PROBABILISTIC TECHNIQUE FOR SOLVING COMPUTATIONAL PROBLEM:

APPLICATION OF ANT COLONY OPTIMIZATION (ACO) TO FIND THE BEST SUPERCRITICAL CO_2 (sCO_2) BRAYTON CYCLE CONFIGURATION

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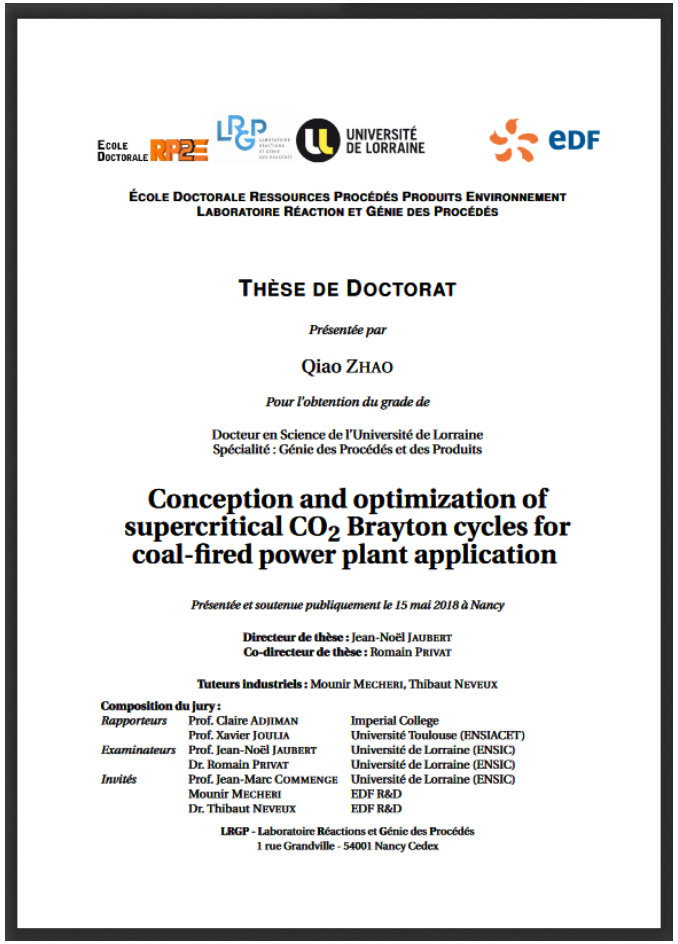
Acknowledgment


ÉCOLE DOCTORALE RP2E

LRGP

UNIVERSITÉ DE LORRAINE

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ÉCOLE DOCTORALE RESSOURCES PROCÉDÉS PRODUITS ENVIRONNEMENT
LABORATOIRE RÉACTION ET GÉNIE DES PROCÉDÉS

THÈSE DE DOCTORAT

Présentée par

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Pour l'obtention du grade de

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Spécialité : Génie des Procédés et des Produits

Conception and optimization of supercritical CO_2 Brayton cycles for coal-fired power plant application

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The results of this study are extracted from the PhD performed by Qiao ZHAO (EDF & LRGP) from 2015 to 2018

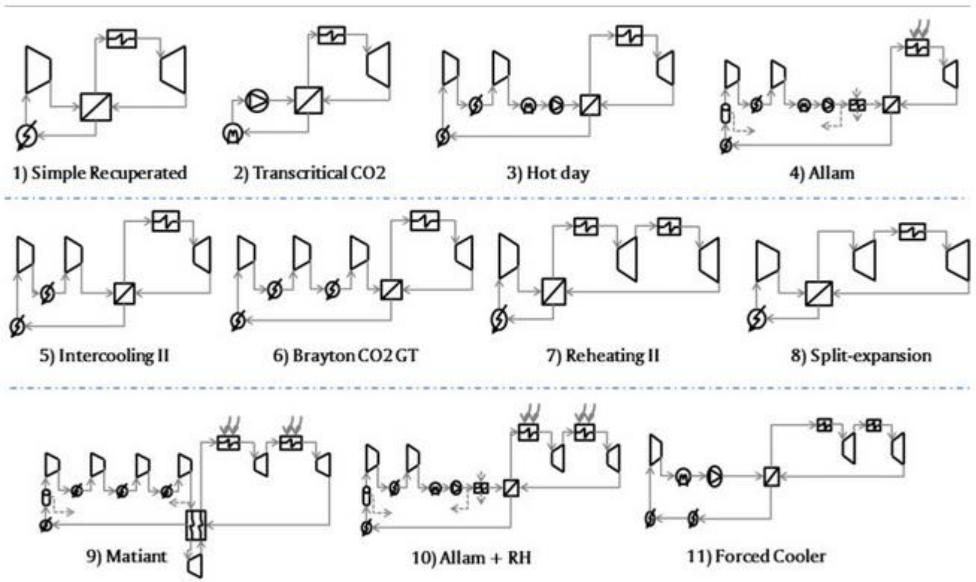
http://docnum.univ-lorraine.fr/public/DDOC_T_2018_0080_ZHAO.pdf

Outline

Introduction and Context

Which sCO_2 cycle for what application

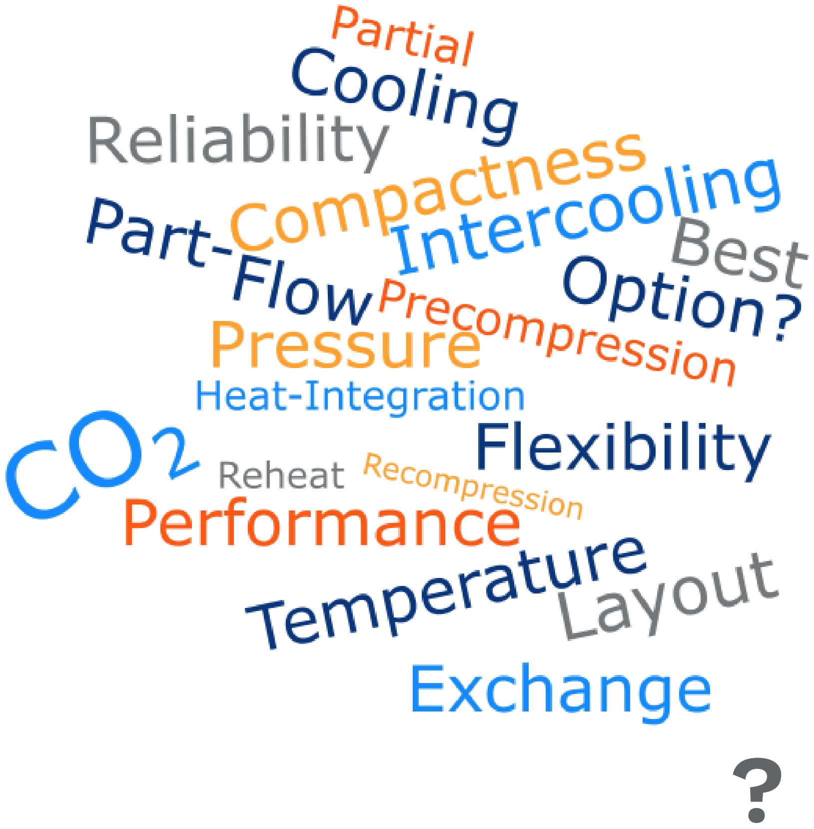
Many many cycle configurations [5] …



Source : Crespi et al. 2017

…and many parameters :

Max./min temperature and pressure, number of reheat, intercooling, part-flow ratios…



Introduction and Context

Sensitivity analysis VS computational optimization

Sensitivity analysis:

- Step by step "hand" calculations/runs
- Non-automatic cycle layout modification
- Manpower time consumption
- Low number of studied cases (risk of missing optimal solution)

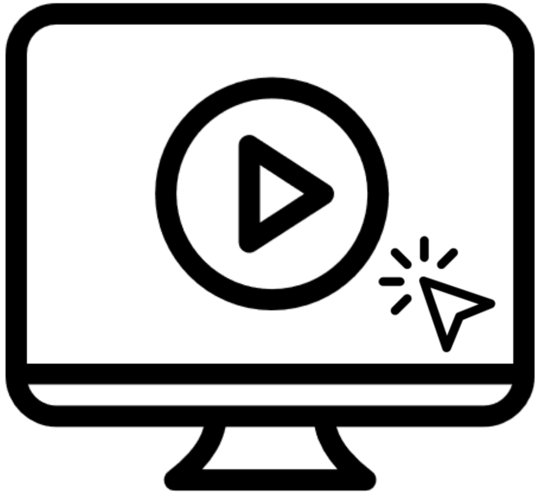
Computational optimization:

- One initial interaction (setting and rules)
- Automatic cycle layout modification and simulation runs
- Computer time consumption
- Computer pre-selection of best cases among high number of possibilities

Introduction and Context

Code approach VS Commercial existing software

VS



- ✓ Very specific to a given problem and methodology (accurate and refined)

- ✓ Existing tools and data
- ✓ No need for code skills

Outline

1. Introduction and context
2. Objectives
3. Methodology
4. Results
5. Conclusions and Perspectives

Objectives

Objectives of the PhD performed by Qiao ZHAO, 2015-2018 [4]:

- ✓ Check the best thermodynamic model for modeling CO_2, particularly near the critical point (comparison with available experimental data)
- ✓ Model and optimize a simple sCO_2 Brayton cycle layout
- ✓ Create and optimize a superstructure using both "commercial process software" and "solver"
- ✓ Perform a multi-objective optimization : energy & economic optimization

Objectives of this paper:

- ✓ Explain the global methodology used in the PhD (superstructure, optimization routine,…)
- ✓ Give the main assumptions and parameters of the study
- ✓ Share the main results and lessons learned
- ✓ Outline the perspectives

Outline

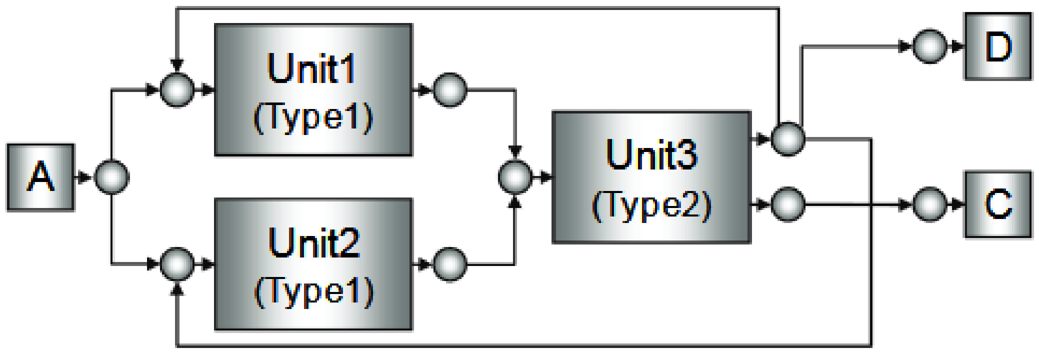
1. Introduction and context
2. Objectives
3. Methodology
   - Concept of Superstructures
   - Non-Linear optimization (definitions, optimization parameters and details)
   - Optimization routine
   - Problem definition and studied cases
4. Results
5. Conclusions and Perspectives

Methodology

Automatic flowsheet generation: superstructure

How to enable automatic switch between cycle architecture ?

Optimization solver = able to modify variables (continuous or integer) → **Make possible to select a cycle architecture by changing a variable** → **One big architecture containing "all" architectures to be studied (and even more?) → superstructure**



The superstructure can easily be created in the Process Simulation Software, by using "split" modules (concept of "switch")

Strongly non-linear problem

!

Methodology

Optimization parameters: seed concept, objective function,

❑ **Non-linear problem** → can't be solved with classic/basic optimization methods (like gradient…)

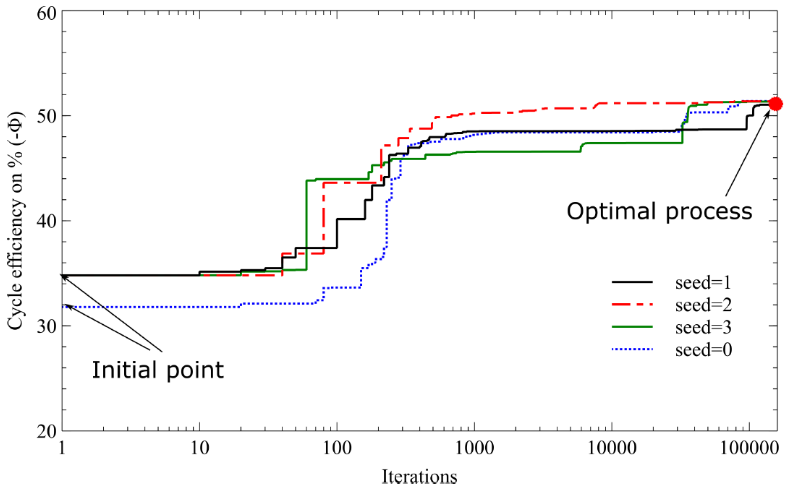
➔ Mixed Integer NonLinear Programming (MINLP) approach combined with meta-heuristic optimization technique : Mixed Integer Ant Colony Optimization (MIDACO) solver

MIDACO® solver

- ✓ Probabilistic technique
- ✓ Can be applied to continuous (NLP), discrete/integer (IP) and mixed integer (MINLP) problems…
- ✓ Single or Multi-objective optimization
- ✓ Suitable for equality or inequality constraints

Seed concept (randomness)

- ✓ Randomness of the initial ant colony population is controlled by a pseudo-random number generator called "seed"
- ✓ More promising strategy to execute several short runs of with different random seeds than performing only one very long run

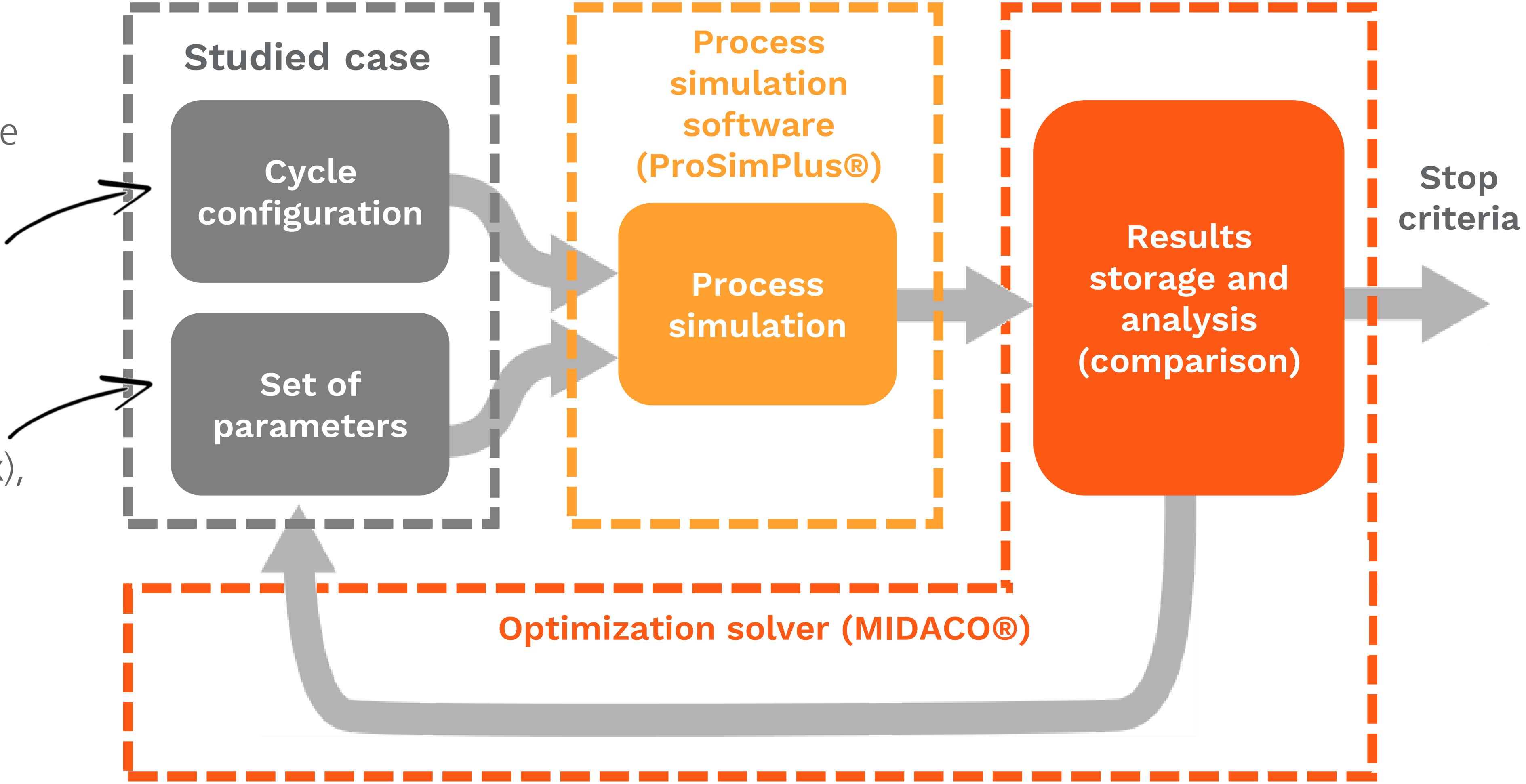


Methodology

Optimization Routine = Coupling Process Simulation Software and Optimization Solver

One initial interaction by the **user** to specify:

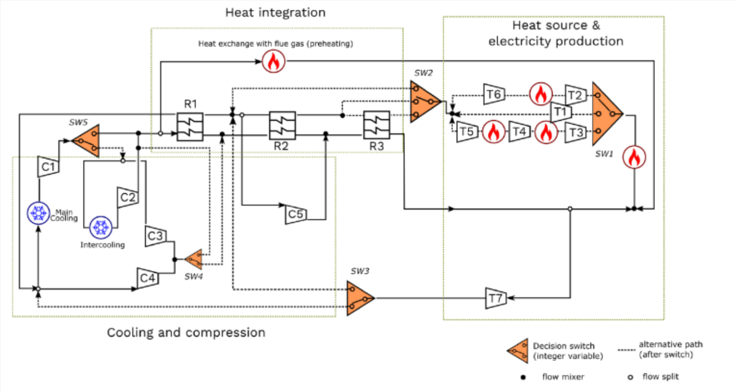
- ✓ Cycle architectures to be studied
- ✓ Operating conditions, boundaries (min and max), parameters values…



Methodology

Problem definition and parameters

Superstructure



- ❑ Three “2-paths switches” and four “flow splits”
- ❑ Two “3-paths switches”
  → $2^{(3+4)} \times 3^2$ = 1 152 alternatives
- ❑ 32 unit operations (incl. splitters and mixers)

Variables and bounds

- ❑ Main compressor inlet pressure (3.3 to 10 MPa)
- ❑ Compressors’ outlet pressure (3.3 to 30 MPa)
- ❑ Cooling temperature (31 to 100°C) – (~87 to 212°F)
- ❑ Part flow rates (0 to 0.5)
- ❑ Heat exchanger cold and hot side outlet temperature (31 to 620°C
- ❑ Turbine ratios (1 to 5)

Assumptions, fixed parameters

- ❑ Turbine inlet temperature = 620°C (1148°F)
- ❑ CO_2 flowrate before main cooling (kg/s) = 6000
- ❑ Minimum-Tpinch (K) = 10 (if relevant)
- ❑ Turbine is. efficiency (-) = 0.9
- ❑ Compressor is. efficiency (-) = 0.89
- ❑ Pressure drop in every component (% of inlet pressure) = 1

See more in the thesis report [4]

Methodology

Case study: specification of objective function(s)

Case 1 : Mono-objective function

Search for best performance (cycle net efficiency) in a given frame

➔ Technical constraints such as minimal pinch value (10K) to avoid theoretical results with "infinite heat exchanger surface)

Case 2 : Multi-objective functions

Search for:

1. Lowest electricity production cost (LCEO)
2. Lowest investment costs (CAPEX
3. Best performance (cycle efficiency)

➔ **Relaxing of technical constraints**

Optimization result = initialization of

See more details (formulas, economic hypotheses) in the thesis report [4]

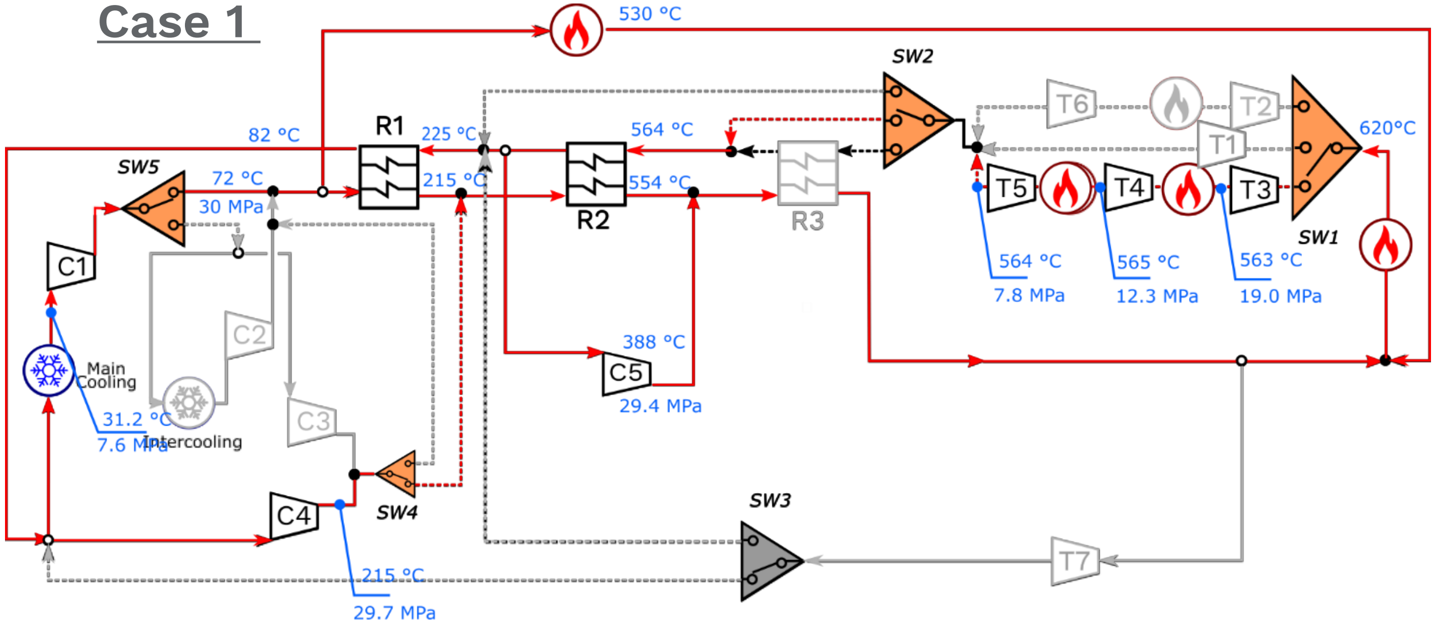
Outline

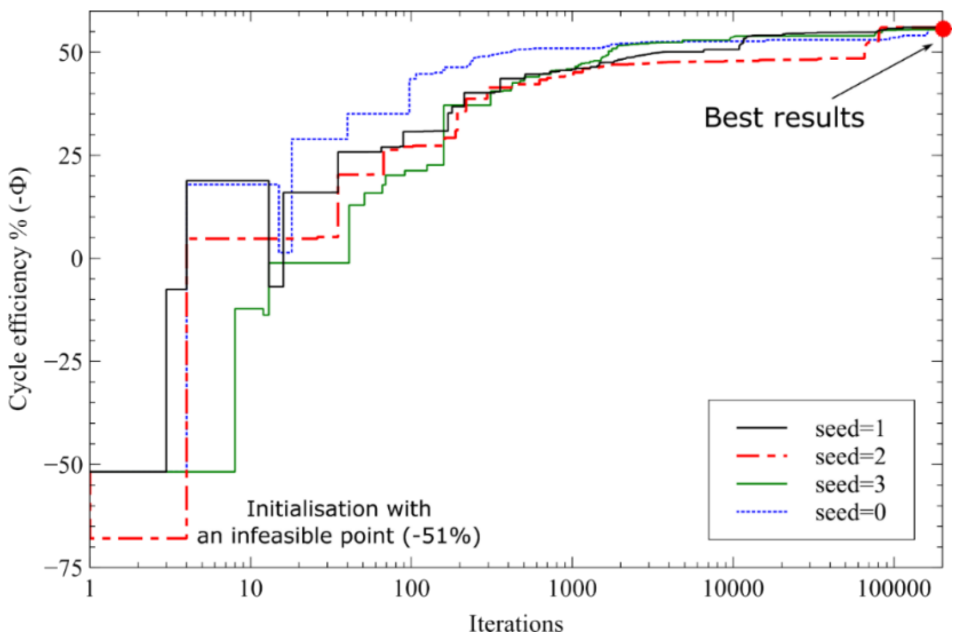
1. Introduction and context
2. Objectives
3. Methodology
4. Results
   - Mono-objective optimization results
   - Multi-objective optimization results
5. Conclusions and Perspectives

Results

Mono-objective results: performance & energy maximization

Case 1





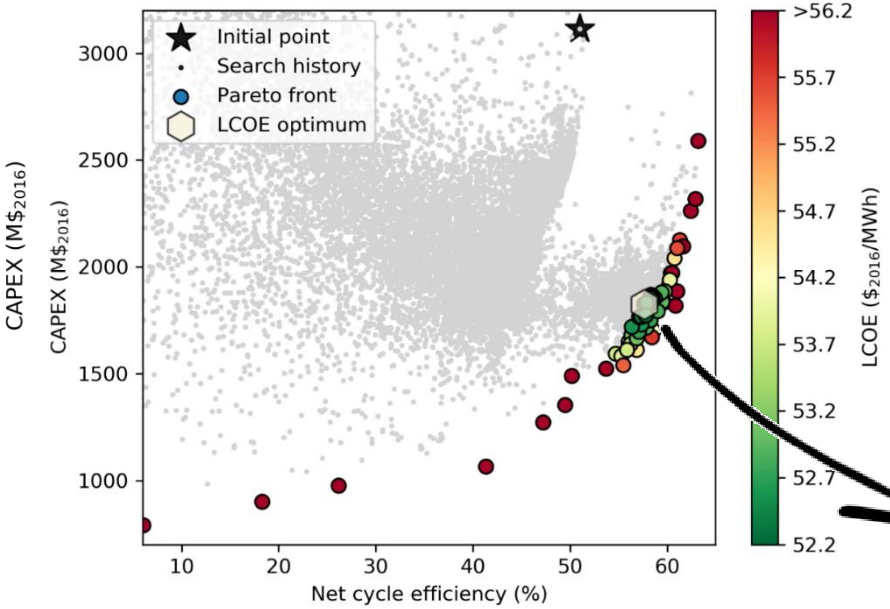
$\eta = 51$ %

Double reheating-double recompression-preheating cycle

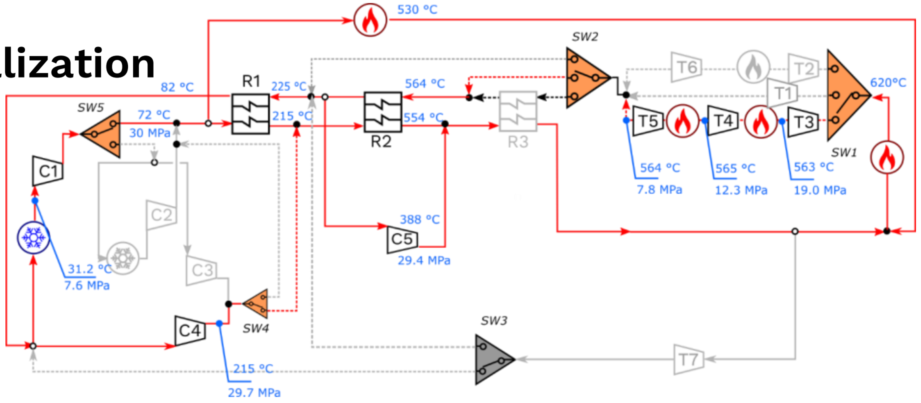
→ Initialization of next case

Results

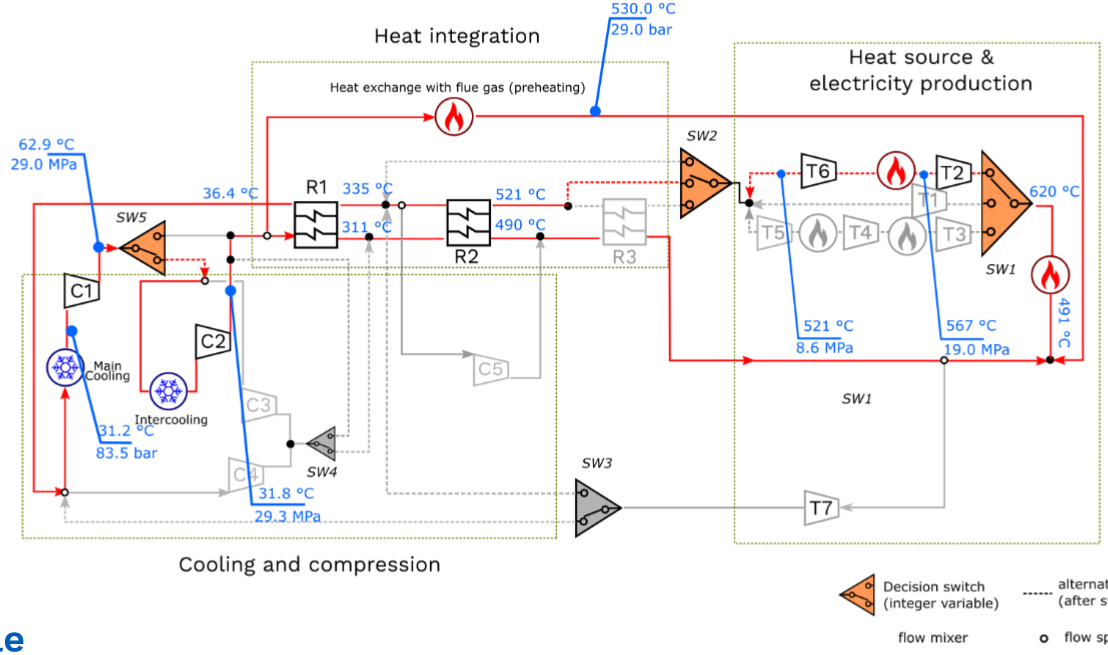
Multi-objective results: Cost of electricity & Investment costs & Performances



Initialization



New solution

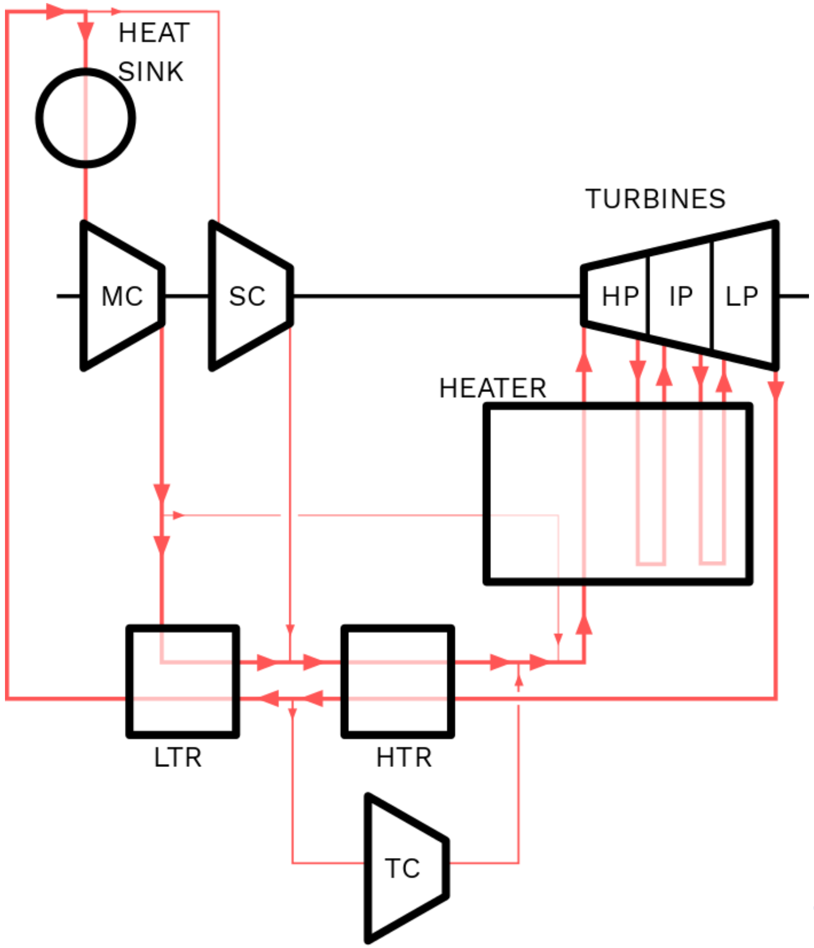


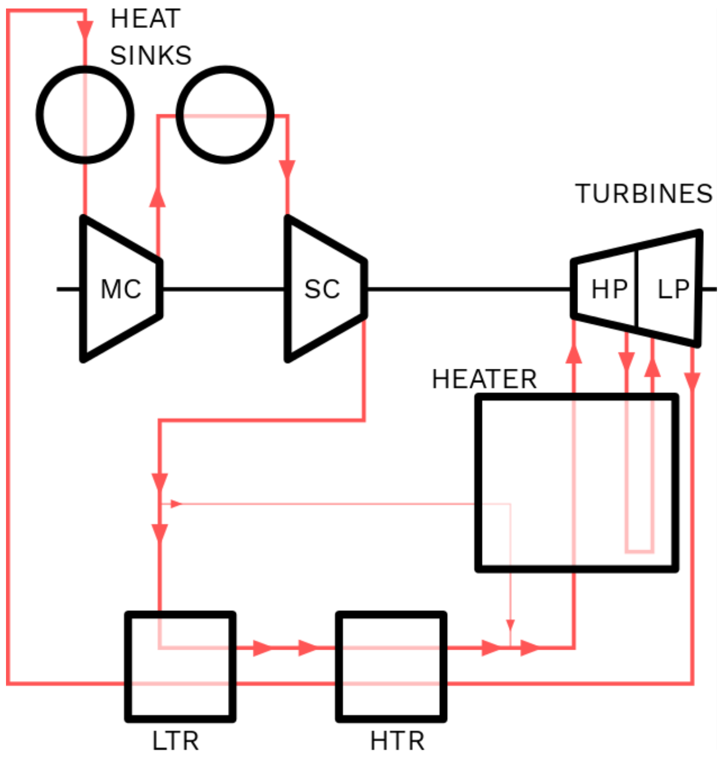
η = ~ 57 %

Single reheating - intercooling – no recompression-preheating cycle

Results comparison

Mono-objective	vs	Multi-objective
0	Intercooling	1
30 MPa	C. pressure outlet	29.3 MPa
2	Recompression	0
10 K	LTR pinch	5K
10 K	HTR pinch	24K
2	# of Reheat	1
7.8 MPa	LP-Turbine outlet pressure	8.6 MPa
51 %	Net. Eff.	57 %*
3,124 M$	CAPEX	1,826 M$
61 $/MWh	LCOE	52.3 $/MWh





*thanks to very low LTR pinch value

Outline

Conclusions and perspectives

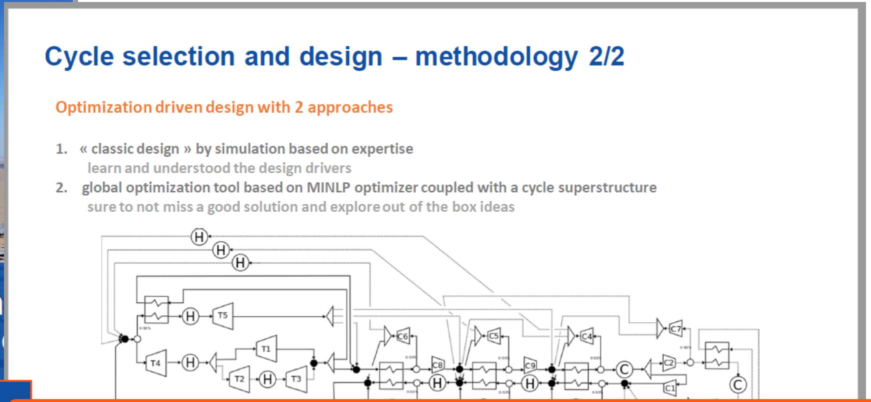
- ✓ Successful coupling of "commercial software" and "optimization solver"
- ✓ Interesting and Encouraging results
- ✓ Impact of the objective function and hypotheses
- ✓ List of advantages and drawbacks of this method

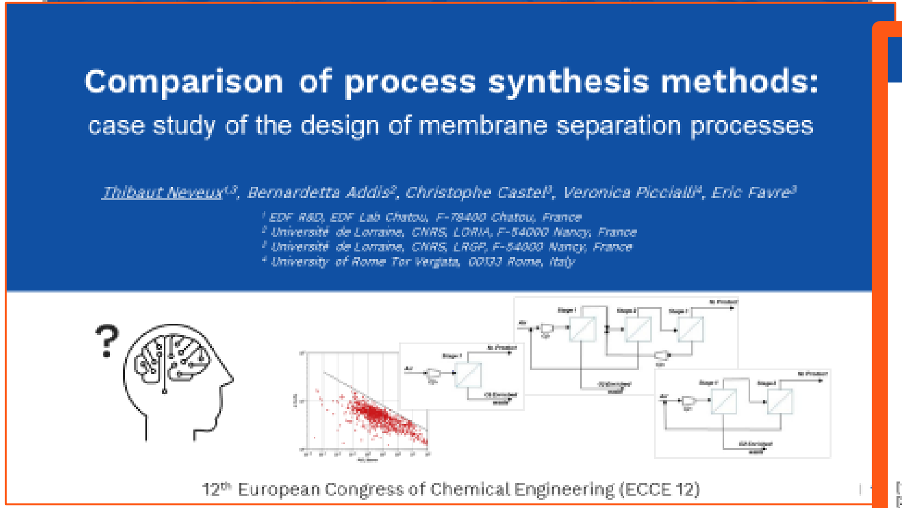
- ➢ Check, benchmark and refine the economic models
- ➢ Improve the CPU consumption time (several opportunities like meta-models…)
- ➢ Improve the reliability of calculation: inclusion of uncertainties, variability…
- ➢ Extension of the methodology to other applications
- ➢ Comparison of different stochastic/probabilistic optimization methodologies

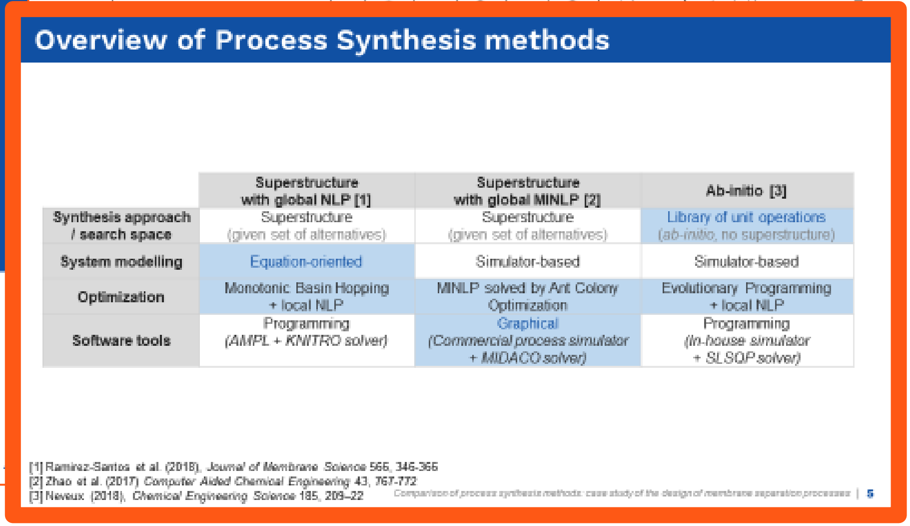
Related optimization topics in EDF R&D…

12th European Congress of Chemical Engineering (ECCE12) – sept. 15th/16th 2019

by Dr. Thibaut NEVEUX







Overview of Process Synthesis methods

	Superstructure with global NLP [1]	Superstructure with global MINLP [2]	Ab-initio [3]
Synthesis approach / search space	Superstructure (given set of alternatives)	Superstructure (given set of alternatives)	Library of unit operations (*ab-initio*, no superstructure)
System modelling	Equation-oriented	Simulator-based	Simulator-based
Optimization	Monotonic Basin Hopping + local NLP	MINLP solved by Ant Colony Optimization	Evolutionary Programming + local NLP
Software tools	Programming (*AMPL + KNITRO solver*)	Graphical (*Commercial process simulator + MIDACO solver*)	Programming (*in-house simulator + SLSQP solver*)

[1] Ramirez-Santos et al. (2018), *Journal of Membrane Science* 566, 346-366
[2] Zhao et al. (2017) *Computer Aided Chemical Engineering* 43, 767-772
[3] Neveux (2018), *Chemical Engineering Science* 185, 209–22

Comparison of process synthesis methods: case study of the design of membrane separation processes | 5

123 - Machine Learning Based Design of a Supercritical CO_2 Concentrating Solar Power Plant

Nabil, Tahar; Le Moullec, Yann; Le Coz, Adrien

EDF R&D China

Thank you for your attention

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