APM 2013

The Advanced Process Modelling Forum

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PSE

Optimising compression train design and operation for flexible design

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Overview

Model development		*Process operation*	*Equipment design*	
First principle equations and heuristics	*Flowsheet implementation and verification*	*Control strategies*	*MINLP design optimisation*	*Multi-period optimisation*

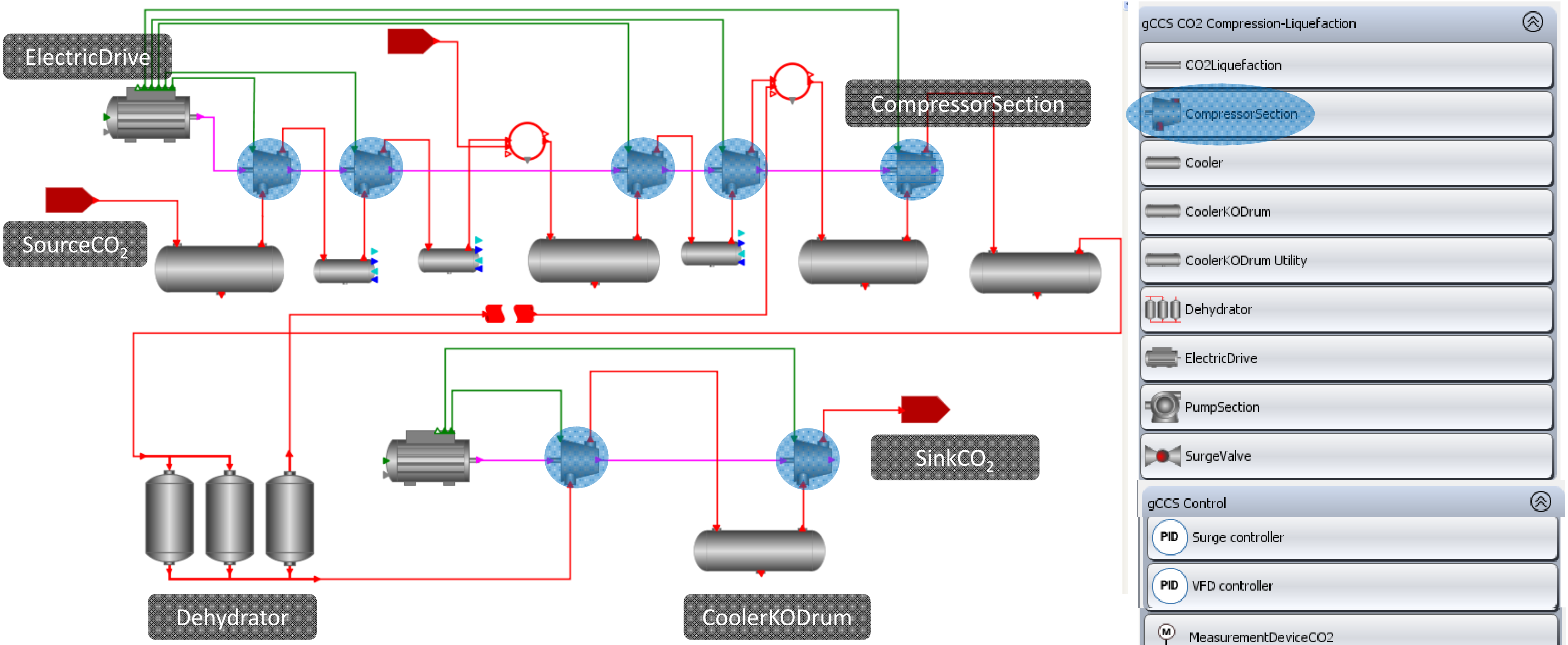
Overview

Model development

First principle equations and heuristics

gCCS Compression-Liquefacion

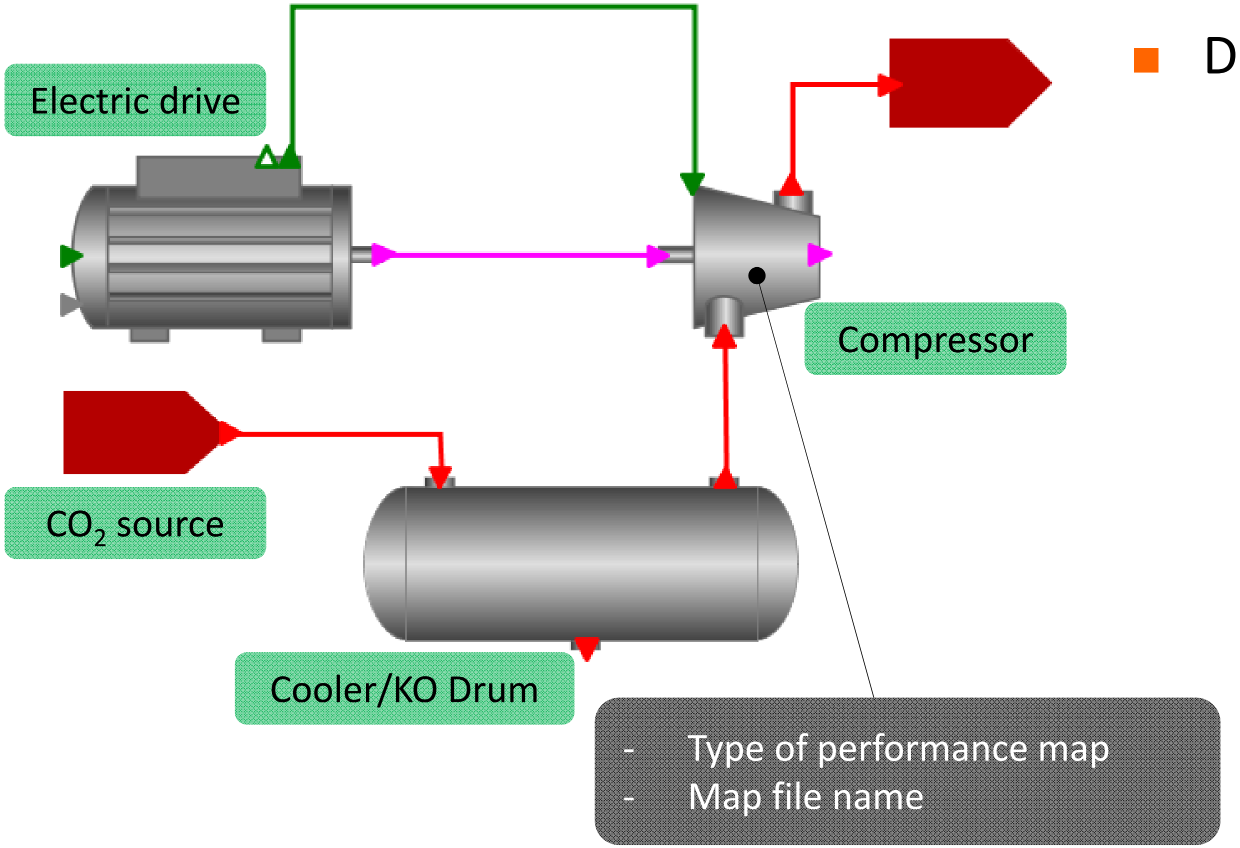
Component models

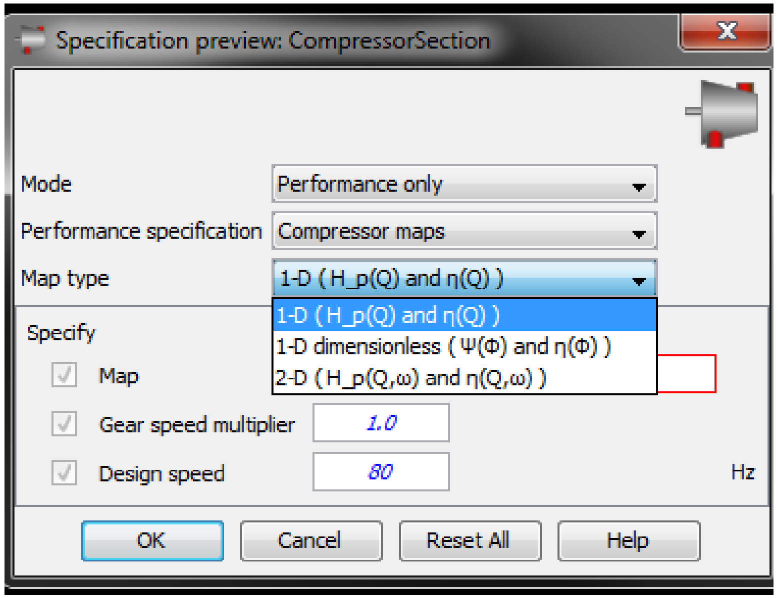


Compressor model

Main specifications

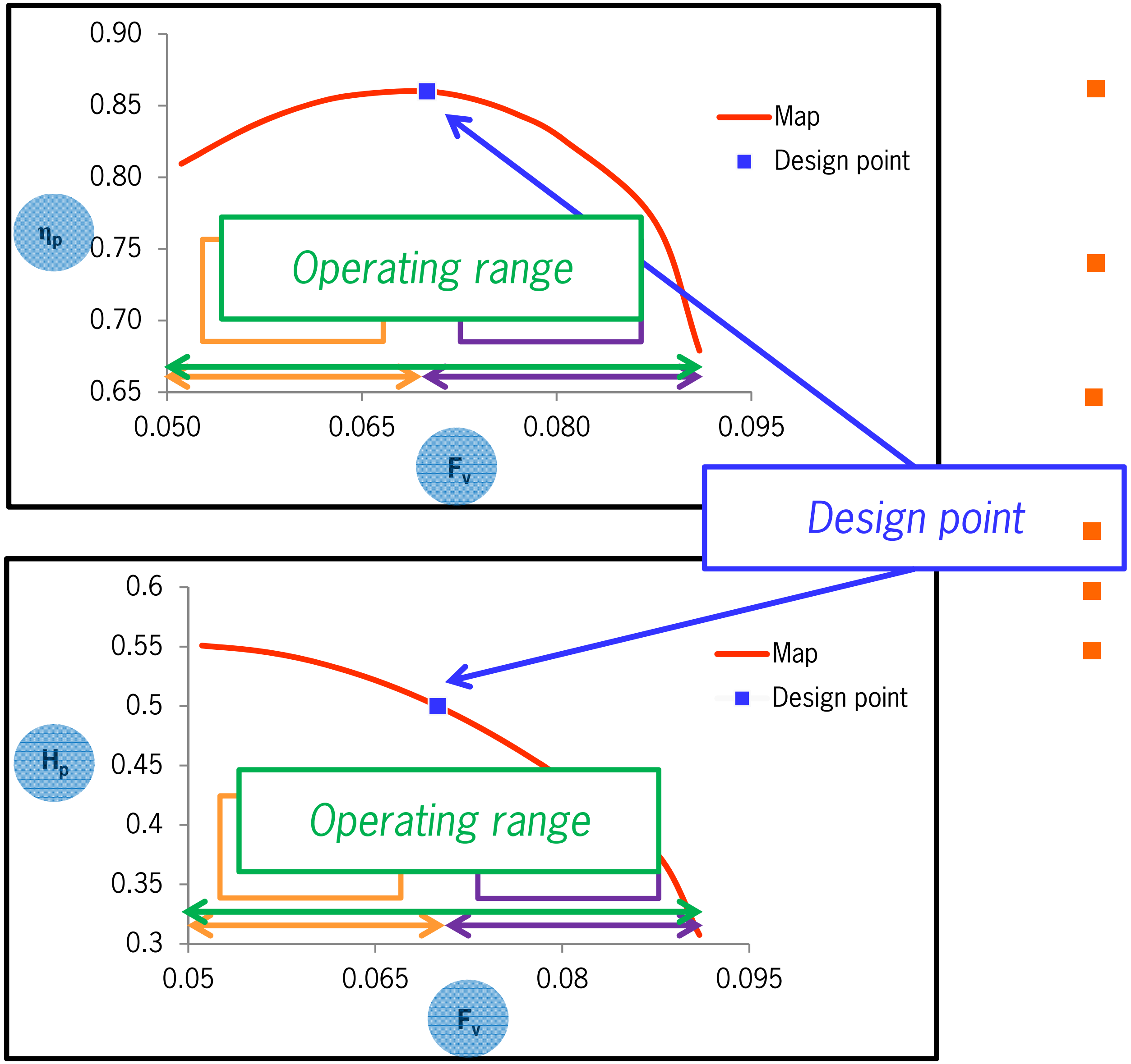
- Detailed compressor modelling
  - know-how & expertise supplied by Rolls-Royce
- Different types of performance map





Compressor model

Performance maps



- Performance map based on **flow/head** and **flow/efficiency** curves
- **Design point** corresponds to the maximum efficiency
- Compressor has a flow **operating range**
- **Surge**: distance from minimum flow
- **Choke**: distance from maximum flow
- Both need to be controlled in order to maintain operability

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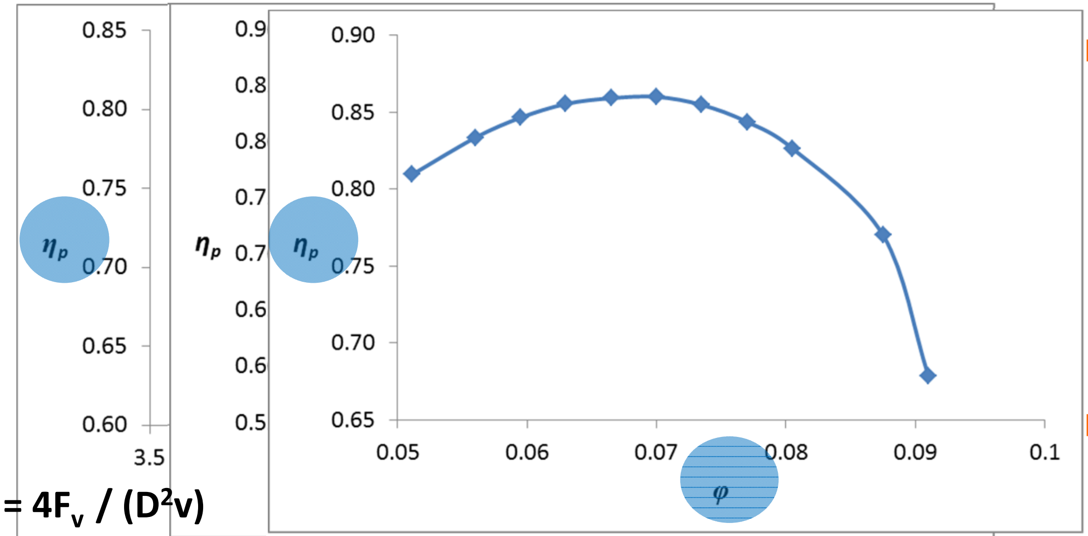
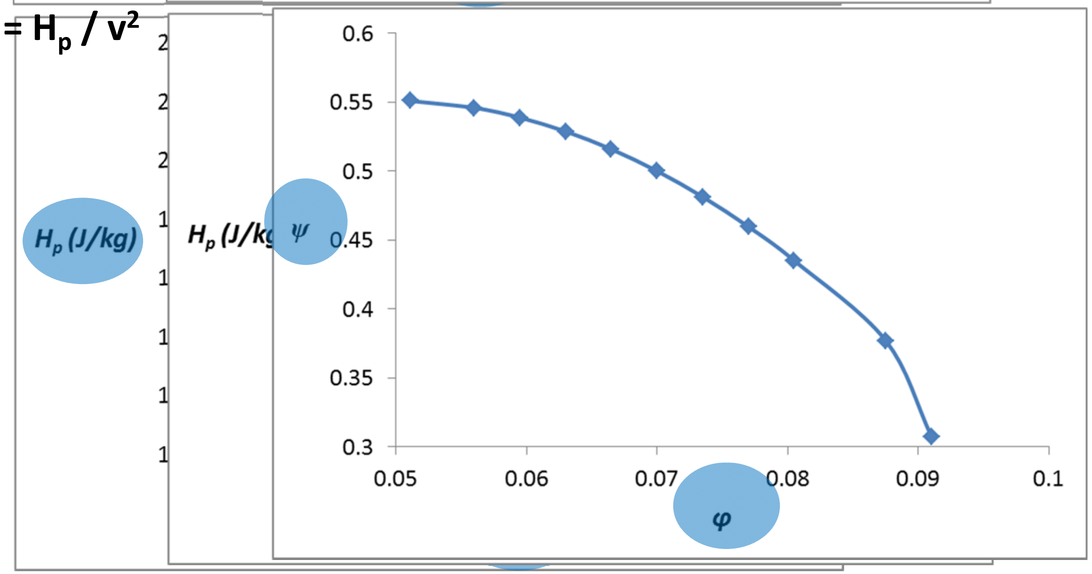
Compressor model

Performance maps



- $\varphi = 4F_v / (D^2 v)$
- $\psi = H_p / v^2$



- **1D maps**
  - Efficiency/flow curve
  - Head/Flow curve
  - Uses affinity laws to extrapolate for different speeds
- **2D maps**
  - Same type of curve as 1D map
  - Multiple curves corresponding to different speeds
  - Interpolates between curves to determine operation for different speeds
- **Dimensionless maps**
  - Curve based on dimensionless flow (φ) and head (ψ)
  - Contains same information as 2D maps

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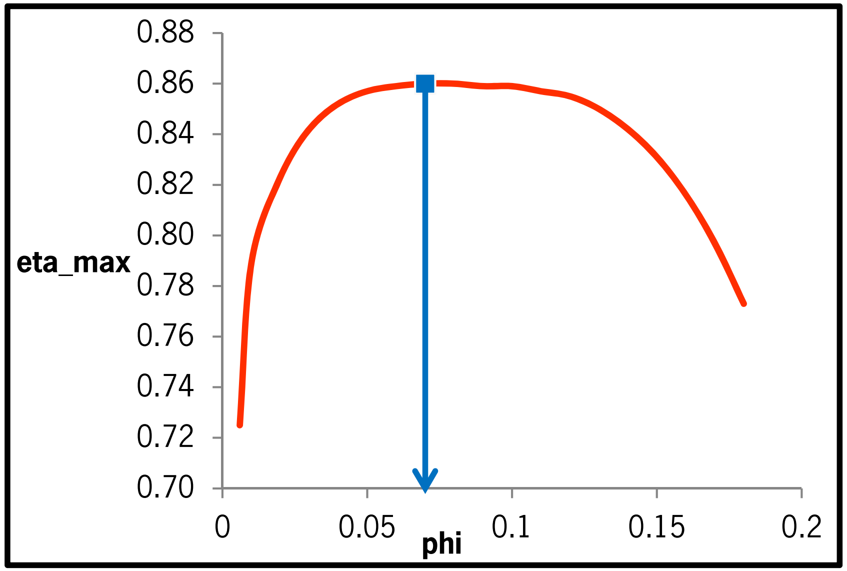
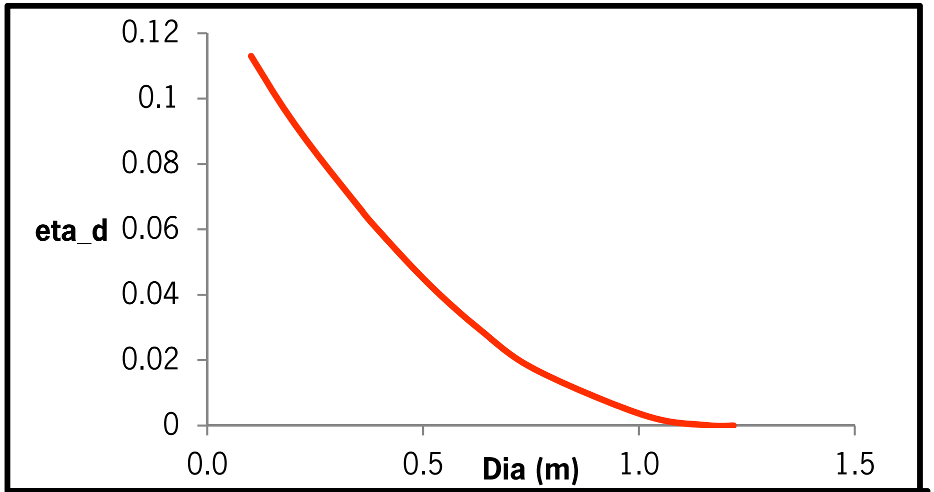
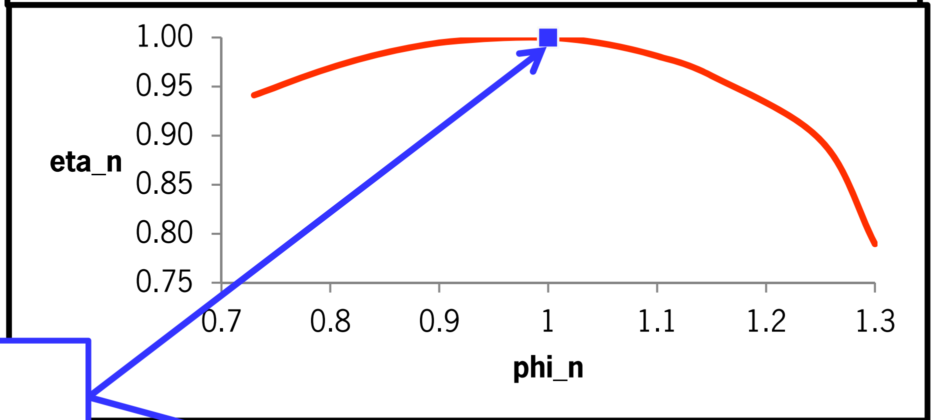
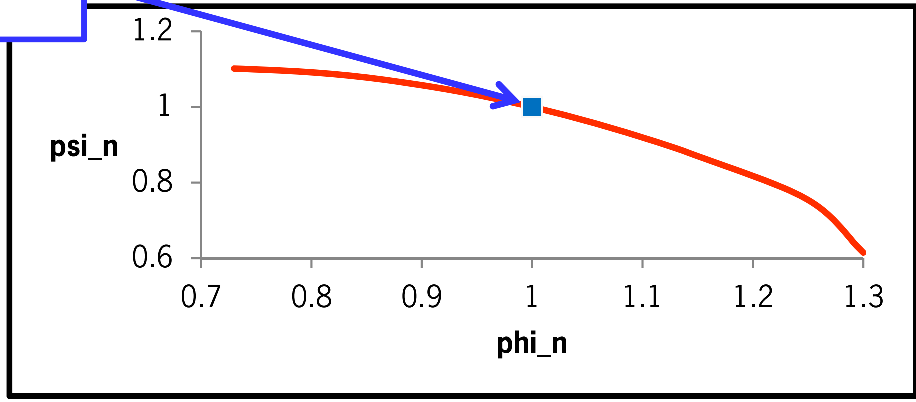
Compressor design

Design heuristics









Design point

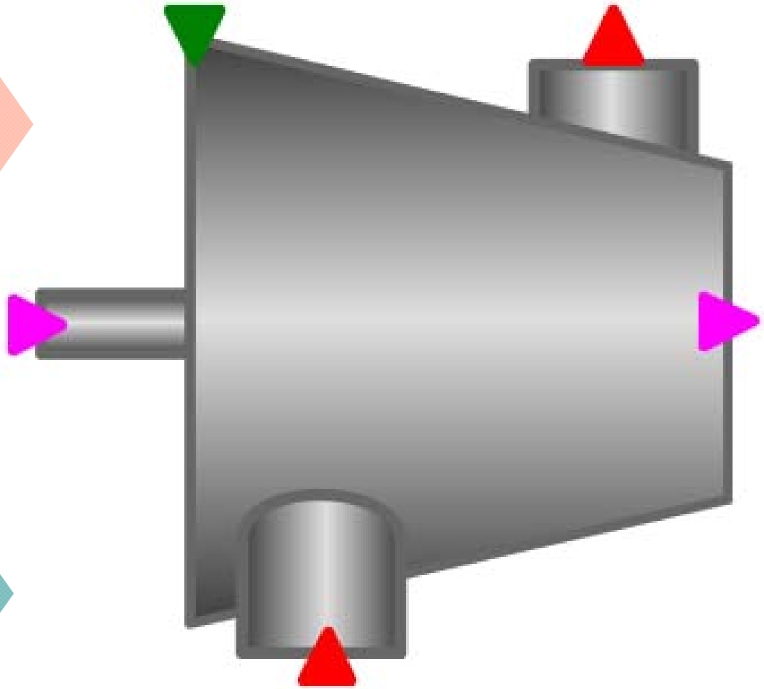
- Knowing flowrate, speed and $\text{phi}_{\text{design}}$, calculate impeller diameter
- With the diameter, calculate efficiency penalty (eta_{d})
- Calculate design eta
- Calculate design psi
- Using the design point and the **normalised map**, establish performance map

Compressor model

Performance vs Design mode

Design
- Inlet conditions
- Speed
- Design discharge pressure

Design
- Outlet conditions
- Power requirement
- Design parameters
- Performance maps



Performance
- Inlet conditions
- Speed
- Design parameters
- Performance maps (1D or 2D)

Performance
- Outlet conditions
- Power requirement

Overview

Model development

First principle equations and heuristics

Flowsheet implementation and verification

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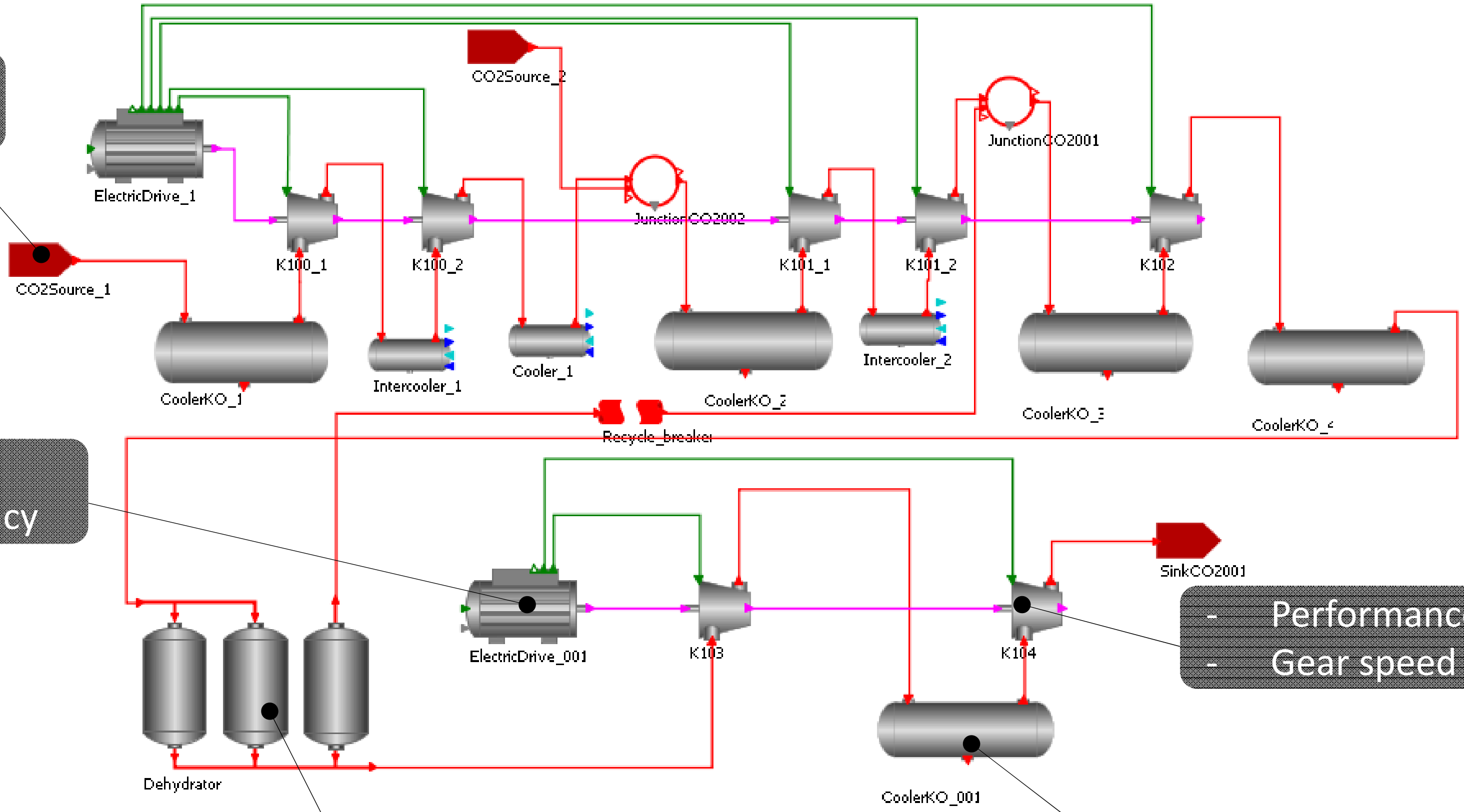
Model verification

IEAGHG Case A0

- F, T, p, w
- Phase

- Drive speed
- Mechanical efficiency



- Performance map
- Gear speed multiplier

- Outlet temperature
- Pressure drop

- Moisture content
- Pressure drop
- Heat of adsorption
- Recycle fraction
- Heating efficiency
- Regeneration temperature

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Model verification

IEAGHG Case A0

Ref: "International Energy Agency Greenhouse Gas" (IEA GHG) report (August, 2010)

Compressor	Discharge temperature (°C)			Discharge pressure (bar)		
	Report	gCCS	Deviation (%)	Report	gCCS	Deviation (%)
$K100_1$	83.6	83.7	0.05	3.65	3.64	0.3
$K100_2$	45.7	45.7	0.1	5.00	4.98	0.4
$K101_1$	69.1	70.1	1.5	10.5	10.4	1.1
$K101_2$	68.3	68.5	0.4	18.8	18.5	1.4
K102	69.1	69.5	0.6	34.0	33.3	1.9
K103	90.1	88.4	1.9	70.0	69.9	0.2
K104	79.2	79.4	0.3	111.2	110.7	0.4

- Deviation between simulation results and data is lower than 2%.
- **Good accuracy** from all the compression system models.
- Accuracy condition needed for optimisation is **satisfied**.

Overview

Model development

Process operation

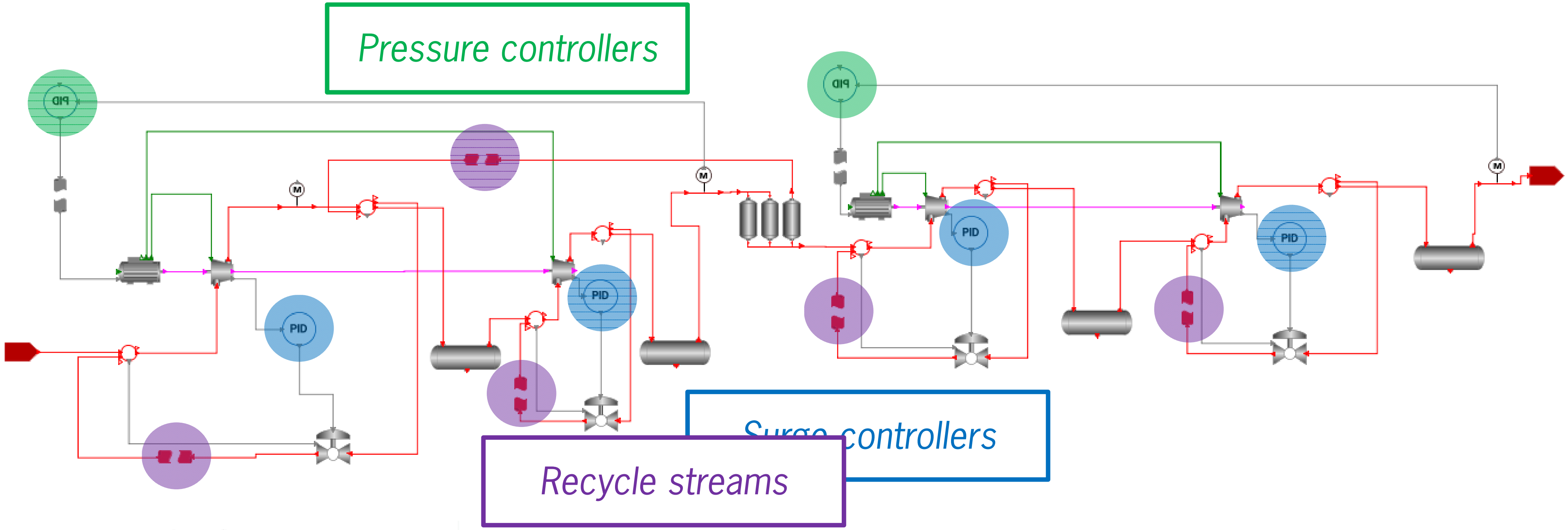
First principle equations and heuristics

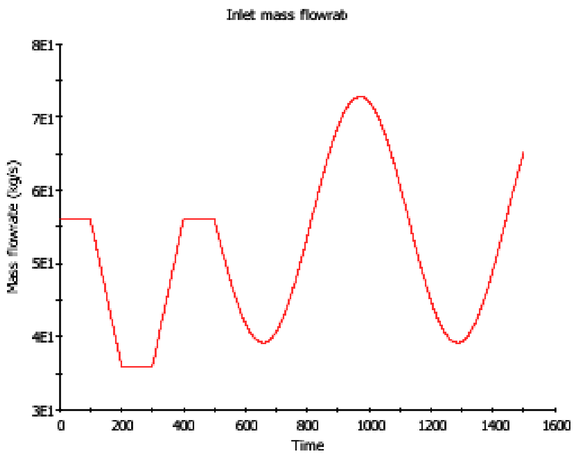
Flowsheet implementation and verification

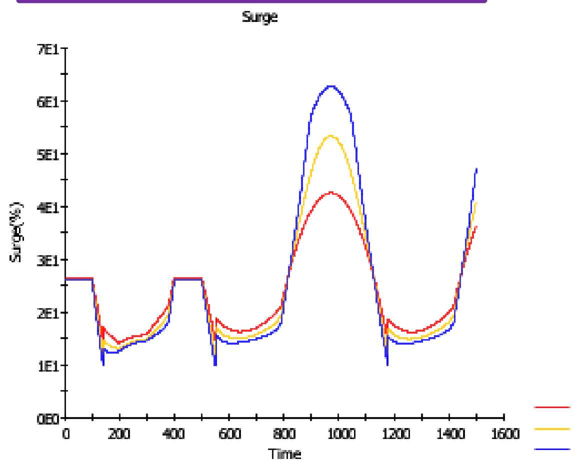
Control strategies

Compressor train – control strategies

IEAGHG Case B0







- Control system **simple to implement**
- **Recycles** can be easily handled
- Surge and final discharge pressure controllers
- By testing different flue gas flowrates, it is possible to tune the control system and analyse the effect of these **perturbations** on the system KPIs

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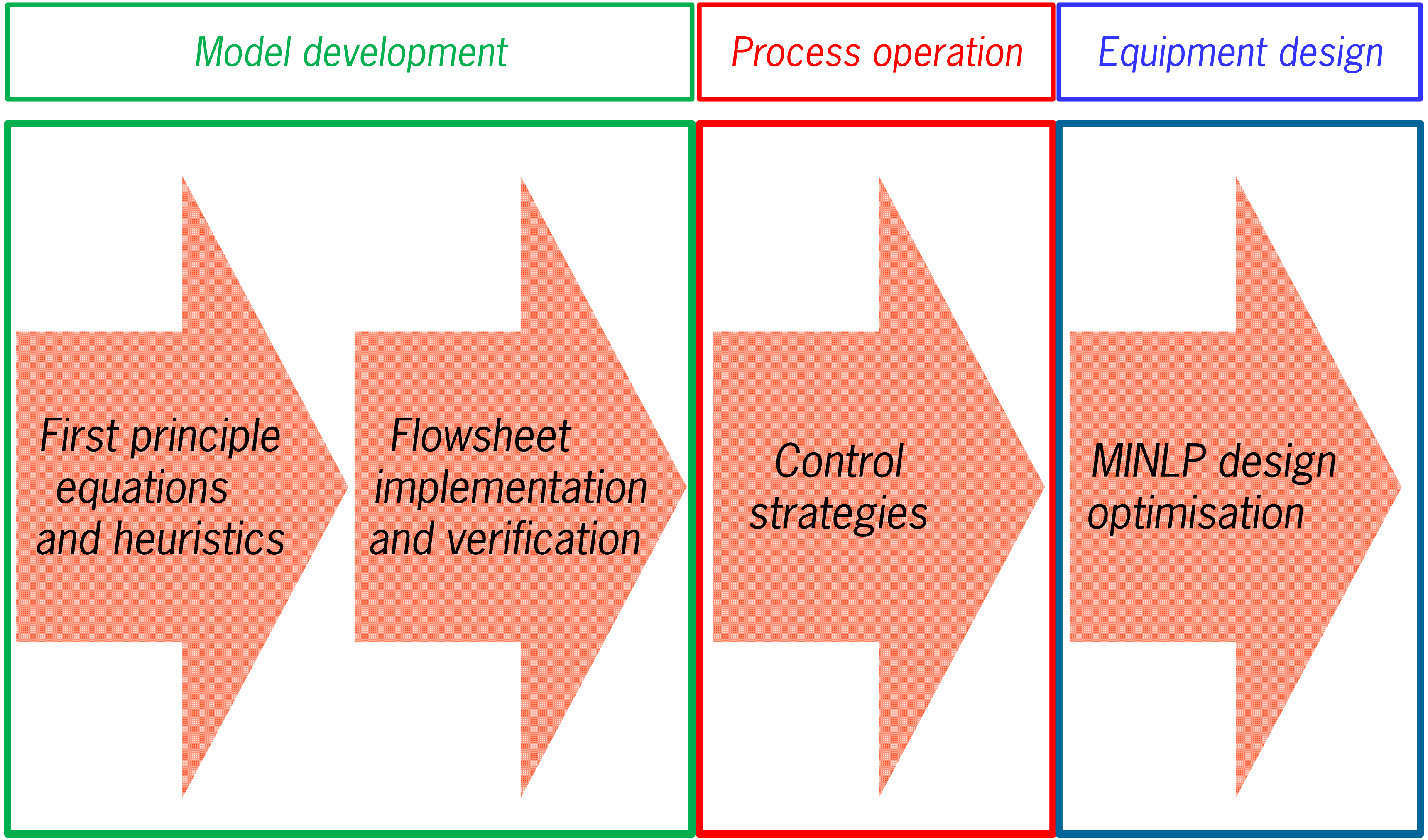
Overview



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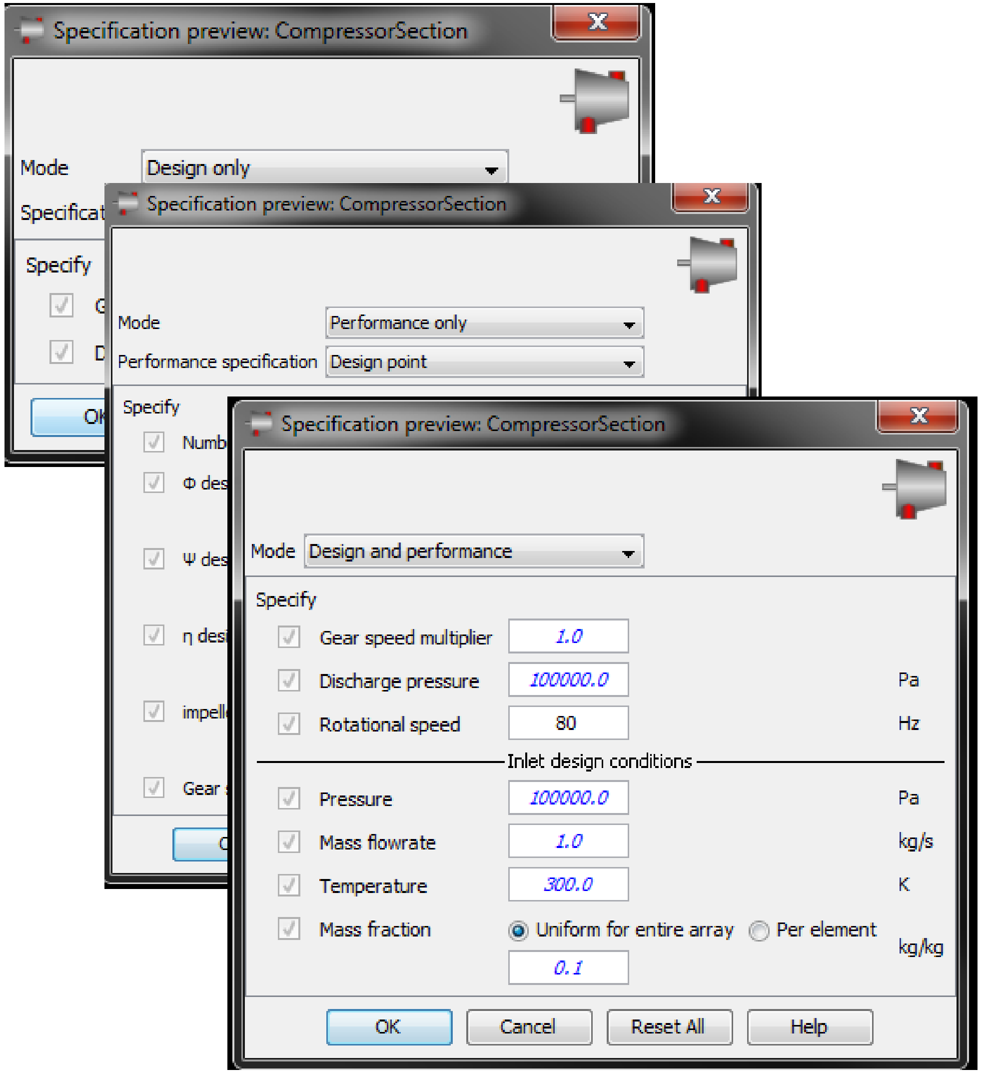
Compressor train design - conventional

Design methodology

For a given train configuration,

- First, ***design*** the compressor for a specified discharge pressure, where the inlet conditions come from upstream equipment.
- Then, run a simulation in ***performance mode*** introducing the diameter and design point calculated in the previous design.
- The user can skip the first step by using ***design/performance*** mode by giving the design conditions while operating at off-design.



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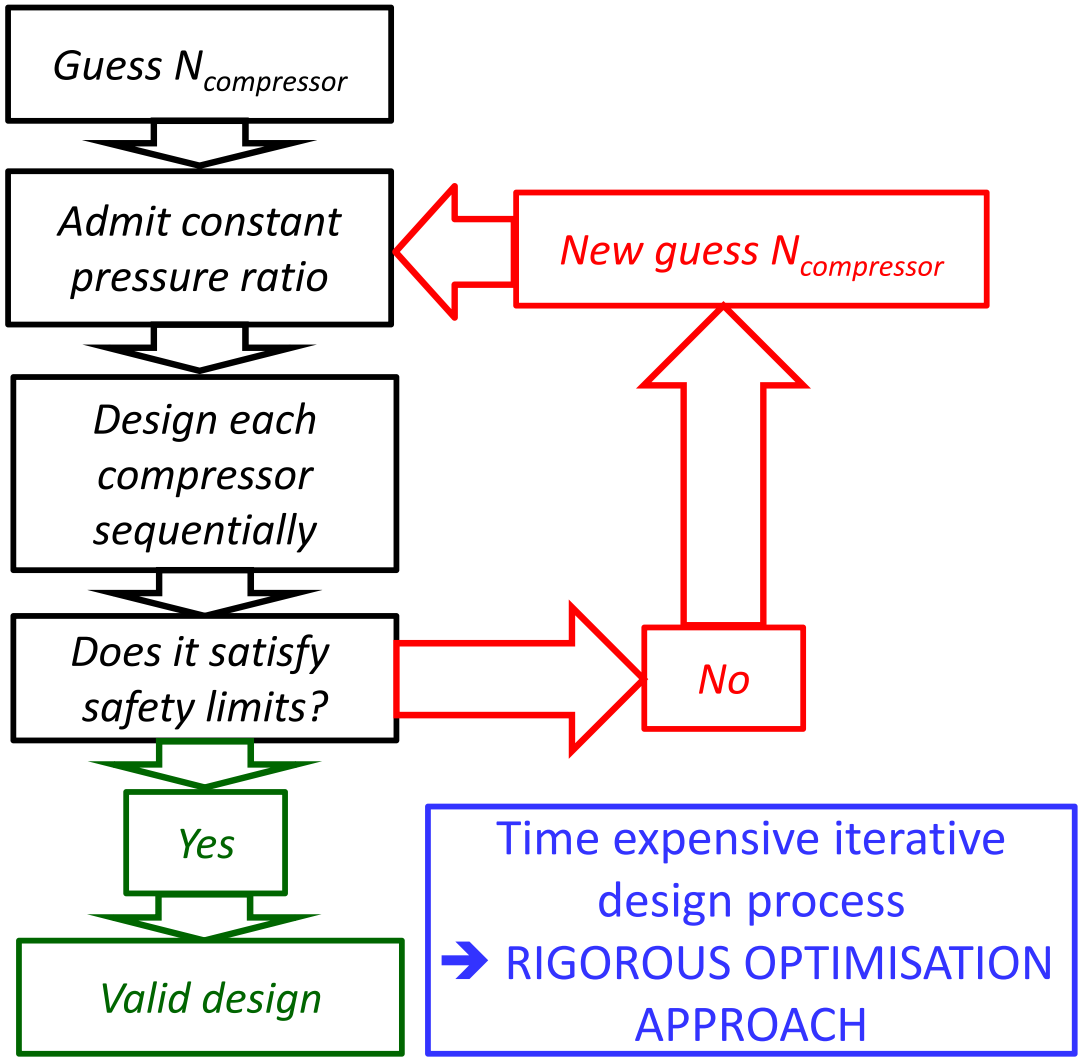
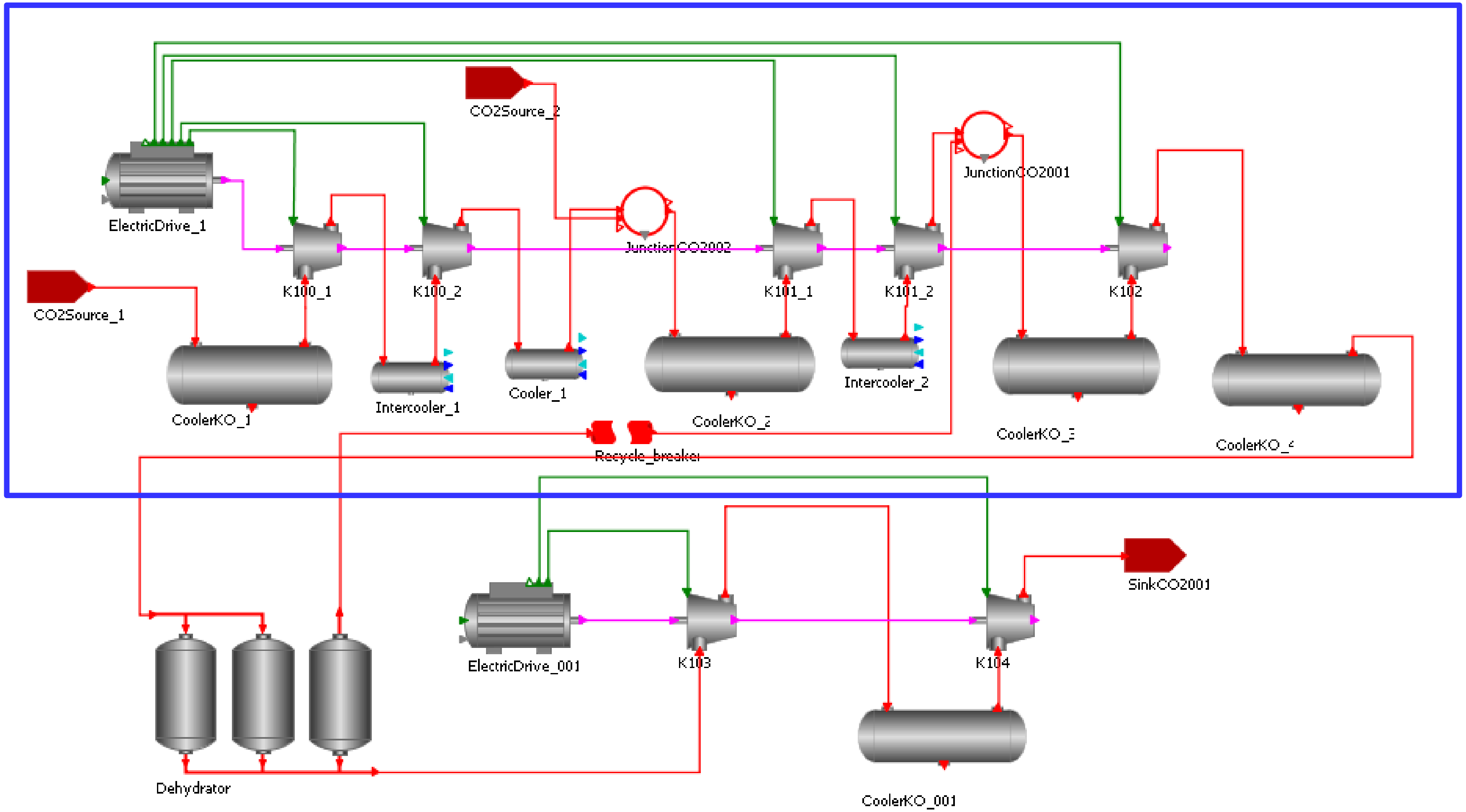


Compressor train optimisation

Concept



- Here focus on optimising the "first half" of the train (before dehydration)

Compressor train optimisation

Problem description (Based on Case A0 from the IEA GHG report)

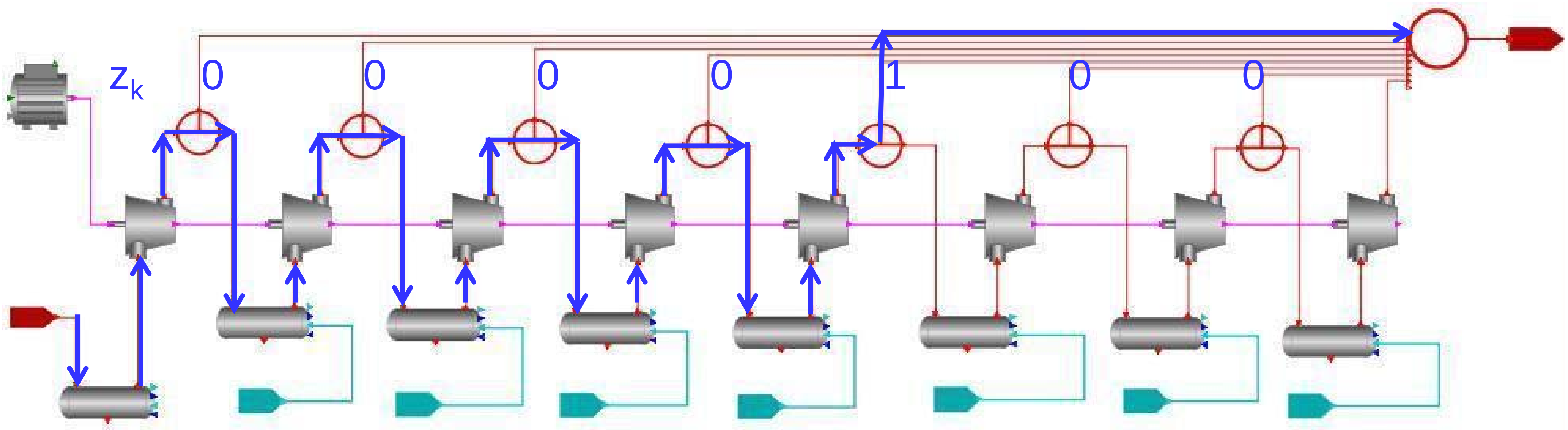
Objective: Minimize total cost

- CAPEX (Peters & Timmerhaus)
  - Compressors
  - Coolers
  - Electric Drive
  - Instrumentation and control
  - Project
  - Spare parts
- OPEX
  - Electricity
  - Cooling water
  - Maintenance
  - Interest

- Degrees of freedom
  - Number of compressor sections
  - Pressure ratio of each compressor
- Constraints
  - Final discharge pressure specification

Compressor train optimisation

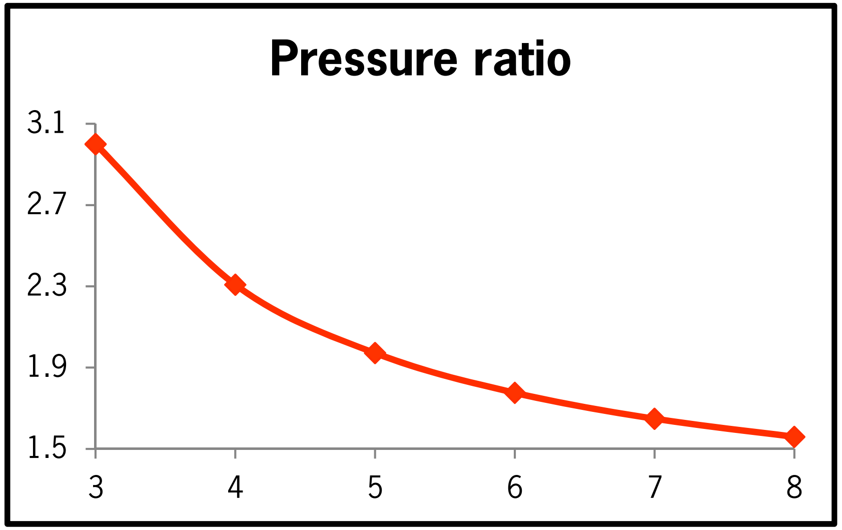
Superstructure

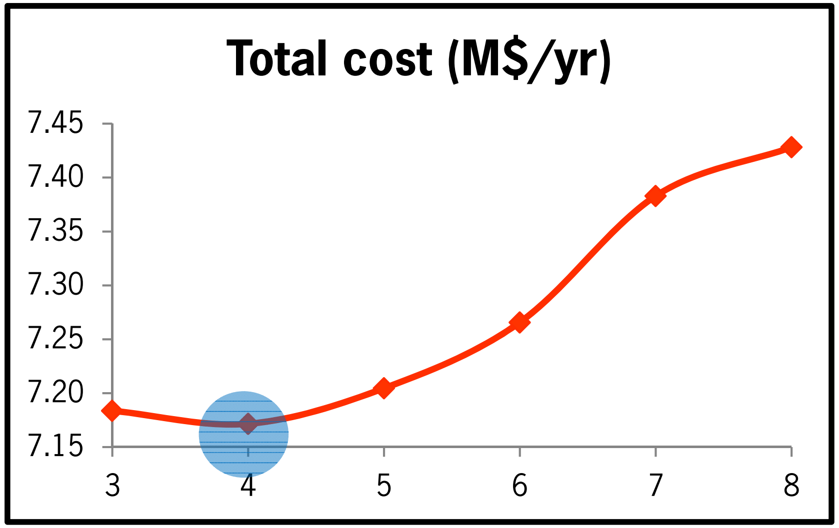


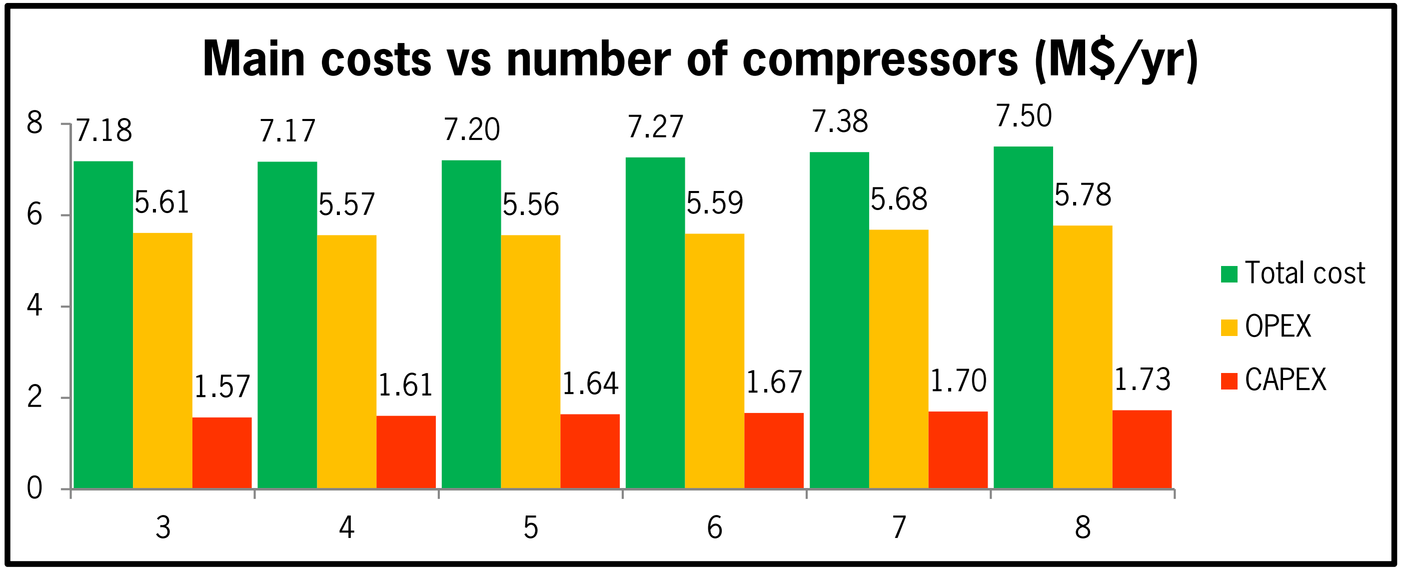
- Binary “flip variables” Z_k
  - Z_k determines whether compressor k is included or bypassed
  - e.g. $Z_5 = 1$ ➔ 5 compressors in train
- Number of coolers = Number of compressors
- By-passed compressors and coolers have zero cost

Compressor train optimisation

Total cost, CAPEX and OPEX







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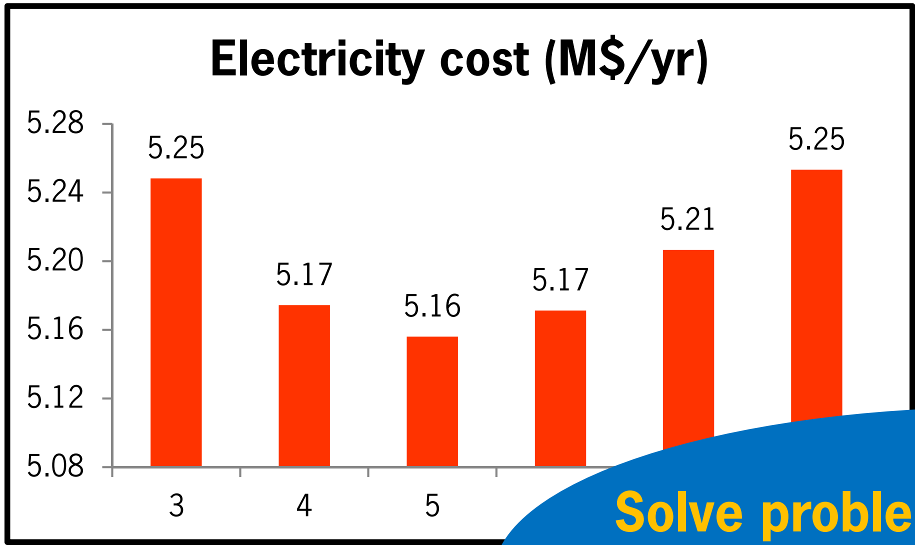
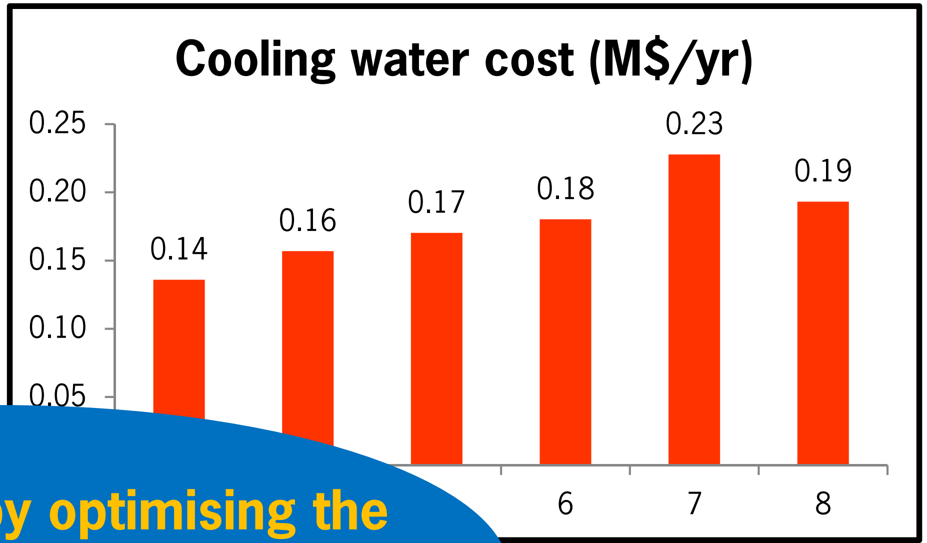
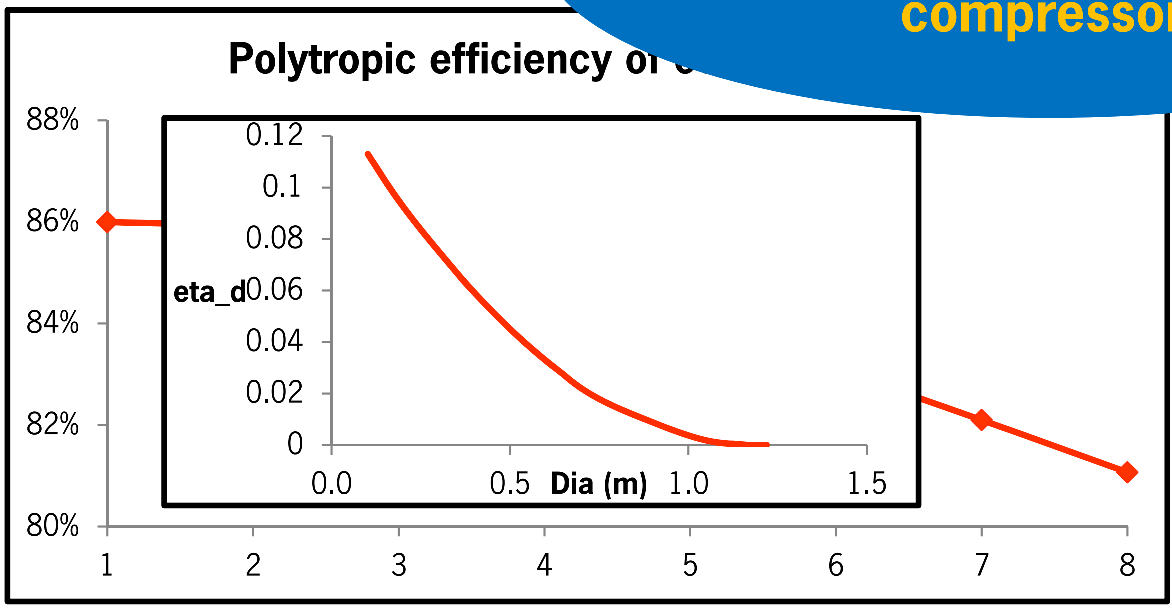
Compressor train optimisation

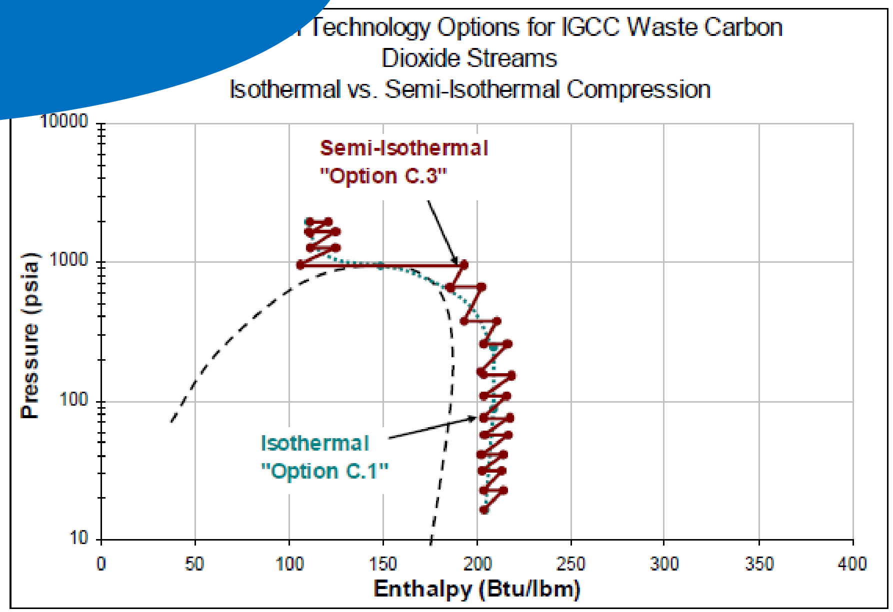
Operating cost, efficiency





Solve problem by optimising the pressure ratio of each individual compressor!





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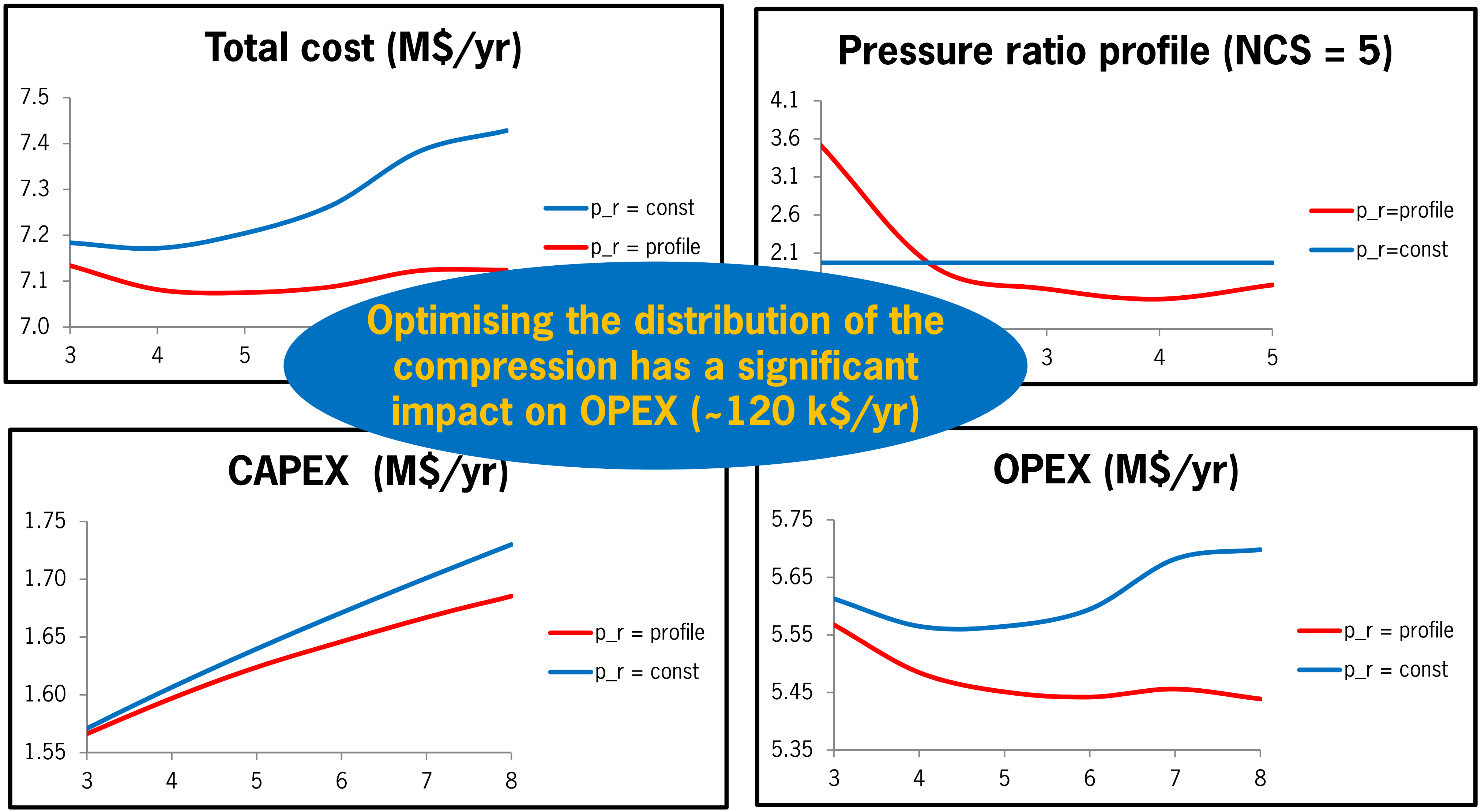
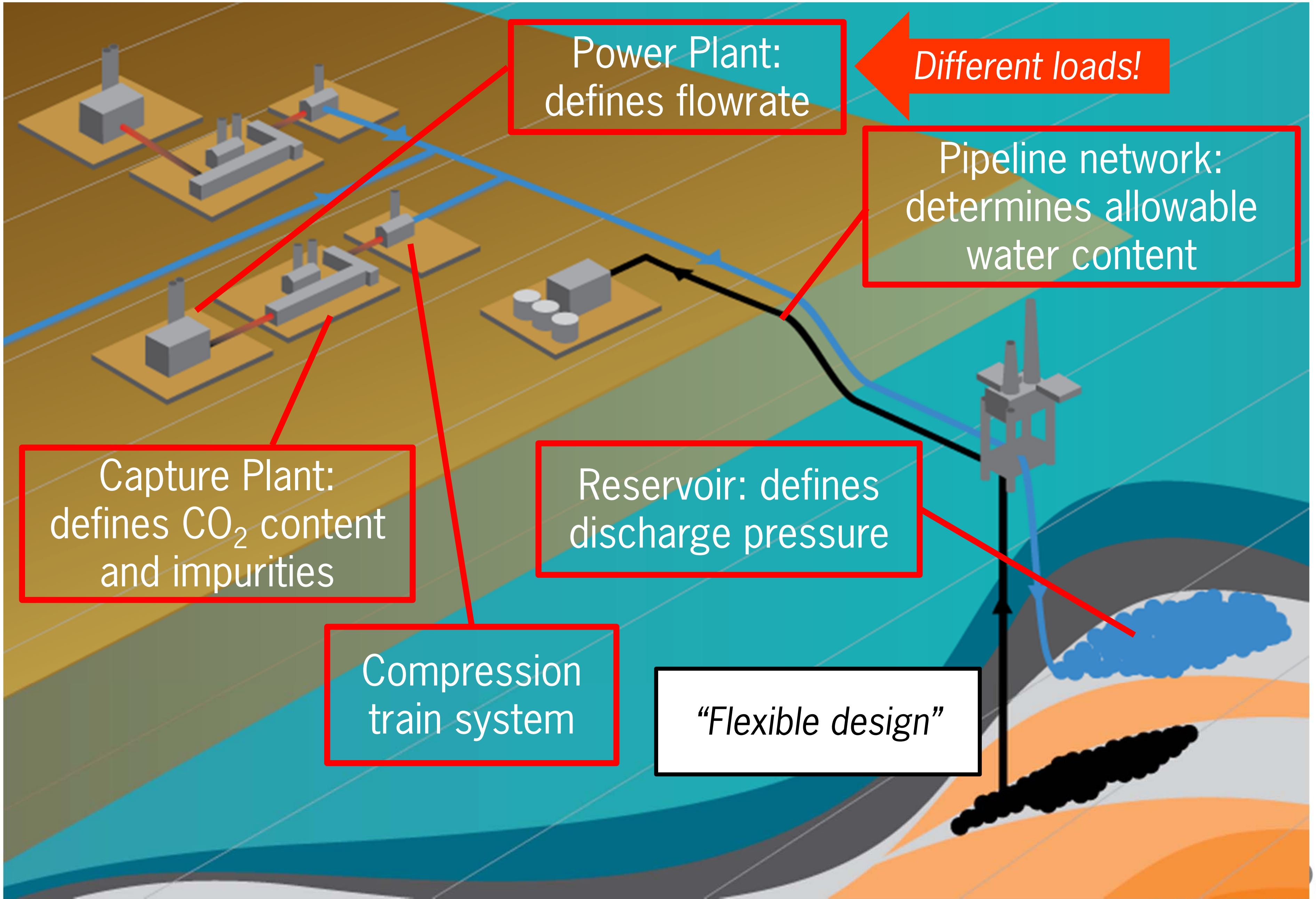
Compressor train optimisation

New formulation



Compressor train optimisation

CCS chain



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Overview

Model development		Process operation	Equipment design	
First principle equations and heuristics	Flowsheet implementation and verification	Control strategies	MINLP design optimisation	Multi-period optimisation

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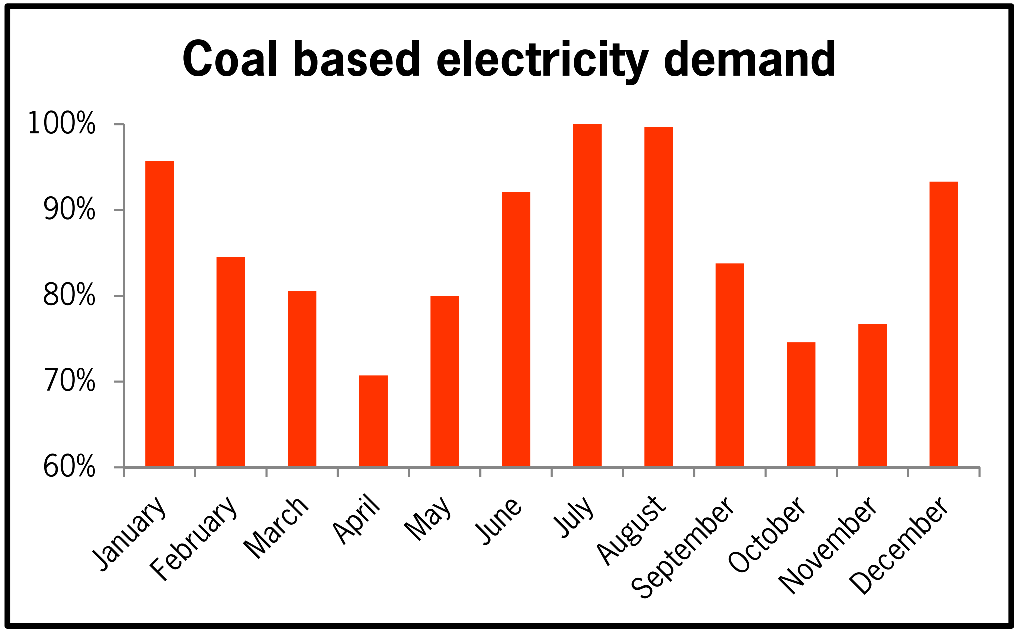
Multi-period optimisation

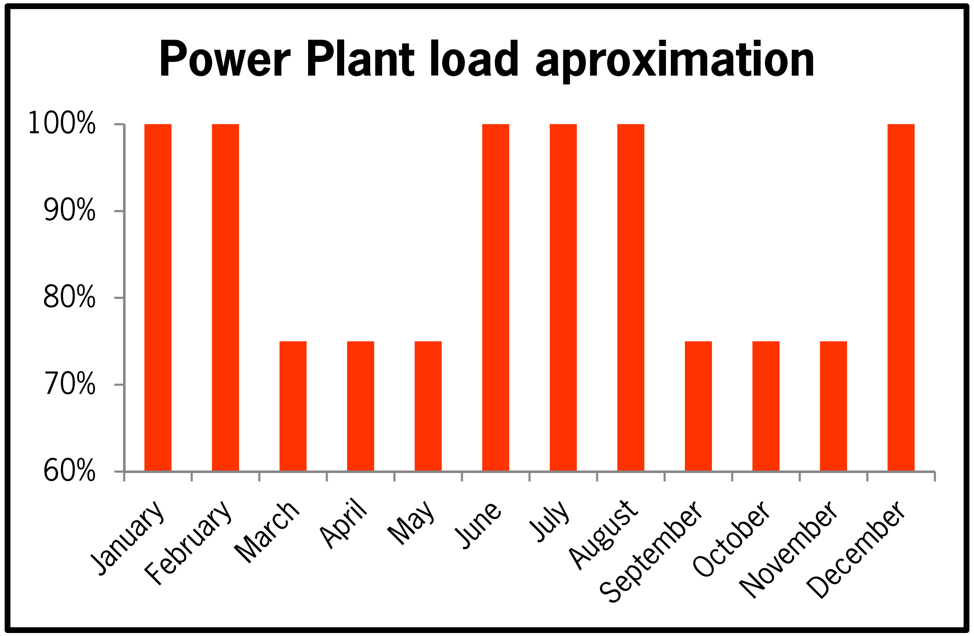
Design flexibility

- OPEX stability
  - Compressor **efficiency** greatly **decreases** when operating in “off-design” conditions
  - Major increment of OPEX
  - Important if the compression train operates in “off-design” conditions for a significant amount of time
- Safety limits
  - Discharge **temperature limit** determined by materials of construction
  - Electric drive can only operate within a certain **range of speeds**
    - range may not be sufficient to maintain desired discharge pressure
- Above issues are already known at the design stage
  - → Avoid relying on control system or safety procedures for resolving them
- Design system to operate over **set of anticipated scenarios**
  - Scenario probabilities taken into account in determining **expected value** of OPEX in objective function

Multi-period optimisation

Scenarios





*U.S. Energy Information Administration (EIA)

$$\text{Total cost} = \text{CAPEX}_{100\%} + 0.5^*\text{OPEX}_{100\%} + 0.5^*\text{OPEX}_{75\%}$$

- Power plant load changes during the year
  - Electricity **demand fluctuations**
  - Optimising design for only 100% load might not be the best approach
- **Two scenarios** (100% load and 75% load) with equal probability were taken into account in the multi-period design optimisation

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Multi-period optimisation

Formulation

- Decision variables
  - Number of compressors
  - Pressure ratio of each individual compressor
  - Speed of drive in “off-design” scenario

- Safety limits (for both scenarios)
  - Maximum discharge temperature
  - Minimum surge margin
  - Final discharge pressure specification

Multi-period optimisation

Results

	Previous train	New train	Δ (%)
Load	100%	75%	-
$N_{compressor}$	5	5	-
$Nu_{100\%}$ (Hz)	80	80	-
$Nu_{75\%}$ (Hz)	76.6	76.2	-0.5%
C_{cap} (M$/yr)	0.85	0.86	0.5%
C_{ope} (M$/yr)	1.78	1.80	1.3%
C_{tot} (M$/yr)	2.63	2.66	1.0%

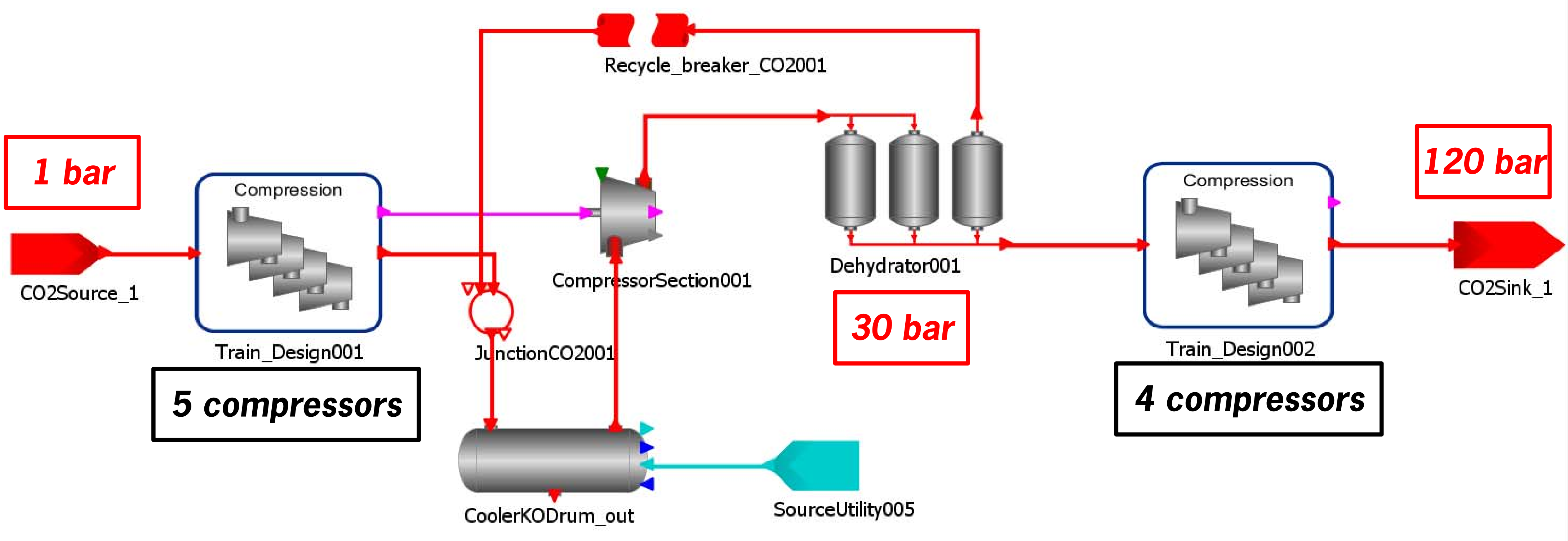
	Pressure ratio				
Compressor	1	2	3	4	5
Previous train	3.33	1.88	1.56	1.53	1.87
New train	4.05	1.89	1.61	1.33	1.75

	Surge (%)				
Compressor	1	2	3	4	5
Previous train	8.1	8.3	8.4	8.3	8.4
New train	10	10.3	10.7	11.4	12

- New train design is 1% more expensive than previous design
  - due to the surge lower limit constraint (10% minimum)
- HOWEVER, previous train design **doesn't satisfy** all operational constraints for the "off-design" scenario
- The train **work balance** changed, compressing more in the first 3 compressor due to the efficiency penalty in the "off-design" scenario
- Significantly increase in **process flexibility** with a small cost penalty

Full train optimisation

Results – IEA GHG Case A0



9 compressors

C_{cap} = **16.4 M$**

C_{ope} = **4.2 $/tonne CO_2**

Conclusions

Summary

- Rigorous compressor model
  - Performance maps (1D, 2D and dimensionless)
  - Design heuristics
- Compression train simulation
  - Model verification (steady state)
  - Control system implementation
- Rigorous multi-period mixed-integer optimisation
  - Design the train considering a set of anticipated scenarios
  - Minimises total cost (CAPEX + OPEX)
  - Ensures all operational constraints are met under all scenarios
- Techno-economical decisions based on a rigorous design modelling tool
- Applicable to any range of conditions and gases (CO_2, LNG, etc.)

Acknowledgements

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Thank you!

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