A methodology for designing heat engines in industrial mass/heat integration problems based on MILP models

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Abstract:

The use and reuse of effluents within process units, instead of being discarded to the environment with costly treatments, may result in substantial operating cost reduction. Additionally, the heat content of those effluents can be recovered reducing the global utility consumption. However, in numerous cases, the use of heat engines (heat pumps, Rankine cycles …) can help increase the energy recovery and provide heat potentials better suited to the current needs of the industrial process.
Selecting and designing such technologies in a simultaneous mass and heat integration problem is difficult and time consuming. Indeed, contrary to a classic heat integration problem, the heat requirements created by the mass allocation network are unknown prior to the whole design, and the size of the problem is important. Besides, designing sequentially the mass allocation network (MAN) and the heat exchanger network (HEN) can lead to sub-optimal solutions.
This paper proposes a three-step methodology based on MILP models to evaluate economically suitable technologies that can help improve the overall profitability of the solutions while reducing strongly the computational time.
After the selection of parameters during a preliminary step, a first MILP model evaluates economically a great number of technologies simultaneously. In this model, the objective function is the sum of the operating costs, the capital costs of the heat engines and an estimation of the associated HEN capital costs (roughly estimating the number of heat exchangers and their area). The problem size remains sufficiently small to be solved quickly. By the end of this step, the best potential candidates of heat engines are identified and used in a second MILP solving the larger problem including the actual HEN design.
The performances of the proposed methodology are assessed using a case study and discussed.

Keywords:

Mass integration, Heat integration, MILP, HEN, Heat Engines

1. Introduction

Nowadays, in the light of environmental and economic issues, policies are carried out in order to reduce energy consumption. The industrial sector is particularly concerned with this issue. Indeed, in France, 19% of final energy consumed comes from industrial activities in 2015 [1]. Techniques like process integration and pinch design are often employed for material and heat recovery as well as cost reduction. Optimizing the design of heat exchangers network (HEN) and mass allocation network (MAN) of industrial processes can lead to important GHG emission reductions and cost savings as energy and material consumptions are reduced. Moreover, the energy consumption can also be decreased by the implementation of heat engines in the industrial process that can lead to cost savings. Therefore, a methodology is developed here in order to design heat engines (HE) in industrial process during mass/heat integration problems.

The question of identifying suitable heat engines to industrial process has been tackled by several studies before, considering a heat integration problem. Townsend [2] proposed rules for appropriate placement of heat pumps in process networks for the minimization of utility consumption. Becker

[3] developed a methodology for the integration of heat pumps in industrial processes. Their operating conditions (condenser and evaporator temperatures) are computed through a multi objective optimization problem and heat pumps are chosen among a heat pump data base. Thibault [4] developed a methodology based on Grand Composite Curve analysis and an optimisation problem for integrated heat pumps in industrial processes. His criterion for designing heat pumps is the global exergy cost. Finally, Farhat [5] and Bagajewicz [6] extend the methodology, combining Total Site Analysis and the integration of thermodynamic energy conversion systems.

However, these authors only dealt with classic heat integration problem, and did not address the case of simultaneous mass and heat integration, contrary to the works of Ghazouani [7-9]. Indeed, the presence of material streams in the industrial process complicates the resolution. The mass allocation is unknown, thus the heat requirements created by the allocation of mass streams is also unknown. Therefore, the analysis of the composites curves to help configuring the problem prior to the optimisation cannot be done. Moreover, the design of the mass allocation network and heat exchanger networks can be a large scale and a time consuming problem. Thus, adding the selection and design of heat engines in this linear problem would make it too large to be solved in an acceptable length of time, if ever.

To circumvent this computational time, a three-step methodology (a preliminary analysis and two MILP problems) is proposed in order to first select economically relevant heat engines and then optimize the HEN and MAN designs considering these systems. Heat engines modelling is added to Ghazouani's models [7-9] and in this paper, two new MILP problems are developed, based on his works. The first problem (MILP 1) selects the best potential heat engines among a great number of technologies. The objective function is an estimation of the total annualized cost (composed of operating costs, heat engines capital costs and an estimation of the HEN capital costs). Then, the second problem (MILP 2) is solved and the actual designs of the HEN and MAN are done, including the best potential heat engines selected in the previous step.

2. Mathematical formulation

The model used in this paper for the simultaneous mass and heat integration has been developed by Ghazouani et al [7-9] in which a mixed integer linear programming (MILP) model for the simultaneous design of the mass allocation and heat exchangers networks is presented without considering heat engines. The objective function is the minimization of the Total Annualized Cost (TAC). Heat engines modelling are added to his model.

2.1. Heat engines modelling

Four types of heat engines (HE) are modelled: the heat pump (PAC and TFP) provides heating to cold streams and cooling to hot streams, Organic Rankine Cycle (ORC) is used for waste heat recovery and for electricity production, Combined Heat and Power (CHP) provides heating to cold streams and generates electricity and the absorption chiller (AbsChill) provides cooling to two hot streams. Since the model used is linear, all the equations described here will be linear. The aim of this subsection is to define linear relations describing the behaviour of each heat engine.

All the heat engines (except TFP heat pumps and absorption chiller) are modelled by a single utility heat stream exchanging the heat Q_h with process streams. These heat engines are connected also with ambient temperature. The TFP heat pump is modelled by a utility at temperature T_1, transferring the heat Q_{h1} and by a utility at temperature T_2, withdrawing the heat Q_{h2} to the other streams of the process. The absorption chiller is modelled by two utilities at temperature on both sides of ambient temperature T_0, withdrawing Q_{h1} and Q_{h2} to the process streams.

In this subsection, ΔT_{pinch} is the pinch at the heat exchanger and corresponds to the minimal temperature difference needed at the heat exchangers, η_{II} is the second law efficiency (exergy efficiency) and η_{elec} is the electrical efficiency of the heat engine.

First, the efficiency or the coefficient of performance (COP), defined as the ratio between heating or cooling provided and mechanical work required, is computed for each type of heat engines, from the thermodynamics laws (Equations (1 – 6)) :

$$COP_{TFP} = \eta_{II} \frac{T_1 + \Delta Tpinch}{T_1 + \Delta Tpinch - (T_2 - \Delta Tpinch)}, \quad (1)$$

$$COP_{PAC} = \eta_{II} \frac{T_1 + \Delta Tpinch}{T_1 + \Delta Tpinch - (T_0 - \Delta Tpinch)}, \quad (2)$$

$$Eff_{Chiller} = \eta_{II} \frac{T_0 + \Delta Tpinch}{T_0 + \Delta Tpinch - (T_1 - \Delta Tpinch)}, \quad (3)$$

$$Eff_{CHP} = \eta_{II} (1 - \frac{T_1 + \Delta Tpinch}{T_f - \Delta Tpinch}), \quad (4)$$

$$Eff_{ORC} = \eta_{II} (1 - \frac{T_0 + \Delta Tpinch}{T_1 - \Delta Tpinch}), \quad (5)$$

$$COP_{AbsChill} = \eta_{II} \frac{T_1 + \Delta Tpinch}{T_1 + \Delta Tpinch - (T_0 - \Delta Tpinch)} \frac{T_2 + \Delta Tpinch}{T_0 + \Delta Tpinch - (T_2 - \Delta Tpinch)}. \quad (6)$$

Then, relations between the heat transfers Q_{h1}, Q_{h2} and the mechanical work W_{meca} can be computed from the definition of the COP and the efficiency of each heat engine for the two modelled types of heat engines (Table 1 and 2).

Table 1. Linear relations for heat engines modelled by two utilities

Heat Engine	Relation	Mechanical and electrical power
Heat Pump (TFP)	$Q_{h1} = \frac{COP}{COP - 1} Q_{h2}$	$W_{TFP,elec} = \eta_{elec} W_{meca} = \eta_{elec} (Q_{h1} - Q_{h2})$
Absorption Chiller	$Q_{h1} = \frac{1}{COP} Q_{h2}$	$W_{AbsChill,elec} = 0$ [1]

1 – The mechanical work required by the absorption chiller is neglected [4]

2.2. Constraints

The heat load provided and taken by the heat engines has to be in accordance to the heat load available in the heat cascade diagram. The limitation corresponds to the total heat entering or exiting the n^{th} temperature interval of the temperature scale [7] (7-10) ($q_{cold,n}$ and $q_{hot,n}$ correspond to the heat required or provided by cold or hot streams going through the nth temperature interval) :

$$Q_{hot,HE} \leq \sum_{n=0}^{Nt_{h1,max-1}} q_{cold,n}, \quad (7)$$

$$Q_{cold,HE} \leq \sum_{n=Nt_{h2,max-1}}^{N_{max}-1} q_{hot,n}, \quad (8)$$

$$\sum_{hot \in HE} Q_{hot} \leq \sum_{n=0}^{\min_{h \in HE}(Nt_{h,max}-1)} q_{cold,n}, \quad (9)$$

$$\sum_{\text{cold} \in \text{HE}} Q_{cold} \le \sum_{n=\min_{h\in HE}(Nt_{h,max})}^{N_{max}-1} q_{hot,n} \, . \qquad (10)$$

More specifically, (7-10) mean that any heat engine cannot provide or withdraw more heat than the streams need.

Table 2. Linear relations for heat engines modelled by a single utility

Heat Engine	Relation	Mechanical and electrical power
Heat Pump (PAC)	$Q_h = COP \cdot W_{meca}$	$W_{elec} = \eta_{elec} W_{meca}$
Chiller	$Q_h = (COP+1) \cdot W_{meca}$	$W_{elec} = \eta_{elec} W_{meca}$
ORC	$Q_h = \frac{1}{Eff} \cdot W_{meca}$	$W_{elec} = \eta_{elec} W_{meca}$
CHP	$Q_h = \frac{1-Eff}{Eff} \cdot W_{meca}$	$W_{elec} = \eta_{elec} W_{meca}$

2.3. Objective Functions

Two objective functions are used, for each MILP problem. It consists in the minimization of the total annualized costs (TAC) (11). In MILP 1, the capital costs of the HEN (CC_{HEN}) is an estimation (the number of exchangers and their areas are roughly estimated) whereas in MILP 2, CC_{HEN} corresponds to its actual cost (HEN design is done).

$$\min \text{TAC}=\frac{1}{N_{op}}\left(CC_{HEN} + \sum_{he\in HE} CC_{he} + \sum_{n=1}^{N_{op}} \frac{AOC}{(1+r_a)^n}\right), \qquad (11)$$

where N_{op} is the operating years, r_a is the actualization rate. The annualized operating costs (AOC) are formulated in (12). It is the same expression as the one utilized in [8] (it includes fresh material costs C^f_j, waste disposal costs C^w_i and utility costs C_{hu}) but it includes now the electrical costs (or income) of the heat engines C_{elec}.

$$AOC = h_{op}\left(\sum_{j\in J_f} C^f_j L^f_j + \sum_{i\in I_w} C^w_i G^w_i + \sum_{h_u\in H_u} C_{h_u} q_{h_u} + \sum_{he\in HE} C_{elec} W_{he,elec}\right). \qquad (12)$$

The capital costs of the heat engines CC_{he} include a fixed cost CC^{fixed}_{he}, a variable cost based on the electric power CC^{elec}_{he} and two variable costs $CC^{h1}_{he}, CC^{h2}_{he}$ based on the heat exchanges of the two utilities h_1 and h_2 composing the heat engine (13). (If the heat engine is modeled by a single utility, then CC^{h2}_{he} =0)

$$CC_{he} = CC^{fixed}_{he} + CC^{elec}_{he} W^{elec}_{he} + CC^{h2}_{he} Q_{h2} + CC^{h1}_{he} Q_{h1} \, . \qquad (13)$$

The capital costs of the HEN are separated between a variable cost, depending on the exchangers area S_{HEN} and a fixed part depending on the total number of exchangers n_{HEN} (Eq 14)

$$CC_{HEN} = CC^{fixed}_{HEN} n_{HEN} + CC^{area}_{HEN} S_{HEN} \, . \qquad (14)$$

2.3.1. MILP 1 - Estimation of HEN costs

The cost estimation of the HEN is based on the number of streams and is developed in [9]. This number is the maximum between hot and cold streams requiring cooling or heating in the process.

Utility heat streams are also included if they are used. The maximum function is avoided by introducing integer variables (n_{hot}^{extra} and n_{cold}^{extra}) because of linear modelling (15).

$$n_{HEN}^{\min} = \max(n_{hot}, n_{cold}) = n_{hot} + n_{hot}^{extra} = n_{cold} + n_{cold}^{extra} . \qquad (15)$$

To guarantee the minimization of number of streams ($n_{hot} + n_{cold}$) involved in the MAHEN, a second term is added with a parameter k_{fixed} chosen small (16):

$$n_{HEN} = n_{HEN}^{\min} + k_{fixed}(n_{hot} + n_{cold}) . \qquad (16)$$

The total area of heat exchangers is also estimated, considering an average temperature difference $k_{area}\Delta Tpinch$ and the heat transfer coefficient of each stream (mass and heat) (17):

$$S_{HEN} = \sum_{ms} \frac{Q_{ms}}{htc_{ms} k_{area} \Delta Tpinch} + \sum_{u} \frac{Q_u}{htc_u k_{area} \Delta Tpinch} . \qquad (17)$$

2.3.2. MILP 2 – Actual HEN design

The detailed model for the actual HEN design is described in [8]. Binary variables are introduced in order to indicate if a stream h_1 exchanges heat with a stream h_2 in the n^{th} interval of temperature. Thus, the required number of heat exchangers can be computed. The heat exchange area is computed with the log mean temperature difference between the two streams h_1 and h_2.

3. Methodology

Designing HEN of industrial processes is a complex mathematical problem. The linear model used in this paper involves several binary variables and combinatorial analysis. If a great number of variables (temperatures, streams...) is implied, the problem can be large scale and time consuming. Moreover, designing relevant heat engines simultaneously in the same linear problem accentuates its size because it implies testing a large number of heat engines in the same problem. Therefore, a three-step methodology is developed to select a few relevant heat engine designs among a wide range of choices prior to optimizing the MAHEN design considering them. These three steps are detailed in the following paragraphs. The methodology is summarized in the figure 1.

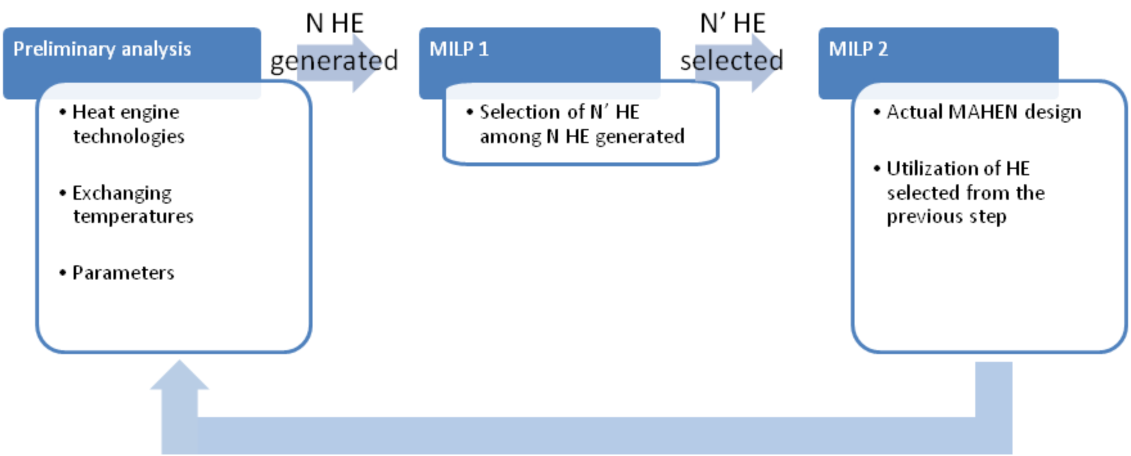

Fig. 1. Methodology for the design of Heat Engines, composed of two MILP models.

3.1. Preliminary analysis

A preliminary analysis is conducted to determine, from raw data (sinks and sources temperatures) or from the Great Composite Curves (in case of heat integration only) which types of heat engines can be relevant to improve the process integration: PAC, TFP, ORC, etc.

Temperature ranges of the process are also identified where heat recovery can potentially be done by implementing heat engines. Based on this analysis (HE types and temperature ranges), a number N of HE (e.g. a hundred) is generated in the temperature ranges previously identified. They correspond to the heat engines to be tested in MILP 1.

3.2. Heat engines design (MILP 1)

Next, the N heat engines generated in previous step are implemented in MILP 1. Their COP and efficiency are computed via equations (1-6). They are tested and compared with an economic criterion (subsections 2.3 and 2.3.1). A selection of N' heat engines that minimize the objective function is done and the large number (N) of heat engines is thus reduced to a much lower number (N') (e.g. few units) of relevant heat engines.

3.3. MAHEN design (MILP 2)

The actual design of the mass allocation networks and heat exchangers networks is realized with the second MILP model (subsections 2.3 and 2.3.2). The N' heat engines selected by MILP 1 are incorporated in the computation. MAHEN is thus designed, integrating the new N' technologies. Eventually, it can be useful to loop the entire methodology between output results and input parameters. Output results may reveal some new information about the selected heat engines and they could be used to find better solutions.

4. Case study

The case study is solved using CPLEX v12.7.1.0 solver on PC (Processor: Intel© Core™ i5-7200U CPU @ 2.50GHz – RAM: 16 Go – OS: Windows© 10).

The case study chosen to illustrate the methodology is an ammonia recovery process case. This case study appears in several studies, particularly in [8] that uses the former MILP model of this paper. The process data is given in Table 3 and the economic data and selected parameters are given in Table 4.

Table 3. Process Data

	Flow rate (kg/s)	*Comp. in impurities(ppm)*	*Temperature (°C)*
Sink			
Sink 1	350	0 – 0	30
Sink 2	677	0 – 40	187
Sink 3	126	0 – 75	55
Sink 4	202	0 – 100	98
Waste		0 – 500	40
Source			
Source 1	530	30	21
Source 2	68	150	43
Source 3	1130	300	130
Source 4	36	500	35
Fresh		0	30

Heat capacity = 2.19 kJ/kg/K ; Temperature of cold utility = 5 – 5.1°C ; hot utility = 230 – 239.9°C

According to [8], the solution tends to use the minimum fresh materials because its cost outweighs all others. Thus, its fresh mass flow rate is set to its minimum (ie 654.9 kg/s) and its cost is set at zero (C_{fresh} = 0€/t) to study more precisely the influence of other parameters. For computational reasons, ΔT_{step} is fixed to 10°C. ΔT_{pinch} is set to 20°C. Electricity costs is set at 0.04€/kWh, between cold and hot utility costs. The number of operating years N_{op} is set to 10 years.

4.1. Preliminary analysis

According to process data (Table 3), cooling and heating needs can already be identified by analysing the temperature of the sources and sinks.

Sink 2 temperature is higher than all sources temperatures (187°C). Thus, any streams linked to sink 2 have to be heating up to 187°C. Considering that sources temperature are located below 43°C (except source 3), a heat pump can be used for preheating the streams up to around 100°C.

Table 4. Economic data and selected parameters

Economic data		*Parameters*			
C_{fresh}	500 €/t	h_{op}	8000 hrs	htc_{NH3}	50 W/K/m²
C_{waste}	0 €/t	N_{op}	10 years	htc_{hot}	1000 W/K/m²
C_{hot}	0.07 €/kWh	r_a	5 %	htc_{cold}	1000 W/K/m²
C_{cold}	0.03 €/kWh	ΔT_{pinch}	20°C	k_{fixed}	1
C_{elec}	0.04 €/kWh	ΔT_{step}	10°C	k_{area}	0.001
C_{HEN}^{fixed}	5291.9 €				
C_{HEN}^{area}	77.79 €/m²				

Source 3 is relatively high in temperature (130°C) and can be linked to 4 sinks of lower temperatures (98°C or below 55°C). Two temperature zones can be identified for cooling source 3: around 100°C and around 60°C.

Therefore, 2 types of heat engines can be potentially used for recovering heat in the process: a TFP heat pump could be used for preheating around 100°C and cooling around 60°C. An Organic Rankine Cycle heat engine could be used in order to cool source 3, below 130°C. Preselecting parameters for MILP 1 are given in Table 5.

Table 5. Preselecting and heat engines parameters

	TFP heat pump		
Cold utility Temperature range	50 – 80 °C	*Hot utility Temperature range*	100 – 120 °C
Step	5°C	*Step*	2.5°C
C_{TFP}^{fixed}	0 €	C_{HEN}^{h1}	0 €/kW
C_{TFP}^{elec}	600 €/kW	C_{HEN}^{h2}	0 €/kW
	ORC		
Cold utility Temperature range	90 – 140°C	*Step*	5°C
C_{ORC}^{fixed}	0 €	C_{ORC}^{h1}	0 €/kW
C_{ORC}^{elec}	1600 €/kW	C_{ORC}^{h2}	0 €/kW

Exergy efficicency: η_{II} = 0.6 – Electrical efficiency: η_{elec}= 0.8 – k_{fixed} = 1 – k_{area} = 0,001

4.2. MILP 1 – Heat engines design

63 heat pumps and 11 ORC are generated and tested in the process and MILP 1 will select 2 heat pumps and 1 ORC among them. The results are presented in Table 6. Two heat pumps are selected, both providing heat at 112.5°C and withdrawing heat at 65°C and 75°C. An ORC is also designed, withdrawing heat at 90°C.

4.3. MILP 2 – MAHEN design

The three selected heat engines are now included in the MILP 2 problem. Table 7 summarizes the results obtained with the presence of the selected heat engines and compares them to the case without heat engines. MAHEN designs for both cases are presented in Fig. 2 and Fig. 3. Mass allocation is the same in the two cases and only heat duty are modified.

Table 6. HE design results with MILP 1

	TFP heat pump					
	Cold utility		*Hot utility*			
	Temperature (°C)	Duty (kW)	*Temperature (°C)*	Duty (kW)	*COP*	*Power (kW)*
HP1	65	5496	112.5	7680	3.5	2730
HP2	75	8245	112.5	10880	4.1	3294
	ORC					
	Utility		*Ambient*			
	Temperature (°C)	Duty (kW)	*Temperature (°C)*	Duty (kW)	*Efficiency*	*Power (kW)*
ORC	90	36754	30	x	0.07	1998

Table 7. MAHEN design results with MILP2

	Without HE	With HE
Q_h (kW)	111,580	112,450
Hot utility	111,580	111,580
HP1 – COP=3.52		0
HP2 – COP=4.13		870
Q_c (kW)	57,881	58,751
Cold utility	57,881	44,516
HP1 – COP=3.52		0
HP2 – COP=4.13		659
ORC – Eff=0.07		13 576
Power (kW)		
HP2 – COP=4.13		263
ORC – Eff=0.07		738
n_{hen}	10	16
S_{area} (m²)	239 153	276 738
C_{HEN} (MM€)	18.888	21.844
C_{HE} (MM€)	0	1.339
Cap. Cost (MM€)	18.888	23.184
Op. Cost (MM€)	76.376	73.017
TAC (MM€)	60.864	58.700

Even if the presence of heat engines in the process degrades the heat integration (heating and cooling needs are superior to the ones in the case without HE), there is an economic gain to use them: TAC decreased by 2MM€ around. The capital costs increase by around 4MM€ (due to larger HEN and heat engines investments) but at the same time, the operating costs drop by 3MM€. The operational costs reduction offsets the increase in capital costs over 10 years. This is due to the ORC heat engine that earns incomes (it generates an electric power of 738kW) and reduces the cooling needs (44,5kW against 57,9kW). Finally, the utilization of heat pumps and ORC enhances the economic solution as TAC is lowered by 3.5%.

One can note that HE utilization differs between MILP 1 and MILP 2: in MILP 2, the heat engine with lower COP (HP1) is not used and HP2 consumption is lower. Indeed, during MILP 1, heat exchanger network design is not realized, therefore exchanges temperatures are not known. If HP1 can theoretically exchange heat, when considering extraction temperatures, its use is hereafter not possible. Also, HP2 power is reduced as its exchange duty is lower (870kW instead of 10880kW for hot exchange duty).

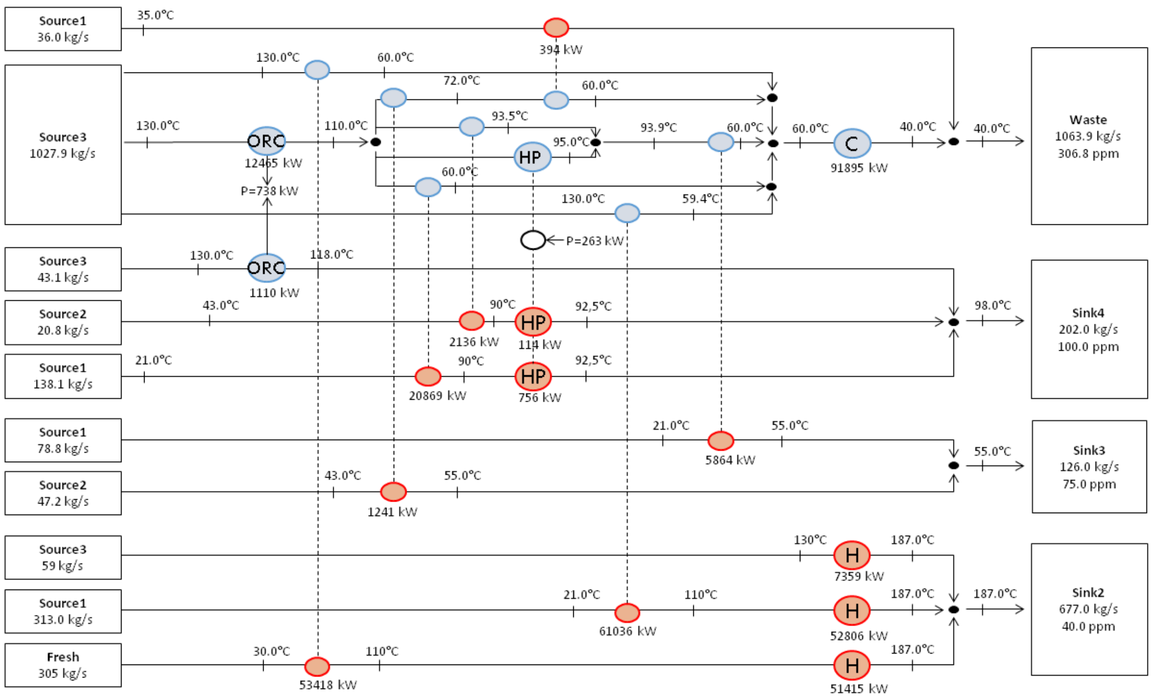

Fig 2. Optimal mass allocation and heat exchanger networks with heat pumps and ORC. (HP corresponds to HP2, H to hot utility and C to cold utility).

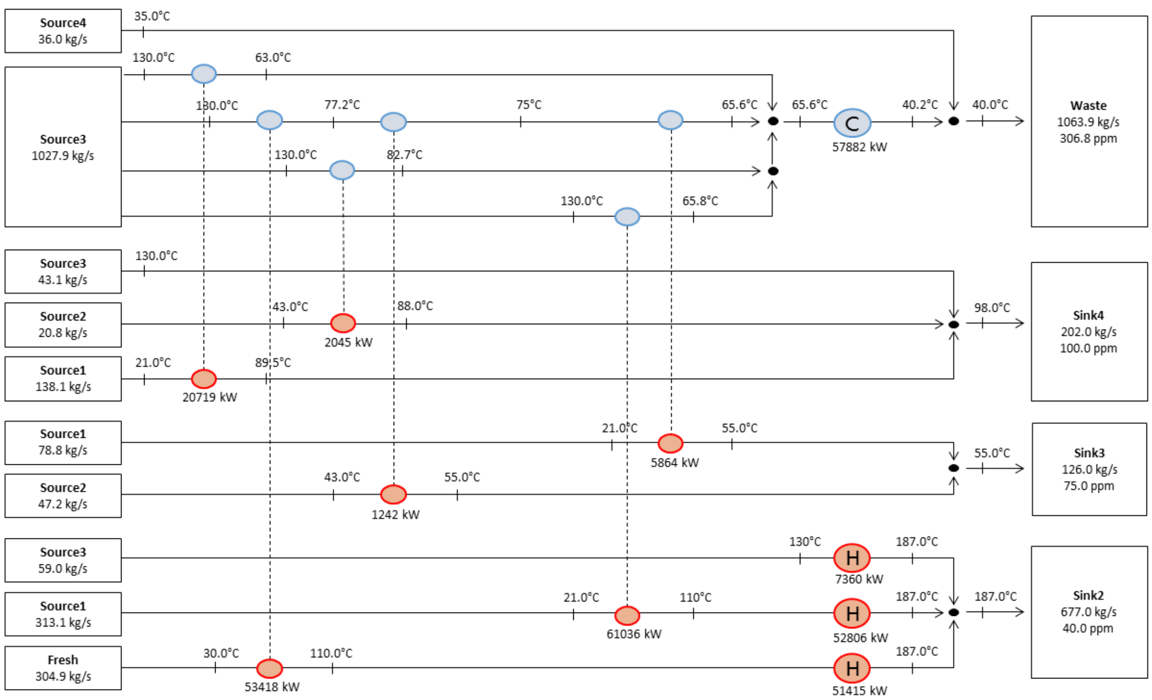

Fig 3. Optimal mass allocation and heat exchanger networks without any heat engines. (H corresponds to hot utility and C to cold utility).

The selected heat engines from MILP 1 may be subject to further checking. Indeed, the suggested heat pump is quite competitive; the hot utility is at 112.5°C, which may be quite high. These types of heat pumps correspond to the high-temperature heat pump (HTHP) range and are mainly pilot units. HP costs are maybe underestimated. Anyway, this methodology requires some expertise in heat engines field in order to choose relevant parameters, during HE design phase.

Finally, the computational time is strongly reduced with the implementation of the methodology. HE design only lasts a few seconds and MILP 2 with 3 heat engines is solved after 15 minutes. It involves 68,492 variables, 21,644 binaries and 87,070 constraints. In comparison, when the 74 heat engines tested in MILP1 are implemented in MILP 2 and HE and MAHEN designs are attempted simultaneously, it generates a very large problem (more than one million variables, 356,618 binaries and 1,300,000 constraints) which cannot be solved in several hours.

5. Sensitivity Analysis

5.1. Influence of ΔT_{step}

The parameter ΔT_{step}, which corresponds to the minimum difference between two consecutive temperature levels on the scale, influences the number of variables of the problem and the accuracy of the solution. More specifically, the size of the problem increases when ΔT_{step} decreases.

The methodology is applied with the same parameters as in section 4, but for different values of ΔT_{step}. Results are presented in Table 8.

The HE design step leads to the same HE in each case. The results are strictly identical (operating costs, HEN structure, and utility duty). The only difference comes from the HEN area and its capital costs.

Table 8. Influence of ΔT_{step}

ΔT_{step} (°C)	5	10	15	20	25
Number of temperature levels	70	53	49	47	46
T (s)	5869	939	1888	4971	5527
$N_{constraints}$	112984	87040	83541	82381	82377
$N_{non\text{-}zeros}$	520146	378382	359932	354716	354709
$N_{variables}$	92863	68492	65348	64712	64709
$N_{binaries}$	27238	21644	20829	20460	20460
S_{HEN} (m²)	276,648	276,738	276,917	276,789	276,789
$S_{HEN, real}$ (m²)	277,486	279,727	281,236	281,151	281,151
Cap. Cost (MM€)	23,009,208	23,183,583	23,300,914	23,294,318	23,294,318
ΔCap. Cost		0,76%	1,27%	1,24%	1,24%
Obj. function (MM€)	58,682,787	58,700,224	58,711,957	58,711,298	58,711,298
ΔObj. function		0,03%	0,05%	0,05%	0,05%

Even if it is difficult to predict computational time (it depends on how the solver tackles the problem), the number of variables and constraints increases with ΔT_{step} decreasing. Also, the objective function does not vary a lot with ΔT_{step} (less than 2%). Thus, a moderate number of temperature levels (around 50), which corresponds to ΔT_{step}=10-15°C seems to be adapted. Computational time is acceptable and results are still precise. However, it could be interesting to check this on several other cases.

5.2. Influence of electricity cost

The two heat engines (heat pumps and ORC) considered in this case have opposite behaviour regarding the electricity cost. A heat pump consumes electricity while ORC generates and sells electricity. Thus, it can be interesting to see the influence of electricity costs on their selection. Table 9 summarizes the selected heat pumps characteristics (after MILP 2) for different electricity costs.

Table 9. Influence of C_{elec} on heat pump's selection (MILP 2 results)

C_{elec} (€/kWh)	0.01	0.04	0.06	0.08	0.1
T_1 (°C)	112.5	112.5	112.5	112.5	x
Q_{h1} (kW)	870	869	838	869	x
T_2 (°C)	70	75	80	80	x
Q_{h2} (kW)	641	659	653	677	x
COP	3.8	4.1	4.5	4.5	x
Power (kW)	286	263	232	240	x

For C_{elec} = 0.01€/kWh to 0.06€/kWh, two heat pumps are selected (in MILP 1) (with a lower COP than the ones presented in Table 9) but only one is actually used (in MILP 2). For C_{elec}=0.08€/kWh, MILP 1 proposes a single heat pump which is the one used in MILP 2. When a heat pump is used (from C_{elec} = 0.01€/kWh to 0.08€/kWh), the same ORC is used at 90°C and generates 739kW of electricity. MAHEN networks are the same as in fig 2.

For C_{elec} = 0.1€/kWh, none of the heat pumps are used. It is not relevant to use heat pumps in the process because hot and cold utility are cheaper than heat pumps. The same ORC is used at 90°C but generates less electricity (638kW). Actually, the presence of a heat pump degrades the heat integration, increases cooling needs and increases ORC utilization. When the heat pump is not used, the cooling potential is lower thus ORC generates less electricity.

Electrical cost has an actual influence on the design of heat engines. One can see that the lower the electricity costs, the lower the heat pump's coefficient of performance is. For cheap electricity (0.01€/kWh), the heat pump COP is 3.8 (the other heat pump selected with MILP has a COP of 3). When electricity is cheaper than hot and cold utilities, less efficient heat pumps can be used as they do not degrade the economic solution. Whereas for expensive electricity, heat pumps with higher COP are favoured (here with a COP greater than 4).

6. Conclusion and perspectives

The methodology introduced here is based on two MILP models for mass allocation and heat exchanger networks design, including heat engines design. A first MILP model is used to select relevant heat engines among a large range of possibilities to reduce the computational time of the problem. Then, the selected heat engines are considered when designing the complete MAHEN while minimizing total actualized costs. This methodology reduces strongly the computational time since a large number of technologies are tested and MAHEN design is performed in a reasonable time.

Future works will be done in order to have more realistic solutions: introducing different electrical cost (purchase and selling prices) and multi-period models to consider the dynamic of industrial processes. Finally, the methodology, limited at the local scale here, will be extended to the territorial scale for eco-industrial parks.

Nomenclature

AOC Annual operating costs, MM€

C operating costs, MM€

CC capital costs, MM€

h_{op} operating hours, hours

n number of heat exchangers

N_{op} number of operating years, years

Q heat load, kW

S heat exchanger area, m²

T temperature, (°C, K)

TAC Total annualized costs, MM€

W_{elec} electrical power, kW

W_{meca} mechanical power, kW

Greek symbols

η efficiency

ΔT_{step} maximum gap between two consecutive level on temperature scale, °C

ΔT_{pinch} minimum temperature approach in heat exchanger, °C

Subscripts

h hot and cold streams

HE Heat Engines

HEN Heat Exchanger Network

n temperature interval

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