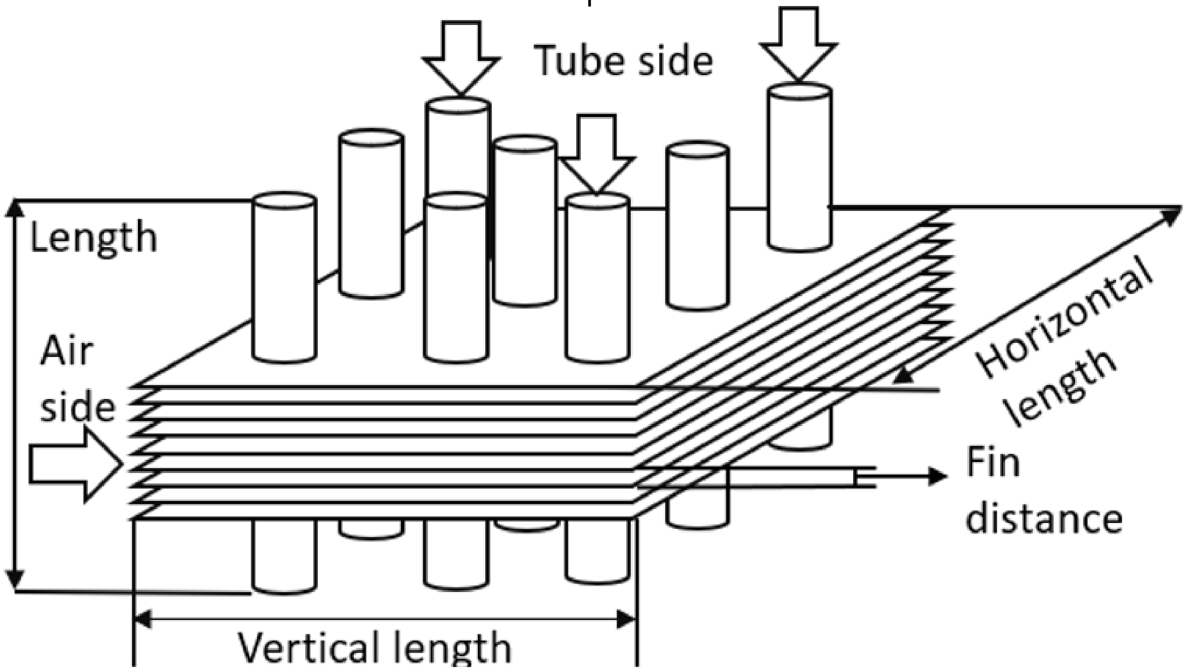
Constraints for CAC optimization problem

- Pressure

Pressure drop < 80kPa

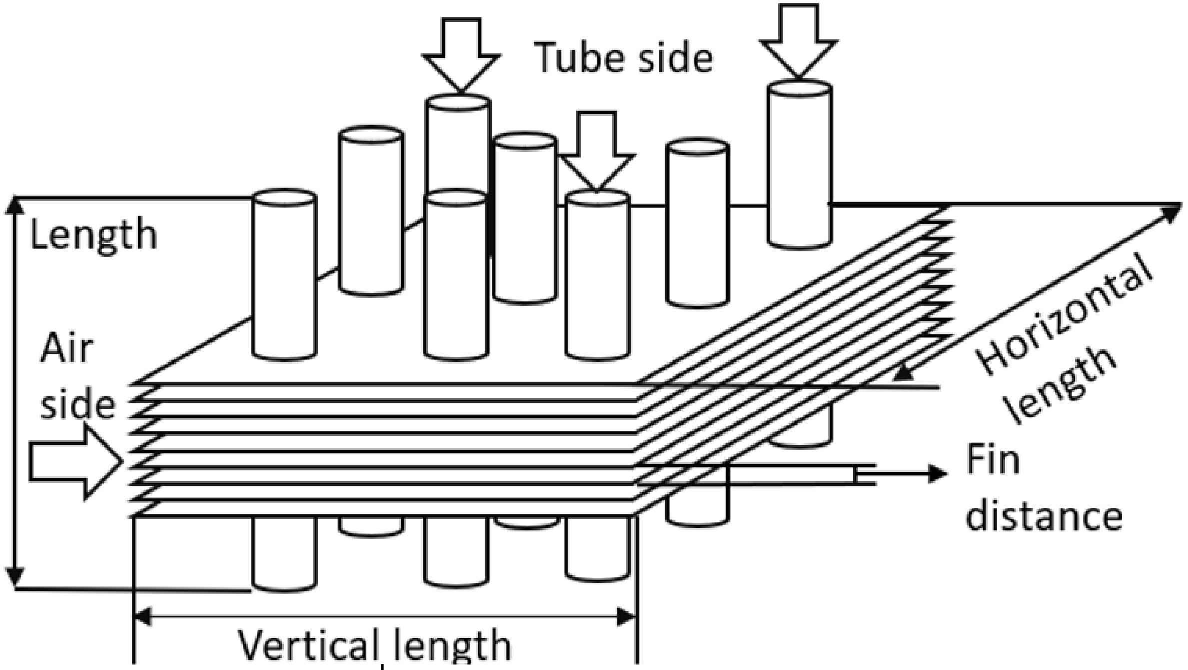


Pressure drop < 2.5 kPa

Approach

Constraints for CAC optimization problem

- Pressure
- Size



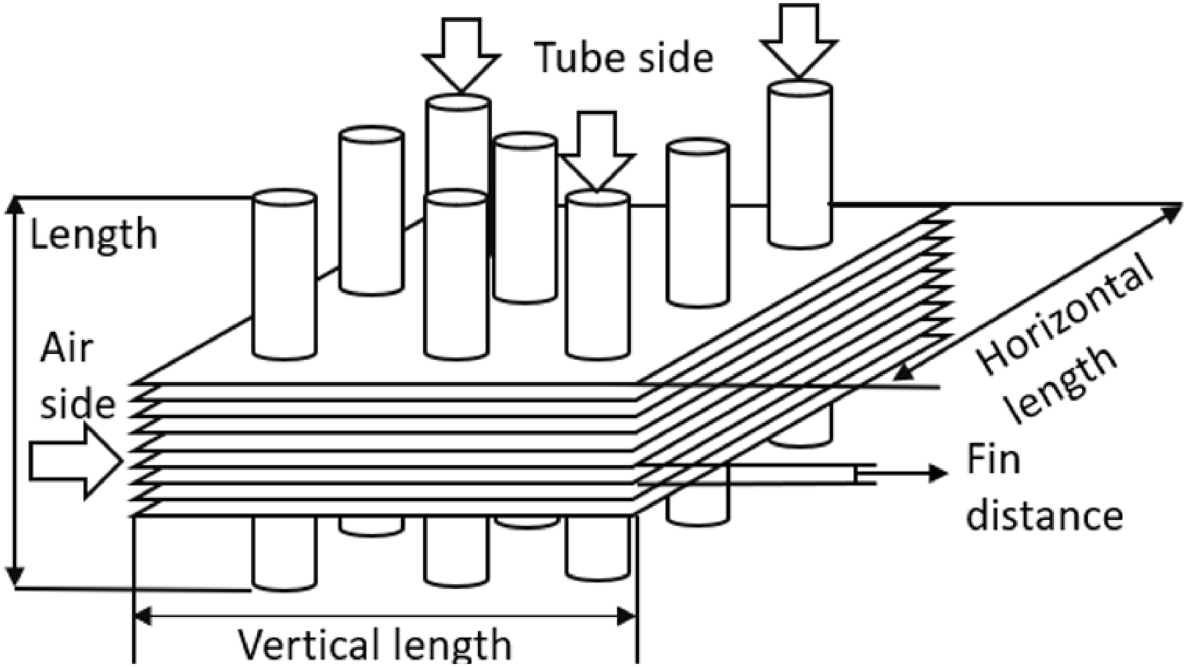
$h\_L < 1.05m$

$v\_L < 0.8m$

Approach

Constraints for CAC optimization problem

- Pressure
- Size
- Weight

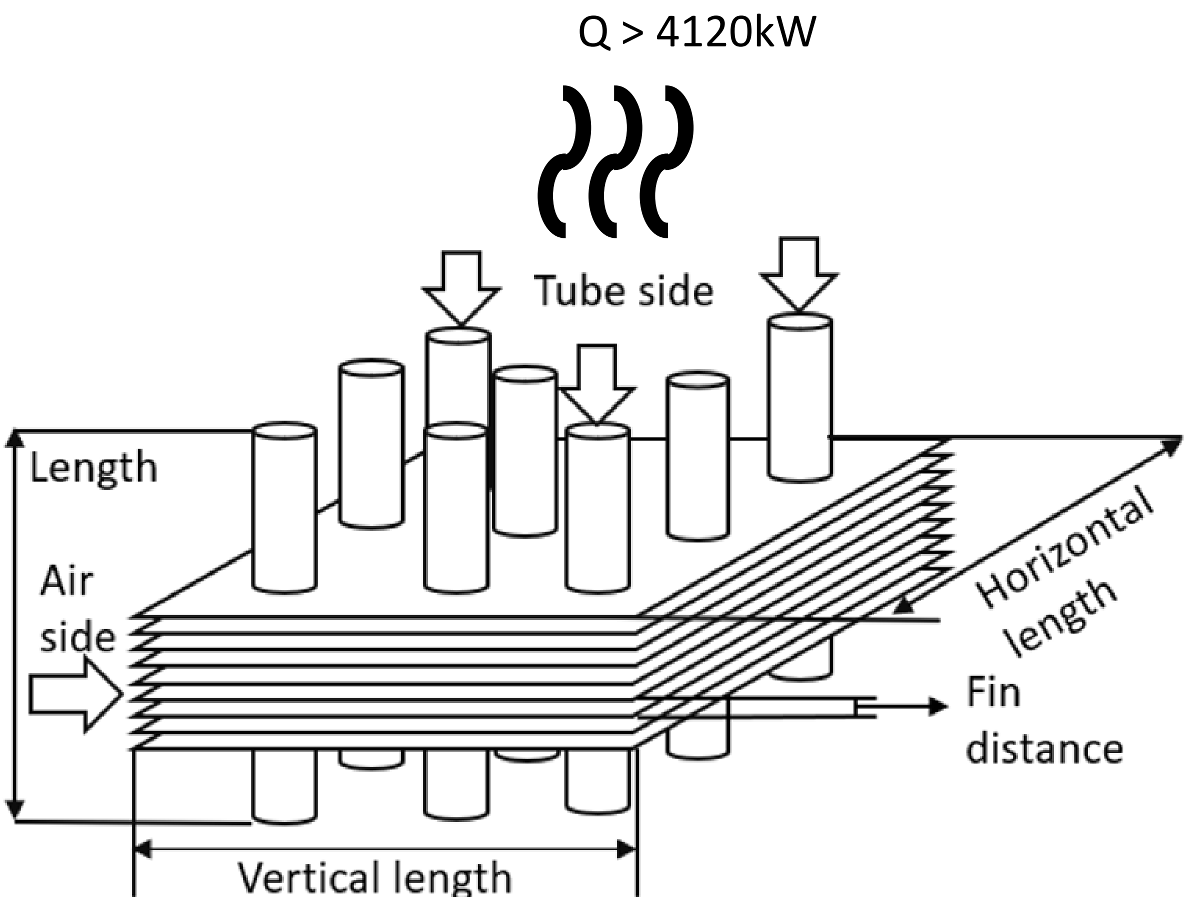


Weight (Tubes + Fins + Plates) < 600 kg

Approach

Constraints for CAC optimization problem

- Pressure
- Size
- Weight
- Power dissipation



Approach

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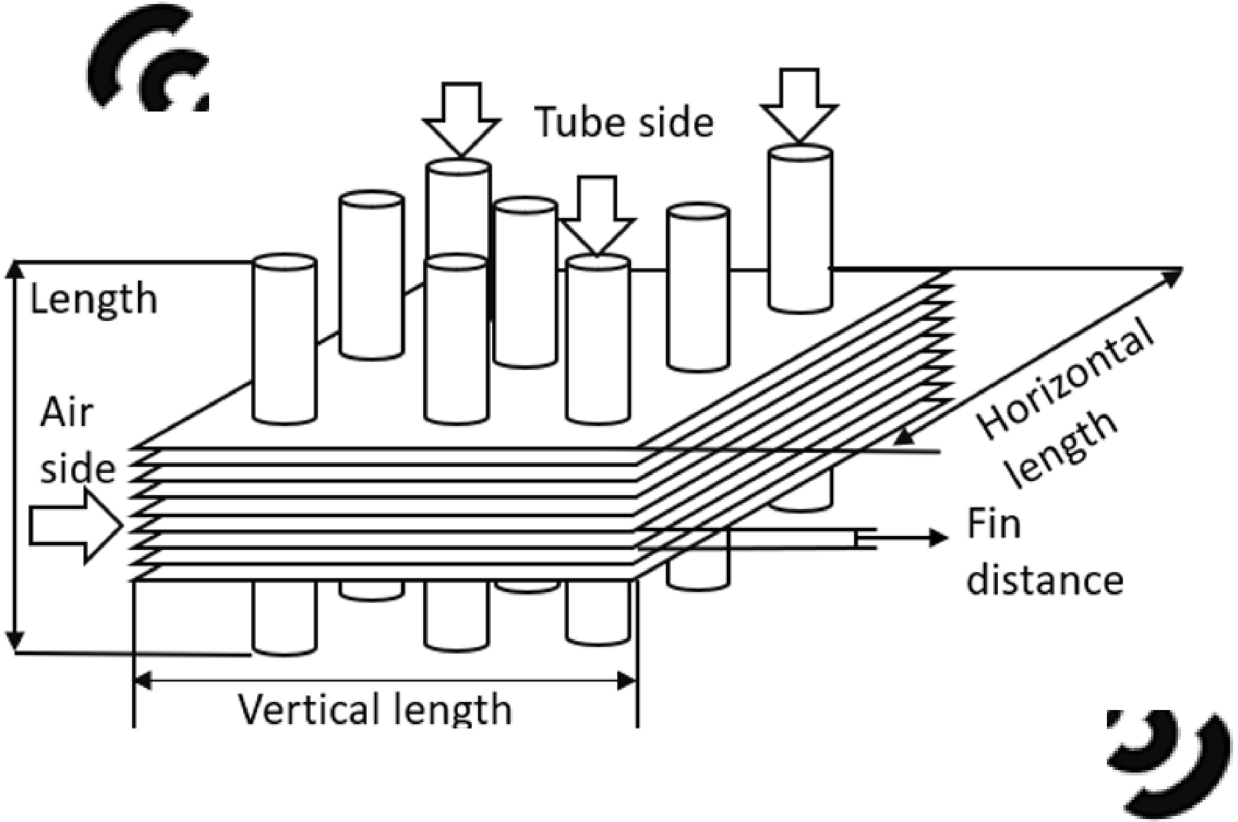
Constraints for CAC optimization problem

- Pressure
- Size
- Weight
- Power dissipation
- Natural frequency



1st bending mode > 100 Hz

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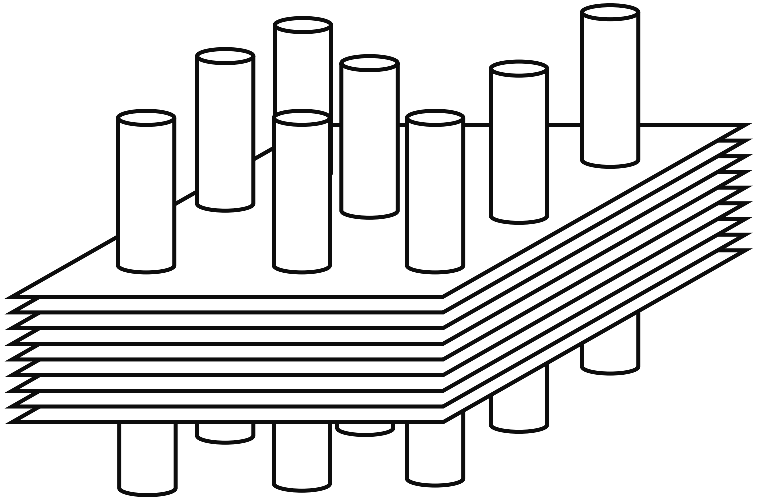
Formal definition

- Minimize $cost_{cac} = cost_{tubes} + cost_{fins} + cost_{plates}$

- such that
  - Weight < 600Kg
  - Pressure drop (air side) < 2.5 kPa
  - Pressure drop (tube side) < 80 kPa
  - Horizontal length < 1.054 m
  - Vertical length < 0.8 m
  - Reynolds number < 60000
  - Velocity in tubes < 1.5 m/s
  - Dissipation > 4120 kW
  - Bending frequency > 100 Hz

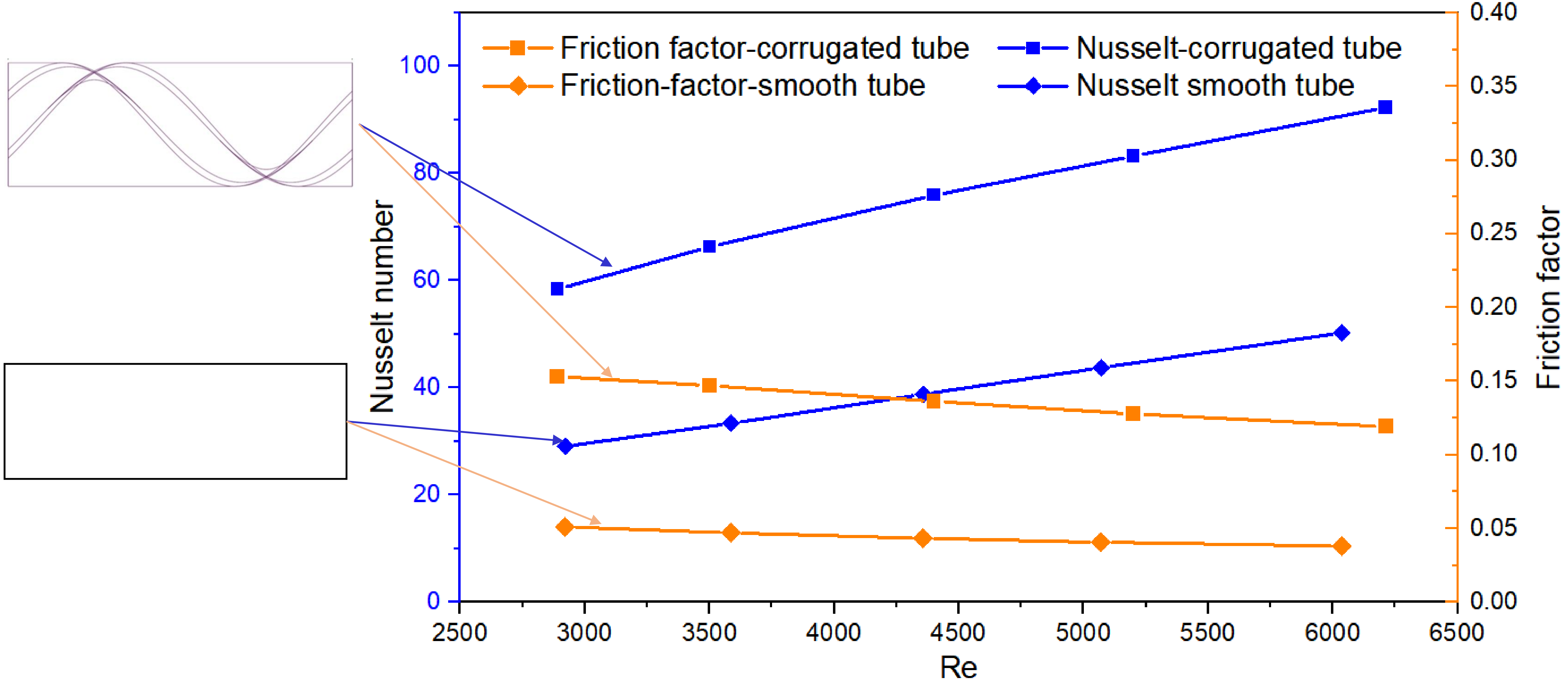


- *Single objective, multi-disciplinary, mixed-variable, constrained optimization problem.

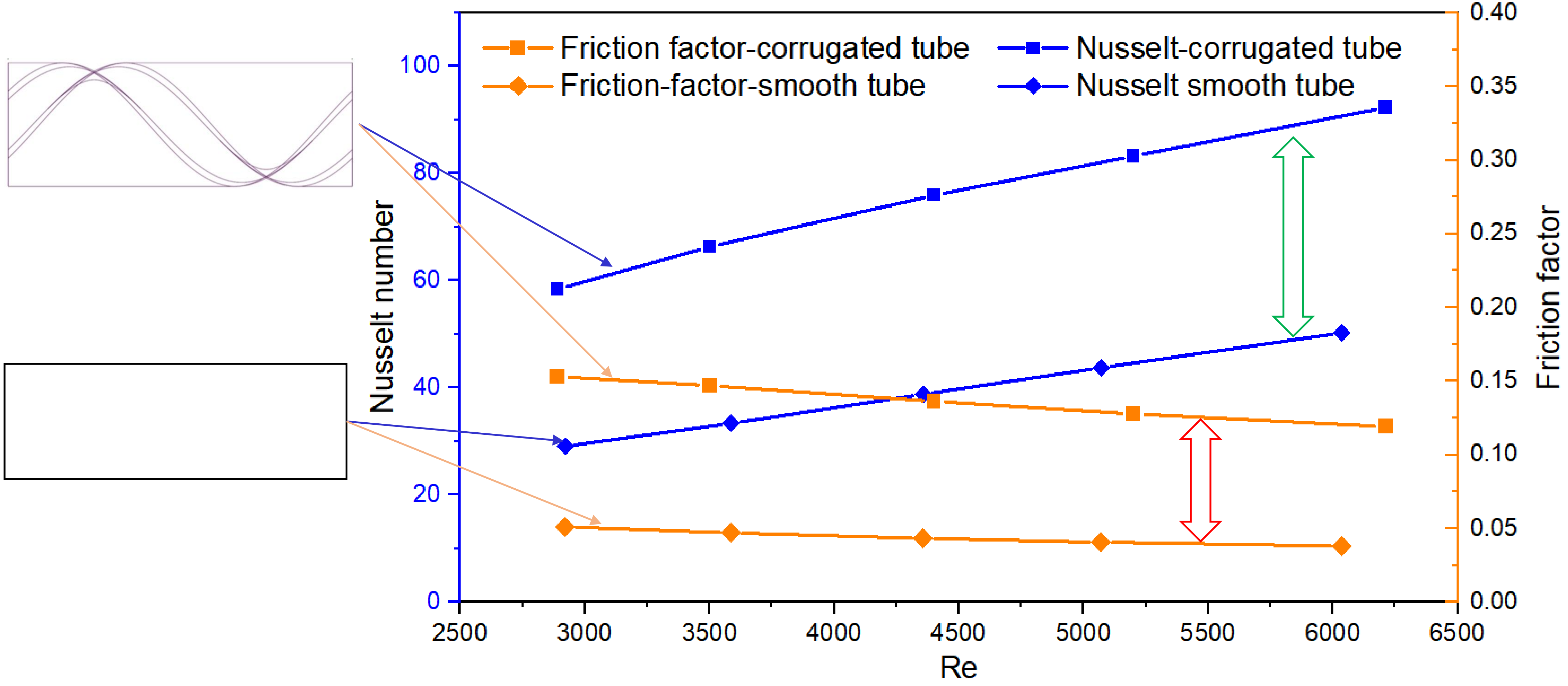
- Solved using NSGA-II, Population size of 1000, 800 gen, 100 offsprings.

Results

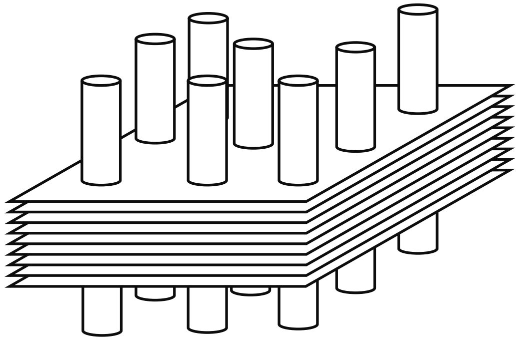
1. Why use corrugated tubes?
   Or are they better than smooth tubes?



1. Why use corrugated tubes?
   Or are they better than smooth tubes? → Yes!!, but at an added cost. [9]



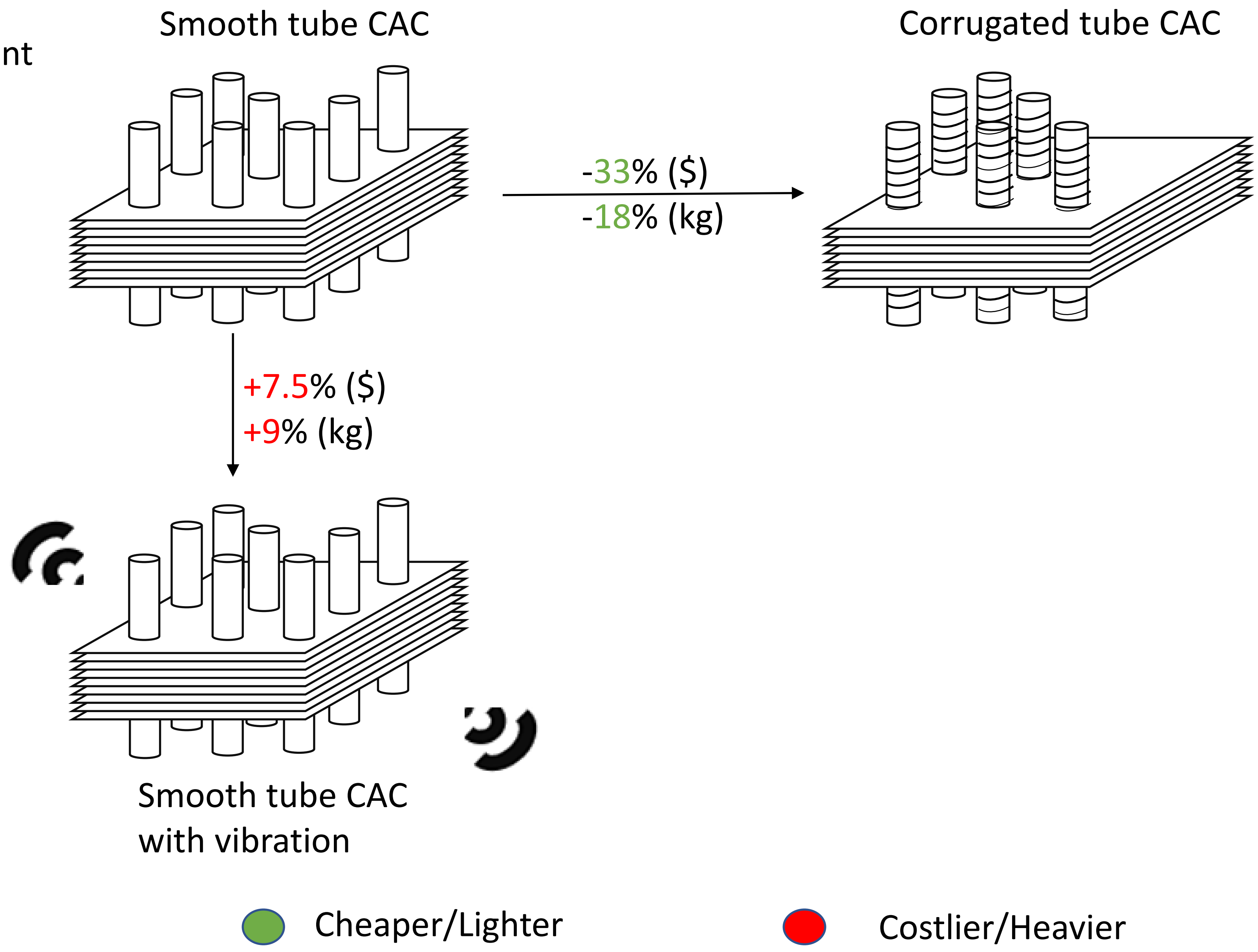
Smooth tube CAC



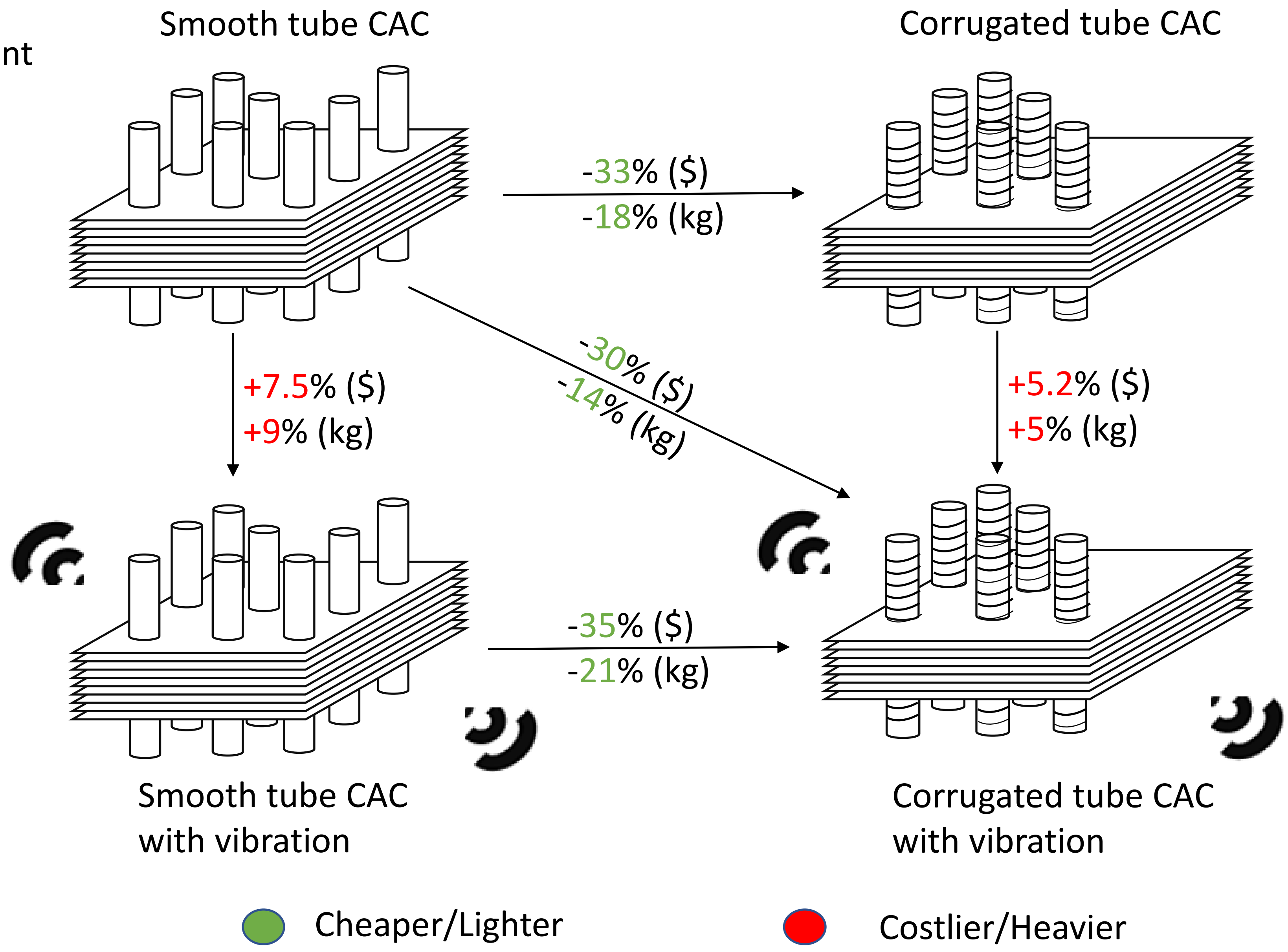
2. Does including a frequency constraint make a difference?

Results

2. Does including a frequency constraint make a difference?



2. Does including a frequency constraint make a difference?



Results

Optimum value of	Smooth tube with frequency constraint	Smooth tube without frequency constraint	Corrugated tube with frequency constriant	Corrugated tube without frequency constraint
N_t	26	26	27	27
N_r	25	25	22	22
N_{pass}	2	2	2	2
γ_e	475	475	474	474
k_f	Al	Al	Al	Al
k_t	Cu	Cu	Cu	Cu
N_{plates}	2	0	1	0
L_t	1.623	1.624	1.44	1.44
he	-	-	0.06	0.06
hp	-	-	0.269	0.269
Cost ($)	5871.43	5458.74	3805.61	3617.11

Table 1: Optimum configurations for smooth tube and corrugated tubes, with and without the frequency constraint.

- Plates, required to achieve the 100 Hz frequency constraint, otherwise indiscernible without the frequency constraint.
- Corrugated tubes are of reduced length, to achieve the desired frequency.

Conclusions

Conclusions

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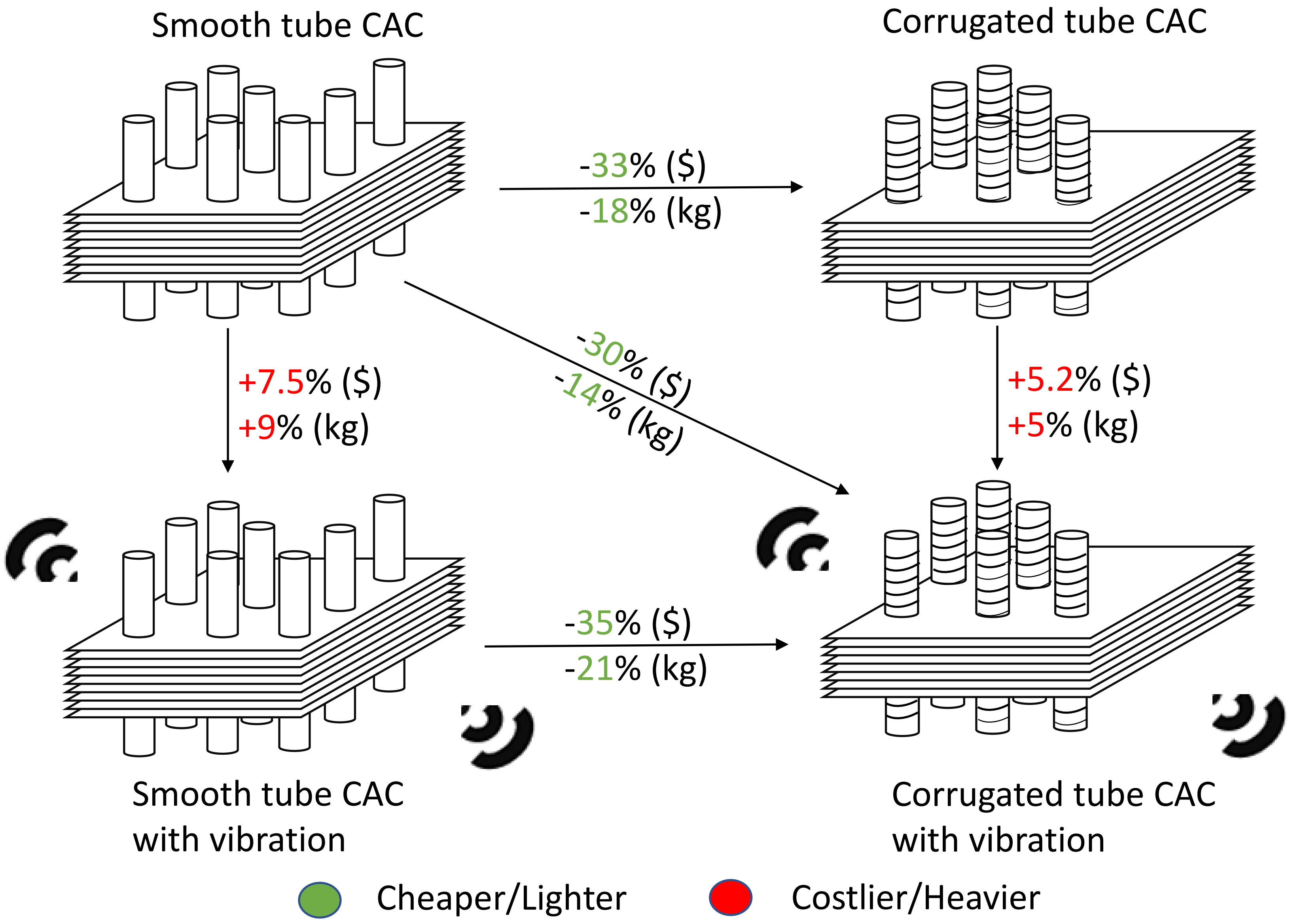
- Non multi-disciplinary approach, misses the 100 Hz requirement.

- Multi-disciplinary approach satisfies the 100Hz criteria, through a support plate, hence increasing price and weight.

- Corrugated tubes provide reduction in cost and weight, achieved by reduced length and number of tubes.



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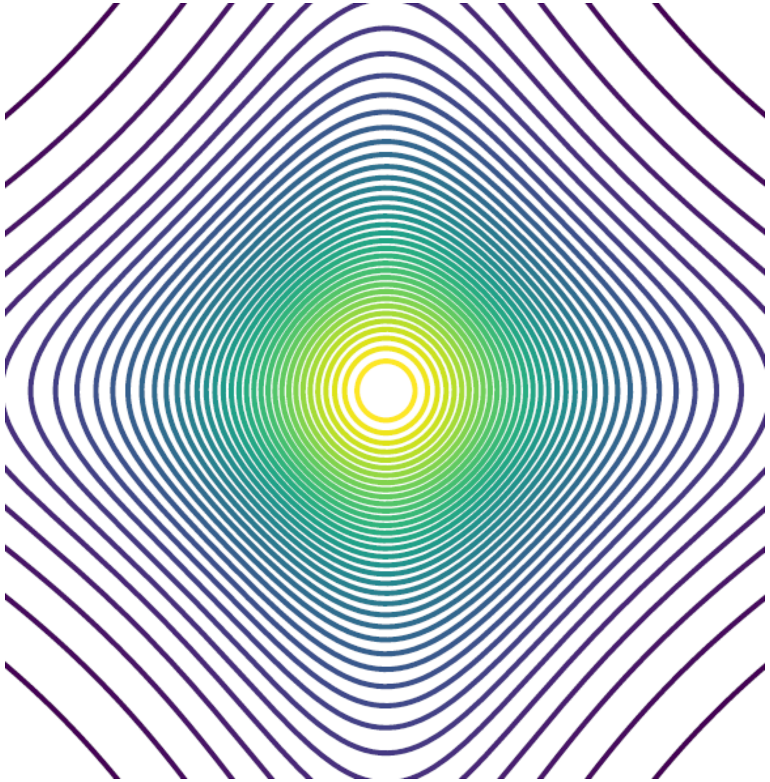
Thank you



Questions?