ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Semester Project

Heat Pump Integration in Industrial Processes-II

January 7, 2011

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Aknowledgments

This project was performed over a semester at the LENI-EPFL. I would like to express my thanks to Prof. D. Favrat and especially Dr. F. Maréchal, for having given me the opportunity to carry on this project and thus to learn. I would like to thank them for their availably in sharing their precious knowledge and experience. I would like to thank Helen Becker, for her availability, support and advice. Her help resulted to be crucial to overcome a number of difficulties encountered during my work.

Abstract

This semester project follows a previous project at LENI-EPFL [10] and aims at finding the best optimization approach in terms of Heat Pump integration in industrial processes. The MultiObjectiveOptimization method chosen seeks the minimum of both operating and investment costs related to HP purchase. Different optimization approaches are tested in order to find the best solution in terms of feasibility and applicability of the results. This report trace the various approaches, analyzing and discussing the results. The choice of the best approach is then justified according to different parameters. This latter has then been implemented in the form of an OSMOSE® model able to find the optimal set of integration solutions among a range of heat pumps equipped with different types of compressors, using different refrigerant fluids. The resulting HP Data Base is then tested in a process belonging to food industry.

Contents

1 Introduction

Pinch Analysis is one of the most powerful tools allowing to minimize the energy consumption of a process and thus is often applied to the optimization of industrial processes. In this context, heat pump integration plays an important role in the rationalization of energy consumption. A correctly placed heat pump upgrades part of the heat available below the pinch point (heat source), making it available above the pinch point (heat sink). Therefore, both heating and cooling requirements are reduced. In practice, an appropriate integration of heat pumps requires the identification of the optimal heat pump(s) and of its operating conditions. Finding the best trade-off between savings in terms of operating costs and the necessary investment for the device purchase is the main aim of *Thermo-economic analysis*.

The method chosen in order to accomplish the abovementioned *Thermo-economic analysis* is the so called MultiObjectiveOptimization (MOO). This latter provides the operator a range of optimal solutions and enables him to choose the setup which best meets his requirements. Evolutionary algorithms are population based algorithms. Such methods generate initially a population of randomly distributed points, determined by the resolution of the model and corresponding to the first generation. Then, the feasible population evolves from generation to generation by recombination of parent points and moves towards a set of optimal solutions [4]. In particular, the tool QMOO (Queuing Multi-Objective Optimizer), developed at LENI by Molyneaux and Leyland (2002), was designed to be combined with the Energy Integration program Ampl.

The Energy Integration or process integration consist in algorithms capable to identify the possible placement and the size of a given utility (boiler, refrigeration cycles, HP) within a process, in order to satisfy its heating and cooling requirements. In the literature different approaches for process integration, applied to HP technology, can be found. The first rules for optimal HP placement in a process have been introduced by Linnhoff and Townsend (1983) [7] according to whom the benefits for the overall process are taken into account. Wallin and Berntsson (1990) [13] propose a methodology to optimize the temperatures of the heat source (evaporation level) and the heat sink (condensation level) together with the size of the heat pumps and the choice of the process streams used by the device (placement within the process). In this case the analysis if the Process composite curves is the main instrument to define the best placement and size of the HP (Wallin and Berntsson (1994) [12]).

A further step in the development of such methods has been done by Bagajewicz and Barbaro (2003) [1] who consider the evaporation and condensation temperature levels decision variables of the integration approach. Thanks to this, discrete temperature levels which need a fine interval partition to get meaningful solutions are avoided. At the same time this approach could lead to non-realistic solutions since multiple condensation and evaporation levels are unlikely to be found in industrial heat pumps. A valid methodology, based on Pinch Analysis could be finally found in Becker et al. (2009) [3], where heat recovery between process streams and energy conversion systems integration are considered. This work is based on Marechal (1997) [9] and Marechal (2002) [8] who developed a method based on mixed integer linear programming (MILP) formulation of the heat cascade to optimize the flow rates in heat pumping systems. Thanks to this approach heat pumps and other utilities (boiler or cogeneration engines) integration is evaluated at the same time.

In chapter 2 we introduce the optimization problem and the way it has been solved thanks to the implementation of the Heat Pump Data Base. The structure of this latter is explained in detail in chapter 3, where important information about the modeling of such devices is reported. The next chapter is focused on the optimization approach. Three different approaches have been tested on the well known Brewery process ([4] and [10]) and the results discussed. It results interesting the trial and error process that leads to the final solution. The discussion of the results of this latter, together with an analysis of advantages and drawbacks of the method conclude chapter 4.

2 Optimization Problem

The final aim of the implementation of the Heat Pump Data Base is providing a tool capable to determine a range of best solutions among which the designer could choose an improvement for the process. In the particular case of Heat Pumps integration in Industrial Processes, the objectives to be minimized are the *operating costs* related to process operation and the *investment costs* related to the purchase of one or more heat pump cycles. The Multi-objective optimization method (MOO) seems to be quite well adapted in this case. It enables, in fact, the determination of the trade-off curve between the two objectives considered, called Pareto-optimal curve. For example, for a given value of the investment cost, the point on the Pareto-optimal curve corresponds to the minimal value of the operating costs.

Evolutionary algorithms such as the QMOO tool (Queuing Multi-Objective Optimizer) tool, developed at LENI by Molyneaux and Leyland (2002) [6], work quite well in the case of optimization problem decomposition. In this particular case the problem has been divided in *master* and *slave* sub-problems as reported in Figure 1 (Gassner and Maréchal, 2009 [5]). The master problem is solved using an evolutionary algorithm. This allows using complex heuristics in the heat pump selection procedure and process integration, without difficulties related to constraints and non-differentiable equations.

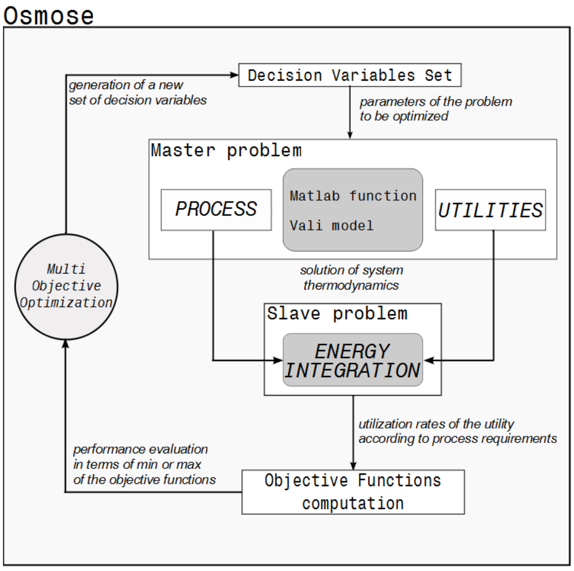


Figure 1: Optimization problem and Osmose® platform

2.1 Master sub-problem

At the master level, as reported in Figure 1 a set of decision variables is chosen by the abovementioned evolutionary algorithm. The choice of the decision variables depends on the system we want to optimize and on the approach chosen in the optimization. These parameters, in fact, represent optimized or optimal values, in other words they are related to optimal (minimum in this case) values of the objective functions (Figure 1).

In the case of heat pump integration, generally speaking, the parameter to be optimized are the 'placement' of such device in the process (identified in practice by the *evaporation and condensation temperature levels*) and the 'size' of the heat pump, according to process requirements. This latter is identified by the *VOLumetric Flow rate* (VOLF) elaborated by the HP compressor. It is depending on the compressor technology and thus on the related investment cost. Both parameters could be optimized at the master or slave level. In this case, by the way, the operating conditions of the heat pump (condensation and evaporation temperatures) have to be fixed in order to enable the thermodynamic model to calculate the HP thermodynamic cycle and the enthalpy-temperature profiles of its hot and cold streams.

2.2 Slave sub-problem

The slave problem solves the Energy Integration problem, optimizing the utilities flow rates. The composite curve of the utilities (of the HP in our case) and those of the process are the required input of the slave problem (Figure 1). The Energy Integration software could minimize the *operating costs* or the *total costs* (sum of the yearly operating costs and the annualized investment costs) under the constraint of the chosen decision variables. The choice of the EI objective depends again on the optimization approach.

Energy Integration tool optimizes the utility flow rates, using the mixed integer linear programming (MILP) formulation of the heat cascade [2]. All utilities are evaluated simultaneously and the optimal flow usage of the heat pumps and other utilities are calculated.

3 Heat Pumps Data Base

As already mentioned the final aim of the implementation of such Data Base is to provide a systematic approach able to determine a range of optimal solutions in terms of Heat Pump integration within a given process. The approach should guarantee accurate and plausible results. In order to achieve an high degree of accuracy and make the results as close as possible to reality, both the optimization approach, as we will see in detail in section 4 and the modeling of the units play a fundamental role. In this section we focus on HPs modeling.

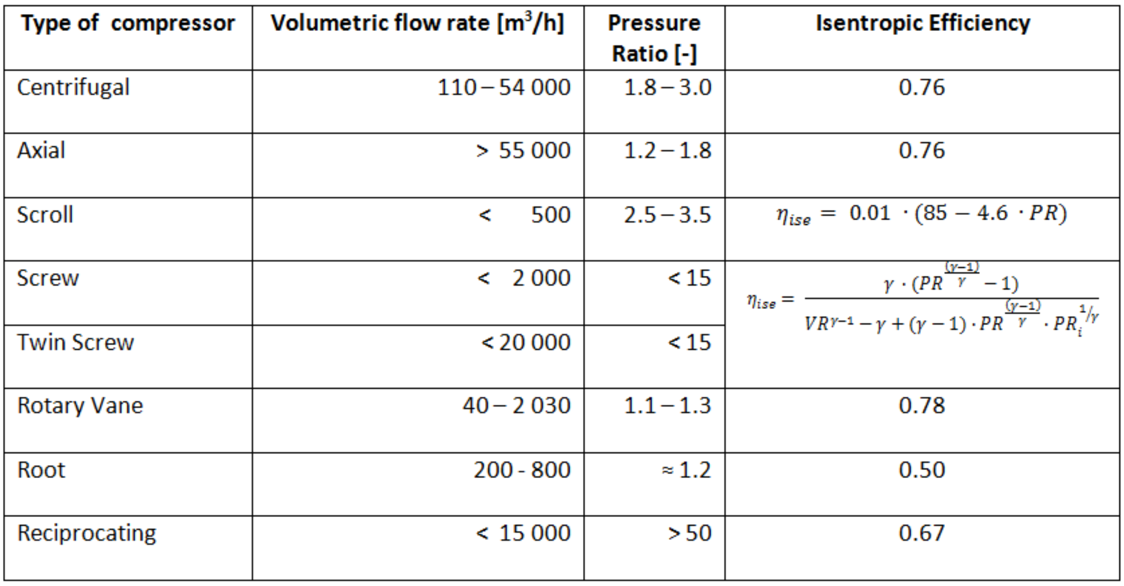
One of the strong points of the implemented Data Base is the possibility of working with several different types of *vapor compression heat pumps* available on the market. As widely known, many compressor technologies are utilized to equip HP cycles. In [10] a detailed description of the overall HP technology is reported. Particular attention is given to compressor typologies.

3.1 Model Implementation

The HP Data Base consists in an OSMOSE® model. The OSMOSE® platform is a powerful tool developed by LENI-EPFL, linking the solution of system thermodynamics (Belsim-Vali® tool) to process requirements meeting, allowing the optimal utility integration within a given process (EIAMPL® software) as reported in Figure 1. The already mentioned QMOO tool has been implemented in the same software, allowing the optimization of some given parameters.

3.1.1 Thermodynamic model - Belsim-Vali®

Belsim-Vali® software is the thermodynamic solver, in which the units are modeled. In this work, the models of *closed compression cycles*, equipped with different compressor technologies and different working fluids are required. Among the wide range of refrigerants available in heat pumping and refrigeration technology, we choose, according to a previous work at LENI-EPFL [4], to work with R717(Ammonia) and R134a (Tetrafluoroethane). Furthermore we model 8 different compressor technologies. As reported in the table of Figure 2, the technologies vary in terms of operating conditions such as *pressure ratio*, *VOLumetric Flow rate* and *isentropic efficiency* (see [10]). The available efficiency correlations have been implemented in the model as well.



Type of compressor	Volumetric flow rate [m³/h]	Pressure Ratio [-]	Isentropic Efficiency
Centrifugal	110 – 54 000	1.8 – 3.0	0.76
Axial	> 55 000	1.2 – 1.8	0.76
Scroll	< 500	2.5 – 3.5	$\eta_{ise} = 0.01 \cdot (85 - 4.6 \cdot PR)$
Screw	< 2 000	< 15	$\eta_{ise} = \dfrac{\gamma \cdot (PR^{\frac{(\gamma-1)}{\gamma}} - 1)}{VR^{\gamma-1} - \gamma + (\gamma - 1) \cdot PR^{\frac{(\gamma-1)}{\gamma}} \cdot PR_i^{1/\gamma}}$
Twin Screw	< 20 000	< 15	
Rotary Vane	40 – 2 030	1.1 – 1.3	0.78
Root	200 - 800	≈ 1.2	0.50
Reciprocating	< 15 000	> 50	0.67

Figure 2: Compressor technology operating conditions

Osmose® works with two models, one working with R717 and one working with R134a. For each of them, the 8 HP units are present 4 times, in order to make possible a multiple HP integration within the same process (multistage heat pumping). Our data base consists now in 8*4=32 HP cycles per fluid, that is to say a total of 64 possible units to be integrated in the process we want to optimize (figure 3).

In figure 5 and 4 we report the cycle of a heat pump equipped with a scroll compressor for R-134a fluid and for R-717. The models are intended to be generic and are likely to be used in any process.

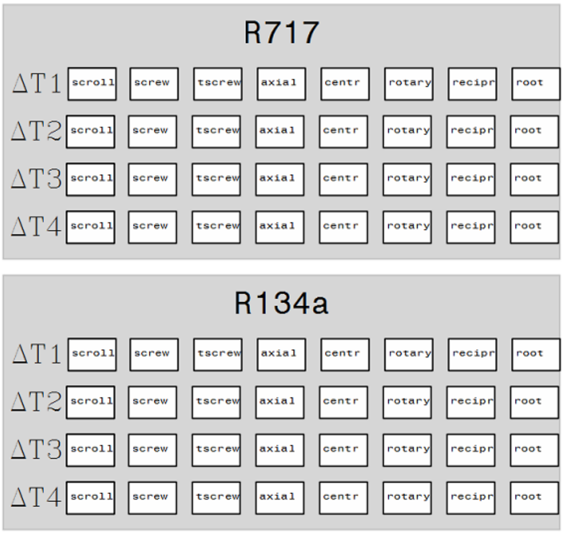


Figure 3: Thermdynamic Model structure

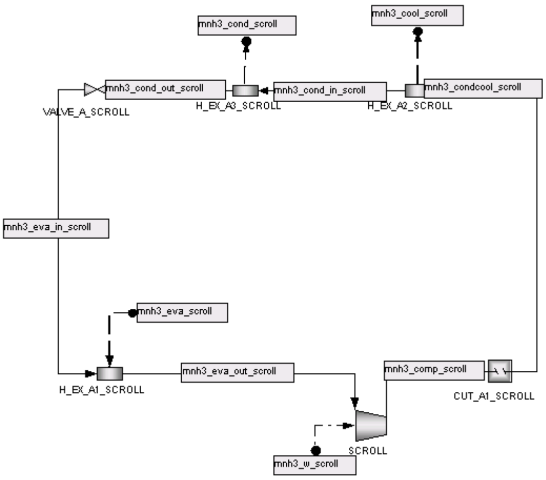


Figure 4: *Belsim-VALI* model of R-717 heat pump equipped with a scroll compressor

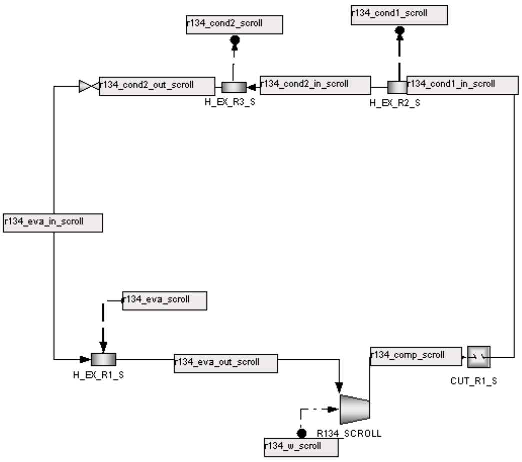


Figure 5: *Belsim-VALI* model of R-134a heat pump equipped with a scroll compressor

4 Optimization Algorithms

As discussed in the previous sections, the choice of the optimization approach and its definitions plays a fundamental role in the accuracy of the solutions. The optimization approach consists in the definition of the optimization problem and it could be summarized in three following points:

Definition of the problem decision variables As mentioned in section 2, the two parameters that have to be optimized are the *evaporation and condensation temperature levels*, that identify the position (in terms of temperature) of the HP in relation to process streams and the *size* of the HP, that should satisfy the requirements of the process.

Instead of directly varying the condensation and evaporation temperatures we decide to vary the two parameters k_1 and k_2. These are related to the maximum condensing and minimum evaporating temperature of a given fluid as depicted in figure 6.

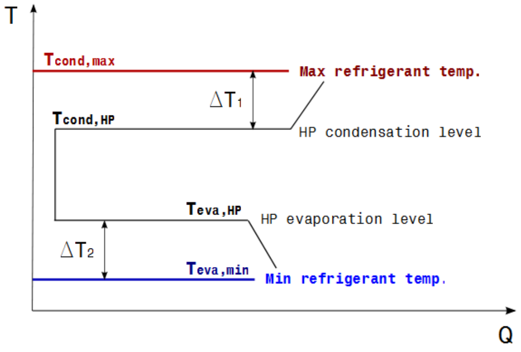


Figure 6: Computation of condensation and evaporation levels of the heat pumps

The temperatures thus calculated, according to Eq. 1 and 2, define the *effective difference of temperature*. ΔT_1 is thus defined as a fraction of the total temperature difference $\Delta T_{fluid} = T_{cond,max} - T_{eva,min}$ and ΔT_2 the fraction of $\Delta T_{fluid} - \Delta T_1$. In this way the temperatures calculated are always coherent. In other words, the condensation temperature is always higher than the evaporation level. Simply choosing the temperature within a given range could lead to the not feasible case in which the evaporation level is higher than the condensation.

$$\Delta T_1 = T_{cond,max} - T_{cond,eff} = (T_{cond,max} - T_{eva_min}) * K_1 \tag{1}$$

$$\Delta T_2 = T_{eva,eff} - T_{eva,min} = (T_{cond,max} - \Delta T_1 - T_{eva_min}) * K_2 \tag{2}$$

where: $k_1 \in [0.1, 0.9]$ and $k_2 \in [0.1, 1]$.

In literature we can find data about the operating temperature range of the refrigerants. These result from a wide range of constraints (safety for instance). For this reason the values are often largely below the critical temperature of the fluid. The working range of ammonia is within 50 to -10 °C. The refrigerant R-134a can work with temperatures in the range 100 - 10 °C [4].

The size of the heat pump is identified by the VOLumetric Flow rate at the compressor inlet ($VOLF$). This parameter is made to vary within a range proper for each compressor technology (Table 2).

Both temperature levels and compressor size could be optimized in the master or the slave level of the optimization problem. It will be seen later on, how this choice could affect the plausibility of the optimization results. Moreover, in order to allow the thermodynamic solution of the given unit, the identification of the temperature levels is required as input by the solver and thus should be present in the set of decision variables. The volumetric flow rate, on the contrary could be easily scaled, once the thermodynamic state at compressor inlet is identified.

Definition of the EI objective As already reported in section 2, the Energy Integration software could both minimize the *(yearly) operating costs* of the system (cost of purchased natural gas (+) and purchased (+) or sold (-) electricity) or the *(yearly) total costs*. These represent the money necessary to pay the energy bill and the annual part of the investment related to the installation of the HP. As it could be easily understood, the latter optimization depends on the cost of the purchased utility and thus is affected by the prizing policy.

Definition of the objective functions The objective functions we aim at minimizing are the *operating costs* and the *investment costs* necessary to purchase a given piece of equipment (HP in our case). The definition of other objective functions, such as the will to minimize the number of utilities, did not give the desired results. For this reason it has not be adopted in this case study.

Another parameter that should be taken in consideration is the definition of the two objective functions. In all the analyzed optimization approaches, the operating costs are computed according to the real, effective needs of the process (after EI computation of units utilization rates). The investment cost related to HP purchase, in this work, consists in the only cost of the compressor. For this reason, they are strictly dependent on the prizing policy. Reliable investment cost correlations, in function of compressor power, are quite difficult to find in the literature. In the following, the choice of the correlations and of the sizing parameter will be explained and discussed.

In order to find the best approach, able to give reasonable results from the optimization but also from the technical point of view, different approaches have been tested, applied to a Brewery process. This latter, already tested and discussed in the previous works [4] and [10], seems to be a good test bench since it requires one refrigeration cycle and it allows many heat pumping possibility. A detailed description of the process could be found in [4]. The list of all process streams is reported in Appendix 1.

4.1 Optimization Approach 1 - 'VOLF'

The first optimization approach aims at optimizing at the master level the temperature levels and the size of the HP (compressor size and type). In other words, once the placement of the HP has been optimized, the compressor has to be chosen, among the difference technologies available, in order to minimize the investment costs, meeting the process requirements. In this case the decision variables are the above mentioned parameters k_1, k_2 and the maximal volumetric flow rate at compressor inlet $VOLF$, that defines per each iteration and each unit, the maximal size of the HP.

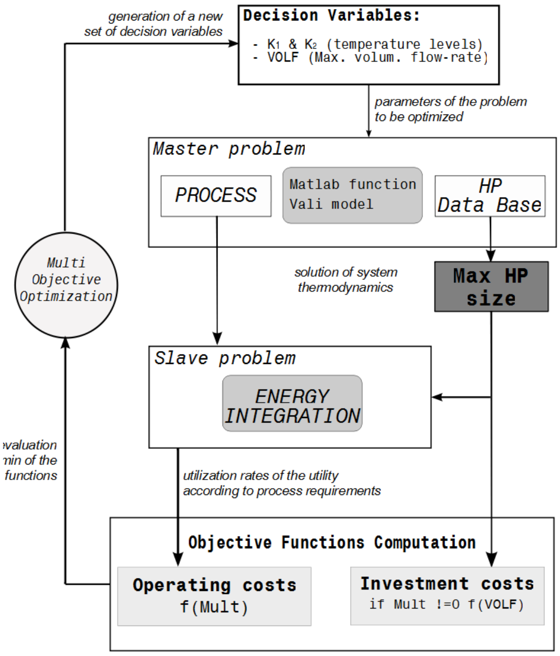


Figure 7: Optimization approach

Once these parameters are launched by the optimization algorithm and once the thermodynamic model converges, the maximal size of the HP, that is to say the maximal electrical power absorbed by the compressor and the maximum heat loads in the evaporator and condenser, are known. At this point the EI software computes the utilization rates of the units, aiming at minimizing the operating costs. After this step, we can proceed in the evaluation of the objective functions. As said already, the operating costs are computed according to the process actual needs in terms of natural gas and electricity. In this case the investment costs are computed, if the unit is integrated (Mult$\neq$ 0), according to Eq. 3, where the sizing parameter is maximal compressor electrical power, relative to the $VOLF$ (max HP size).

In figure 7 we report a scheme of the optimization approach.

$$IC_{compr} = 1.5 \cdot 1500 \cdot 160^{0.1} \cdot (\dot{E}^{+}_{max})^{0.9} \tag{3}$$

4.1.1 Optimization Results 1

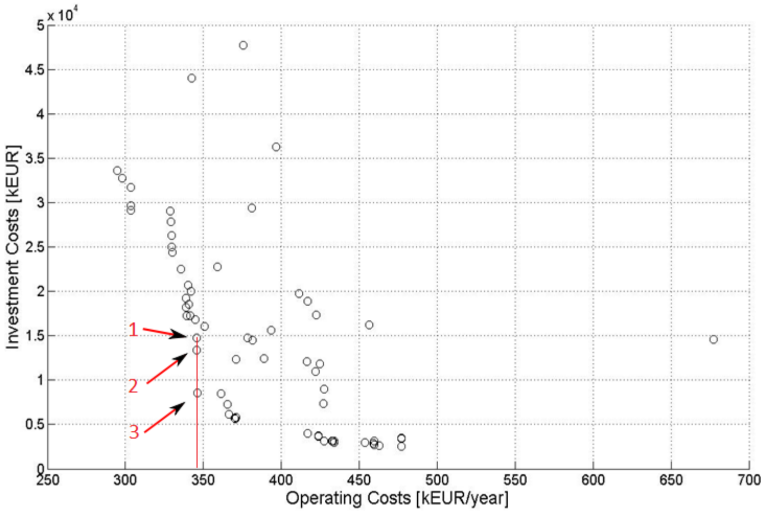


Figure 8: Evolutionary algorithm (MOO) Results (6000 evaluations, 200 Pareto Points)

The approach described above has been implemented and applied to optimize the Brewery process. After 6000 iterations, the MOO computation gives the results presented in the operating-investment costs space of Figure 8. It could be immediately seen how, even after a very high number of iterations, involving long computational time and resources, the optimization has not converged. The same conclusions could be drawn if we analyze the data regarding points 1,2,3, depicted in Figure 8, whose Integrated Composite Curves are reported in Figure 9.

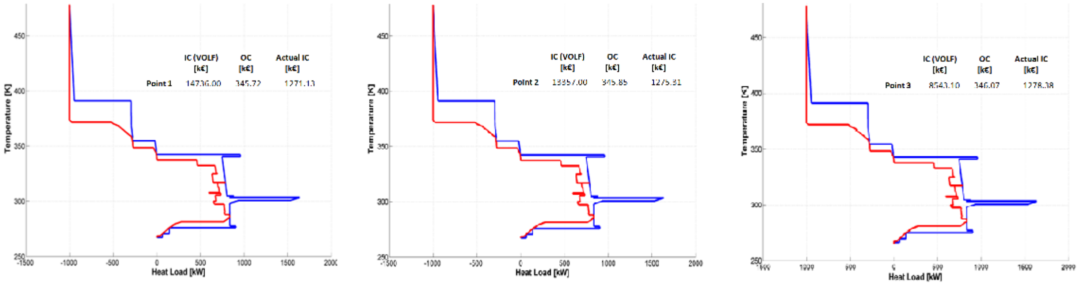
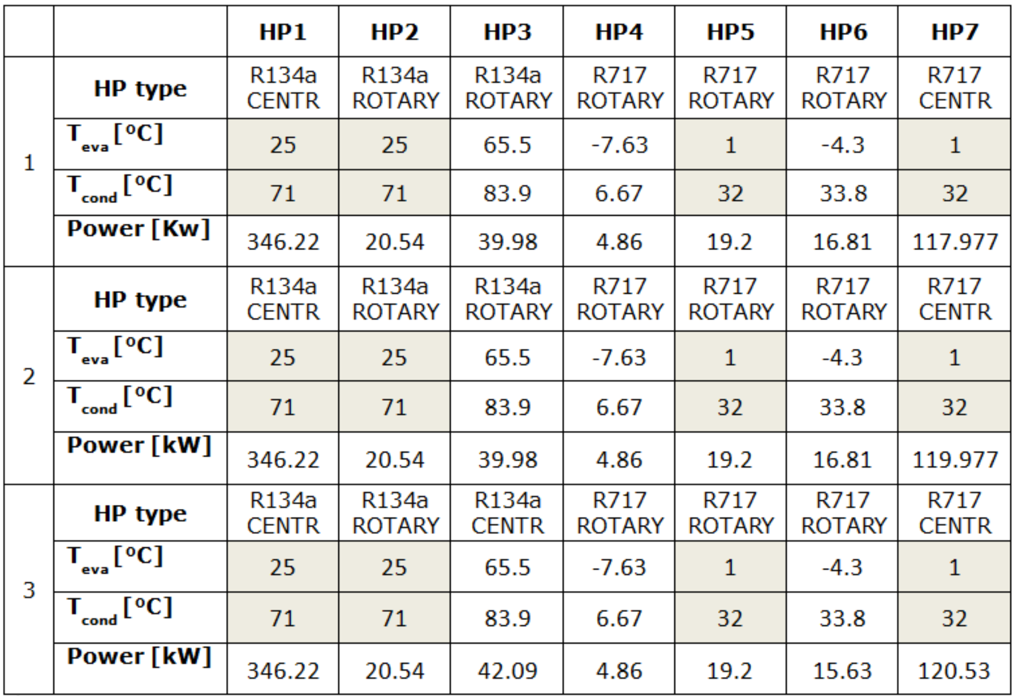


Figure 9: Integrated Composite Curve of Brewery process, points 1, 2 and 3

The operating costs related to these 3 points are very close, while e big difference in terms of investment costs (up to 40%) could be noticed. Their simultaneous presence in the Pareto could be thus explained only with a non convergence of the optimization computation.



		HP1	HP2	HP3	HP4	HP5	HP6	HP7
1	**HP type**	R134a CENTR	R134a ROTARY	R134a ROTARY	R717 ROTARY	R717 ROTARY	R717 ROTARY	R717 CENTR
	T_{eva} [°C]	25	25	65.5	-7.63	1	-4.3	1
	T_{cond} [°C]	71	71	83.9	6.67	32	33.8	32
	Power [Kw]	346.22	20.54	39.98	4.86	19.2	16.81	117.977
2	**HP type**	R134a CENTR	R134a ROTARY	R134a ROTARY	R717 ROTARY	R717 ROTARY	R717 ROTARY	R717 CENTR
	T_{eva} [°C]	25	25	65.5	-7.63	1	-4.3	1
	T_{cond} [°C]	71	71	83.9	6.67	32	33.8	32
	Power [kW]	346.22	20.54	39.98	4.86	19.2	16.81	119.977
3	**HP type**	R134a CENTR	R134a ROTARY	R134a CENTR	R717 ROTARY	R717 ROTARY	R717 ROTARY	R717 CENTR
	T_{eva} [°C]	25	25	65.5	-7.63	1	-4.3	1
	T_{cond} [°C]	71	71	83.9	6.67	32	33.8	32
	Power [kW]	346.22	20.54	42.09	4.86	19.2	15.63	120.53

Figure 10: Heat Pump integration of points 1, 2 and 3

Comparing the ICC of figure 9 and more explicitly the data reported in the data of Figure 10, we immediately realize that the 3 points represent the same solution. The deviation in the computation of the investment costs is due to the random choice of the $VOLF$ which defines the maximal size of the heat pump. As already mentioned, the investment costs are computed according to this maximal size, while, the integrated, actual size of the HP is given by its utilization rates.

Having a closer look at the temperature intervals reported again in Table 10, we can also conclude that the results of this computation are not optimal. We immediately realize how, in the intervals 25 - 71 $°C$ and 1 - 32 $°C$, one single, bigger heat pump would have been economically much more convenient then the two units resulting from the optimization.

If we now consider the type of compressor technology chosen we can state that the solutions are not realistic from the mere technical point of view. Reciprocating and centrifugal compressor are rarely purchased and installed in such applications, since their costs is much higher than that of near-in-size scroll or screw technologies.

4.1.2 Conclusions

As mentioned before, such optimization approach does not give the expected results. Due to the high number of decision variables (80) the convergence of the computation is difficult to achieve (very time consuming). The resulting solutions do not represent optimal neither realistic solutions. For these reasons this approach has been quit. A possible improvement has been expected from the following approach.

4.2 Optimization Approach 2 - 'Mult'

As it could be concluded after analyzing the results of the previous approach, the random choice of the $VOLF$ and the consequent computation of the investment costs spoil the effectiveness of the optimization. For this reason, the following approach aims at optimizing only the parameters k_1, k_2 at the master level. The size of the HP is optimized at the slave problem, when the EI software computes the utilization rates, always willing minimizing the operating costs, that are always calculated according to the effective energy requirements of the process.

In order to obtain more realistic solutions, we decide to choose investment cost correlations, able to take into account the difference in price of the different compressor technologies. As already mentioned, it is very difficult to come into possession of such information. For this reason we adopt here a simple, 'qualitative' costing policy analysis. As reported in the graph of Figure 11 the cost of rotary, centrifugal and axial compressor has been artificially affected, starting from the available correlations in [11] (Eq. 4), in order to obtain the shown behavior. The investment costs related to the purchase of the other technologies have been computed according to Eq. 3.

$$IC_{compr} = 1.14 \cdot f_{BM} \cdot \frac{Index_{2010}}{Index_{1996}} \cdot 10^{(2.9945+0.9542 \cdot log_{10}(\dot{E}^{+}_{HP}))} \tag{4}$$

where f_{BM} is equal to 18 for rotary compressors, 8.8 for centrifugal and 3.5 for axial.

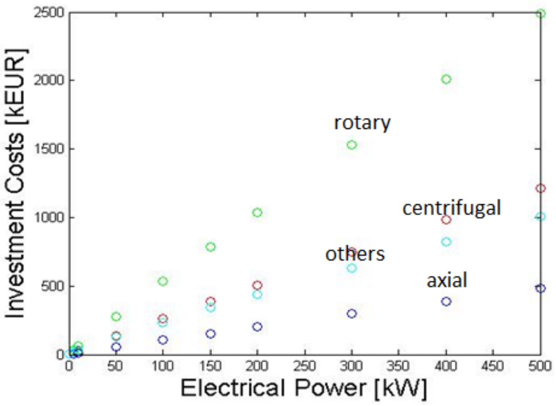


Figure 11: Compressor Investment cost correlations

In order to make the computation more realistic respect to some practice rules of thumb, the possibility of integration of a so called *standard heat pump* has been implemented. This latter consists in a device that could be installed only within a precise range of evaporation and condensation level (as reported in Figure 12) whose relative investment is computed according to Eq. 5.

$$IC_{compr} = 1.5 \cdot (-0.1814 \cdot \dot{E}^{+}_{HP} + 375) \cdot (\dot{E}^{+}_{HP}) \tag{5}$$

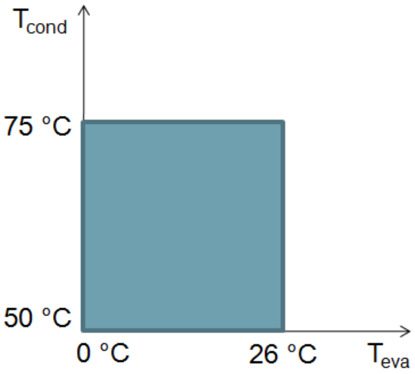


Figure 12: Standard Heat Pump evaporation and condensation temperature ranges

In all cases the chosen sizing parameter is the actual electrical power absorbed by the compressor, according to the utilization rates computed in the slave level. This represents a breaking point with respect to the previous unsuccessful approach, where the investments are computed in function of the maximal compressor size. In Figure 13 we report a scheme of the optimization approach here adopted.

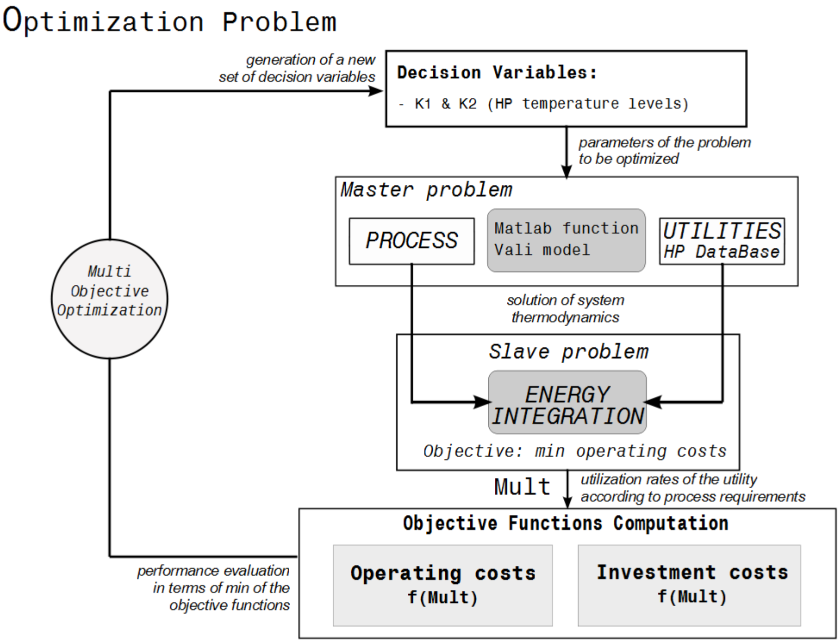


Figure 13: Optimization approach

4.2.1 Optimization Results 2

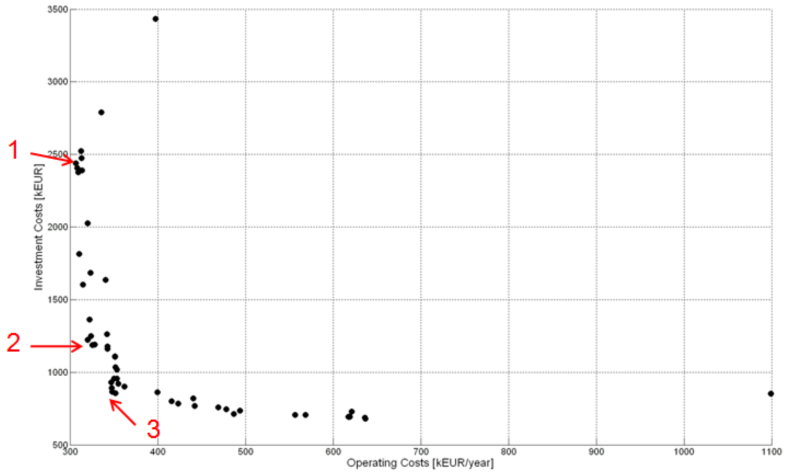


Figure 14: Evolutionary algorithm (MOO) Results (3000 evaluations, 200 Pareto Points)

A 3000 iterations MOO computation has been accomplished, in order to optimize the Brewery process. The resulting Pareto curve is reported in Figure 14. In Figure 16 we report the data relative to some points whose composite curves are reported in Figure 15.

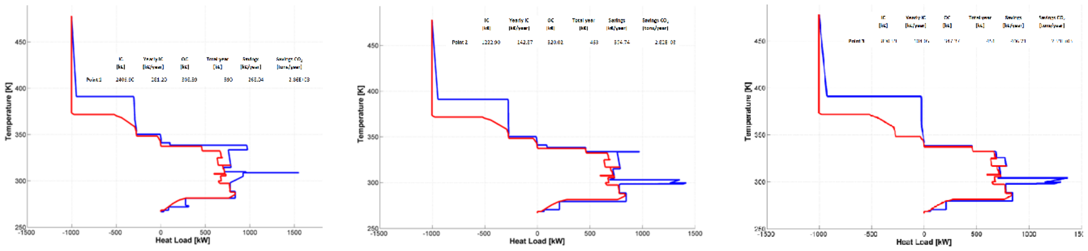
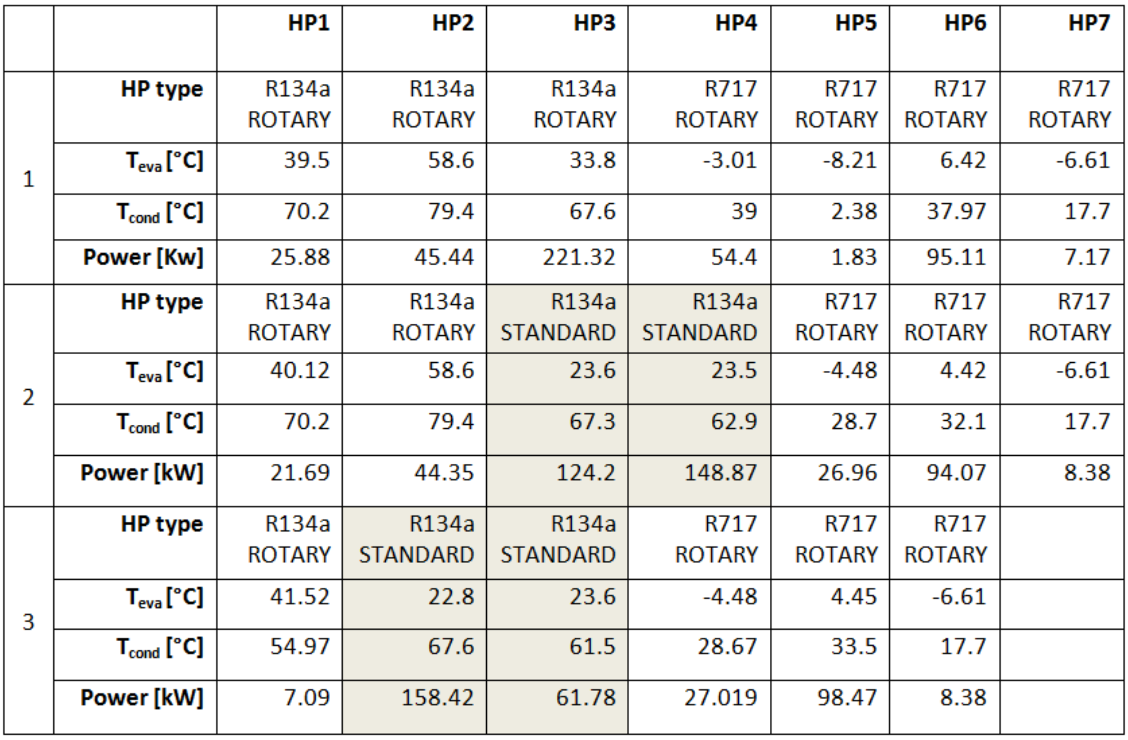


Figure 15: Integrated Composite Curve of Brewery process, points 1, 2 and 3

From the optimization point of view, the different analyzed solutions seem to be quite good. At the same time we notice the integration of rotary compressors in almost all the cases, except when the integration of the standard HP is possible (max efficiency). The reason why also with this new approach the rotary compressor is chosen depends on the choice of the EI objective. Since this latter wants to optimize the operating costs, it will always choose the technology characterized by the highest efficiency, the rotary compressor in this case.



		HP1	HP2	HP3	HP4	HP5	HP6	HP7
1	**HP type**	R134a ROTARY	R134a ROTARY	R134a ROTARY	R717 ROTARY	R717 ROTARY	R717 ROTARY	R717 ROTARY
	T_{eva} [°C]	39.5	58.6	33.8	-3.01	-8.21	6.42	-6.61
	T_{cond} [°C]	70.2	79.4	67.6	39	2.38	37.97	17.7
	Power [Kw]	25.88	45.44	221.32	54.4	1.83	95.11	7.17
2	**HP type**	R134a ROTARY	R134a ROTARY	R134a STANDARD	R134a STANDARD	R717 ROTARY	R717 ROTARY	R717 ROTARY
	T_{eva} [°C]	40.12	58.6	23.6	23.5	-4.48	4.42	-6.61
	T_{cond} [°C]	70.2	79.4	67.3	62.9	28.7	32.1	17.7
	Power [kW]	21.69	44.35	124.2	148.87	26.96	94.07	8.38
3	**HP type**	R134a ROTARY	R134a STANDARD	R134a STANDARD	R717 ROTARY	R717 ROTARY	R717 ROTARY	
	T_{eva} [°C]	41.52	22.8	23.6	-4.48	4.45	-6.61	
	T_{cond} [°C]	54.97	67.6	61.5	28.67	33.5	17.7	
	Power [kW]	7.09	158.42	61.78	27.019	98.47	8.38	

Figure 16: Heat Pump integration of points 1, 2 and 3

4.2.2 Conclusions

On one hand, from the optimization point of view, the solutions seem to be quite good. On the other hand, from the technical and of the application point of view the solutions are not realistic, even if a different prizing policy has been adopted. To be able to obtain more realistic solution, we should modify the EI tool objective. We have seen how this aims at the minimization of the operating costs, just maximizing the efficiency of the system (of the compressor in the specific case of HPs).

The final approach wants to find not only good solutions from the optimization and integration point of view but also solutions meaningful from the engineering practice and technique point of view. The approach that follows represents a possible improvement in this sense.

4.3 Optimization Approach 3 - 'Total cost'

Analyzing the results of the previous approaches we are in possession of some important data. First we have seen that, in any case, the temperature levels are optimized at the master level. In this new approach, K_1 and K_2 are considered as decision variables.

Second, it is clear that the optimization of the size, in terms of HP compressor $VOLF$, at the master level does not give optimal neither realistic results. The optimization of this latter at the slave level, as could be seen in the second approach, gives good results from the optimization (and integration) point of view. As already stated, these results do not reflect the choice the engineer would do in practice. The

EI tool, in fact, in these conditions prefers to maximize the efficiency of the overall system rather than minimize the costs related to the purchase of the equipment.

In order to take into account at the slave level, the effect of the sizing policy, and thus of the units cost, we decide to run the EI software aiming at minimizing the *(yearly) total costs.*

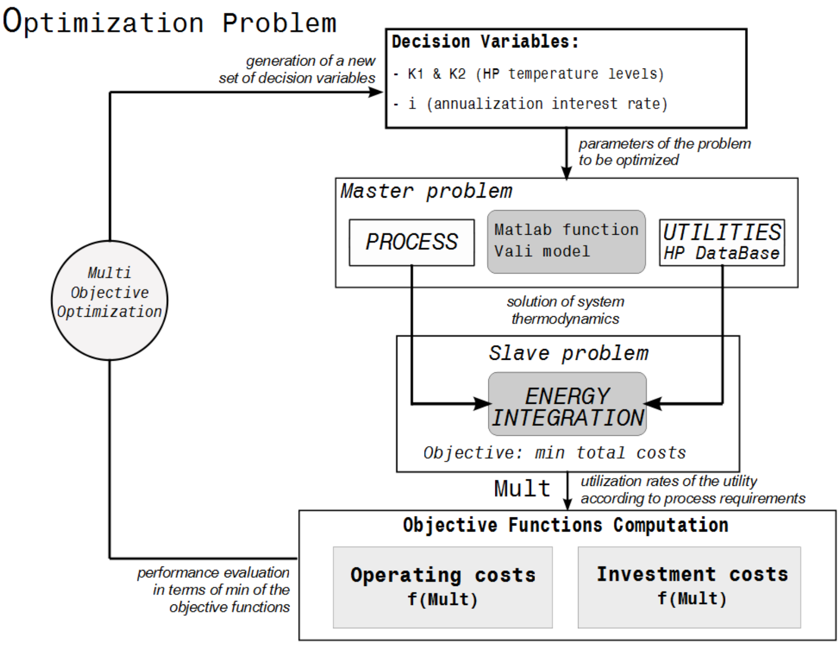


Figure 17: Optimization approach

YearlyTotalCosts computation These are defined as the sum of the *yearly operating costs* and the *annualized investment costs* related to the purchase of a given piece of equipment (HP compressor in this case) as reported in Eq. 6. To be able to take them into account in an annual time scale, the investment costs should be annualized according to the *interest rate* i and the *expected life* n of the components.

$$TC_{year} = OC_{year} + IC_{year} =$$

$$= (\dot{Q}_{natgas} \cdot c_{natgas} + \dot{E}_{in} \cdot c_{el,in} - \dot{E}_{out} \cdot c_{el,out}) \cdot op_{time} + IC_{tot} \cdot \left(\frac{i(i+1)^n}{(i+1)^n - 1} \right) \quad (6)$$

In our case, it results interesting to weight the influence of the investment costs in the total costs. Small influence of investment costs (low weighting factor) would in fact allow the integration of expensive compressors, making it to prevail the efficiency of the system (i.e. rotary compressors), high influence of the investment costs would allow the integration of cheap even if not very efficient units (i.e. scroll and screw compressors).

Since the final aim of the Data Base is to provide the engineer a wide range of possibilities, we want that all the units could in theory be integrated. The definition of the total costs as the simple sum of operating and annualized investment, at fixed interest rate, will in fact allow only the integration of cheap but not very efficient units.

For these reasons we introduce, in our set of decision variables (Figure 17, the interest rate i, that varies within the range [0, 20]. Corresponding to small values of the interest rate i, we see small influence of the investment costs (small weighting factor), on the contrary, values of i close to the upper bound, lead to high weight of the investment and thus the integration of cheap not very efficient units (Eq. 6).

The implementation of such EI objective is possible in OSMOSE®, after having defined the correlations enabling the computation of the investment costs of the given unit. We define as sizing parameter the compressor electrical power resulting from the solution of the system thermodynamics (for a given set of K_1 and K_2). For each unit we define the investment costs according to Eq. 4 or 3 computed in function of the above mentioned power. To take into consideration the real size of the HP, since the utilization rates are not given at this step, we multiply the overall investment cost times the Multiplication factors. As it could be understood, this represents an approximation. The accuracy of this approximation results to be quite good if compared to a simple linearization of the investment cost correlation or a much more resources consuming discretization and linearization of the correlation in the entire range.

Objective Function computation As it results from the previous approaches, the best way to compute the objective function is referring to the effective needs of the process. Also in this case, in fact, the operating costs are computed according to the real requirements of the process in terms of natural gas and electricity (see Appendix 1 for energy costing parameters of the plant). The actual compressor electrical power, resulting from energy integration computation, is used here in the calculation of the investment costs computed according to Eq. 4 for rotary, centrifugal and axial and Eq. 3 for the other technologies.

4.3.1 Optimization Results 3

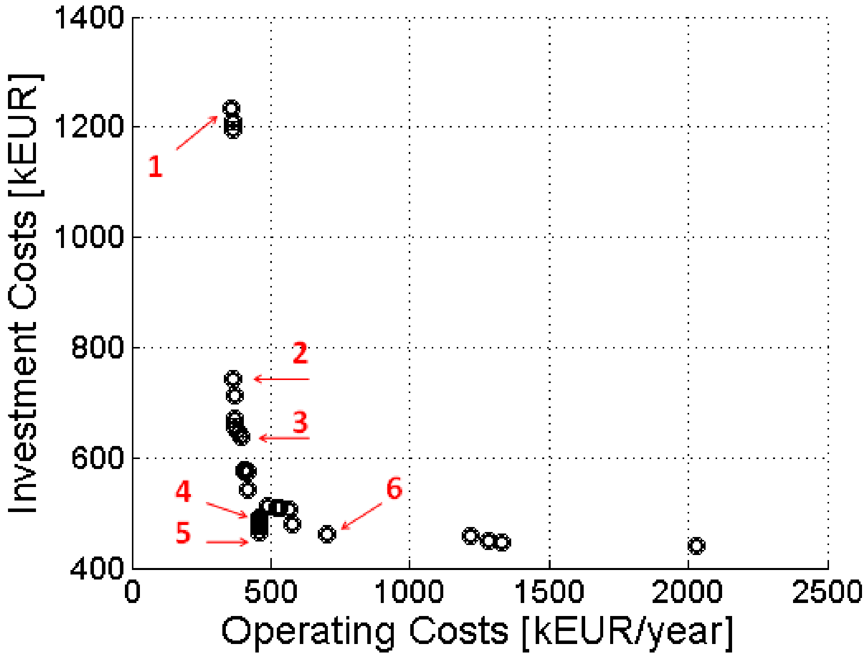


Figure 18: Evolutionary algorithm (MOO) Results (3000 evaluations, 100 Pareto Points)

A 3000 iterations MOO computation has been accomplished, in the frame of the Brewery process optimization. The resulting Pareto curve is reported in Figure 18. In Figure 19 we report the data relative to some points whose composite curves are reported in Figure 20.

	Investment Costs [k€]	Yearly investment costs [k€/year]	Operating Costs [k€/year]	Savings [k€/year]	CO2 savings [tons/year]
Point1	1232.00	143.93	360.86	352.83	2.72E+03
Point2	742.02	86.69	366.29	404.65	2.65E+03
Point3	639.45	74.71	391.96	393.88	2.42E+03
Point4	491.41	57.41	459.77	340.45	1.91E+03
Point5	489.47	57.19	459.48	340.96	1.90E+03
Point6	460.16	53.76	704.54	99.33	7.73E+02

Figure 19: Costs and Savings of computed points

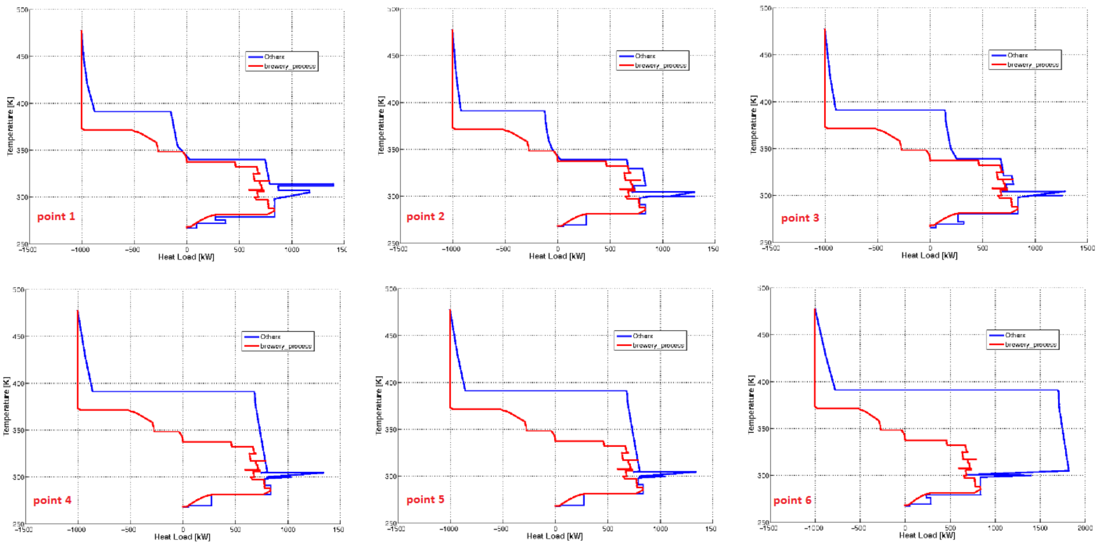
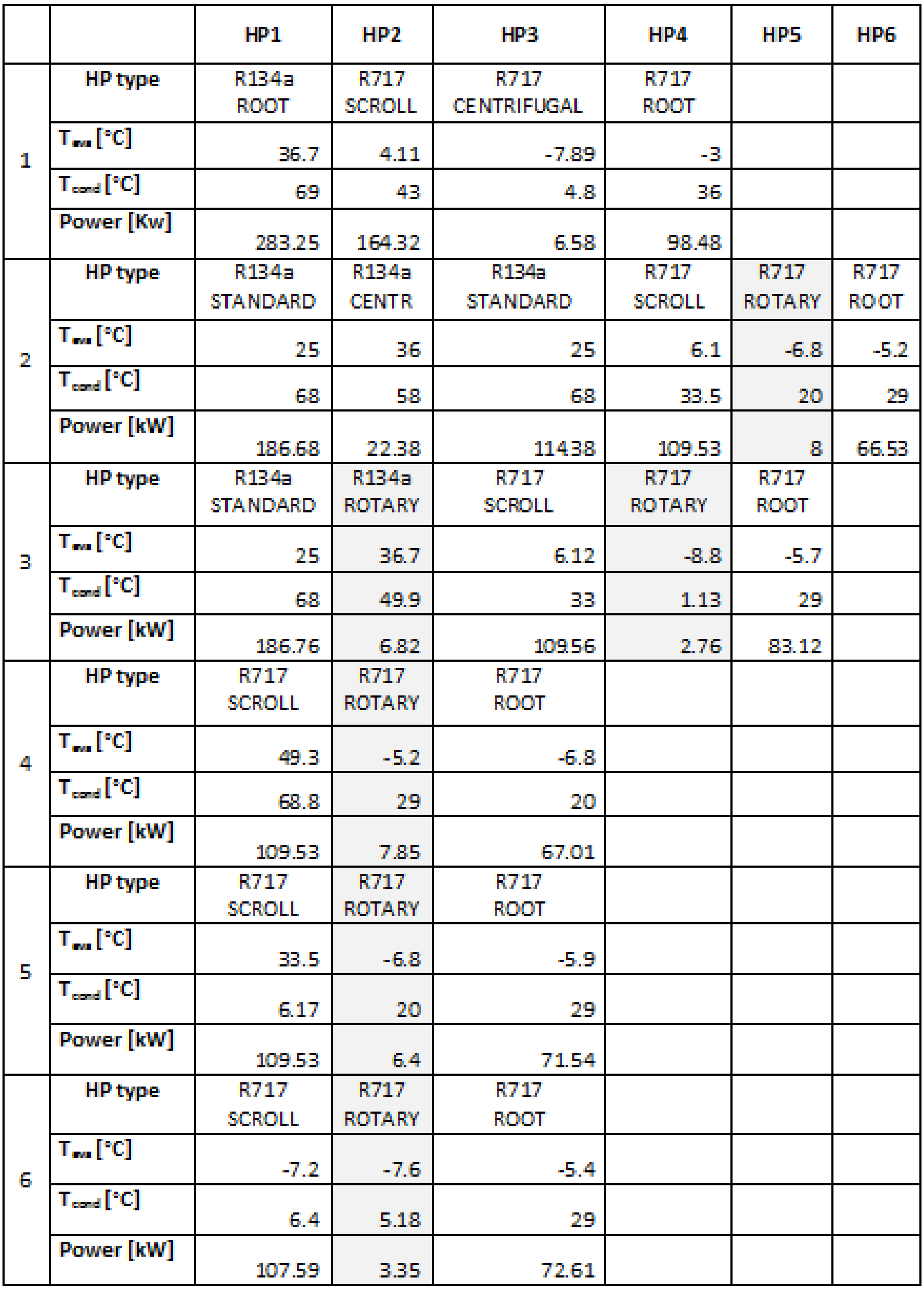


Figure 20: Integrated Composite Curve of Brewery process, points 1, 2 and 3

More interesting is the analysis of the data of Figure 21, regarding the same points.

Point 1 Point 1 is characterized by the highest investment costs and thus by the lowest costs related to process operation. The solution involves the integration of 4 heat pumps, whose temperature levels and electrical powers are reported in Figure 21. We can immediately see that both the temperature levels and the size of the HP are optimal. The small number and the (big) size of the integrated units (4) give a positive feedback in this sense (only non-redundant units are present). Only one small unit, the *centrifugal* HP, is placed in correspondence of the refrigeration cycle. The small difference between evaporation and condensation temperatures (the low pressure ratio) justifies the choice of the centrifugal technology. The size of this latter falls within the range of powers corresponding to which the investment costs for the different technologies are similar, and thus could be chosen by the EI tool. The remaining units are equipped with *root* and *scroll* compressors. According to what already discussed, the obtained solution is not only good from the optimization point of view, but also realistic from the technical point of view.

Point 2 Comparing this solution of this point to that of Point 1, one could state that this solution is less efficient. A large number of units are here present. In one case (interval 25-68 $°C$) two units are placed in correspondence to the same temperature interval. The units chosen are equipped with two standard compressors, whose cost is quite low, justifying the choice. Moreover, the size of these HP is near the maximal allowed for that kind of technologies. In other words, to meet the process requirements, 2 units of comparable size are thus required. In a similar way to what happens in Point 1, a small *rotary* HP is placed where refrigeration is required. As already said, the small size and the related low investment costs, justify the choice of a more efficient compressor technology.



		HP1	HP2	HP3	HP4	HP5	HP6
1	HP type	R134a ROOT	R717 SCROLL	R717 CENTRIFUGAL	R717 ROOT		
	T_{eva} [°C]	36.7	4.11	-7.89	-3		
	T_{cond} [°C]	69	43	4.8	36		
	Power [Kw]	283.25	164.32	6.58	98.48		
2	HP type	R134a STANDARD	R134a CENTR	R134a STANDARD	R717 SCROLL	R717 ROTARY	R717 ROOT
	T_{eva} [°C]	25	36	25	6.1	-6.8	-5.2
	T_{cond} [°C]	68	58	68	33.5	20	29
	Power [kW]	186.68	22.38	114.38	109.53	8	66.53
3	HP type	R134a STANDARD	R134a ROTARY	R717 SCROLL	R717 ROTARY	R717 ROOT	
	T_{eva} [°C]	25	36.7	6.12	-8.8	-5.7	
	T_{cond} [°C]	68	49.9	33	1.13	29	
	Power [kW]	186.76	6.82	109.56	2.76	83.12	
4	HP type	R717 SCROLL	R717 ROTARY	R717 ROOT			
	T_{eva} [°C]	49.3	-5.2	-6.8			
	T_{cond} [°C]	68.8	29	20			
	Power [kW]	109.53	7.85	67.01			
5	HP type	R717 SCROLL	R717 ROTARY	R717 ROOT			
	T_{eva} [°C]	33.5	-6.8	-5.9			
	T_{cond} [°C]	6.17	20	29			
	Power [kW]	109.53	6.4	71.54			
6	HP type	R717 SCROLL	R717 ROTARY	R717 ROOT			
	T_{eva} [°C]	-7.2	-7.6	-5.4			
	T_{cond} [°C]	6.4	5.18	29			
	Power [kW]	107.59	3.35	72.61			

Figure 21: Heat Pump integration of computed points

Point 3 Point 3 represents an intermediate solution in terms of savings and investment costs. Also in this case, small *rotary* units are integrated. All the considerations made above are here valid.

Points 4 & 5 The improvement solutions related to these two points are very similar. They differ in terms of temperature levels, but only small difference could be seen in the compressor's electrical power, slightly affecting the total investment costs. The operating costs are almost the same. Their simultaneous presence in the Pareto curve could be possible in relation to the total number of iterations accomplished in the frame of the optimization.

Point 6 It results interesting to analyze the solutions regarding the points related to high operating costs. Looking at the Integrated Composite Curves of Point 6 (the same is valid for Points 4 and 5 as depicted in Figure 20), we can see that the heating load of the boiler is used to meet process requirements at higher temperatures and used to condense the refrigerant in HP 3 refrigeration cycle (see Table of Figure 21). In this case, in fact, the condensation temperature of the ammonia cycle ($29\ °C$) is higher than the maximal allowed temperature of the cooling water utility ($26\ °C$). This solution requires the purchase of heating energy (natural gas) in order to meet the HP requirements. Being able to reduce the above mentioned condensation level or being able to avoid the utilization of boiler power in such cases would reduce the heat requirements of the system, allowing a more efficient use of energy, meaning a real improvement for the system.

4.3.2 Conclusions

From the optimization point of view, the solutions analyzed give a positive feedback in this sense. The only weak point regards the issue of the possible utilization of the boiler power, at low temperatures, in function of the ammonia HP condensation level. Solutions to this problem could be found in different settings of the cooling water utility. From the technical point of view, this approach finally gives the expected results. The possible integration of a wide range of different technologies is possible.

Looking in detail at the solutions, comparing the related set of the decision variables (Appendix 2), we can explain the integration of small, expensive units. In the EI total costs computation, the total IC of these small units is comparable to the others and, thanks to the low interest rates, the annualized investment is very low. Thanks to the high efficiency of these units, the operating costs are low. The sum of these two will result in low (minimum) total costs, and they can be thus integrated.

Finally, having a quick look at the operating ranges and at the solution adopted, one can state that the modeling of the units is correct. Moreover, it results to be well integrated with this optimization approach, providing the engineer good and realistic solutions. Solutions even more close to reality could be achieved, imposing real correlations for the computation of the compressors investment costs. As mentioned many times, it results very difficult to enter into possession of this information outside the industrial world.

4.4 Advantages and Drawbacks of the Model Implementation

The implementation of this last approach allows the simultaneous integration (at different ΔT) of heat pumps equipped with different compressors and using different fluids is also possible. Moreover, this Data Base is implemented in such a way that any new compressor technology or refrigerant fluid could be added, resulting in an extreme flexibility of the program.

From the computational resources point of view, the lower (18) number of decision variables of the problem brings to faster convergence of the optimization computation. The overall time of the computation depends on the process and on the way the process is defined.

To conlcude, the solutions obtained, if compared to the previous attempts, result to be consistent from the energy integration point of view but also from the technical point of view, allowing a real optimization of the given process. Ufortunately this last point is strictly connected to the correlations used in the compressor investment costs computation, and to the variability and the difficulty to come into possession of such information.

4.5 Further Improvements

As just stated, the flexibility of the Data Base allows the integration of new compressor technologies and of HP working with new refrigerants. Among these it results interesting the possibility of integration of HP characterized by non constant evaporation and condensation temperatures. Models of water-ammonia mixture heat pumps are already available. More complex but flexible models working with many substances and capable to mix them arbitrarily represent another improvement to the data base. In relation to the use of many chemical substances, many considerations have to be done, in relation to their compatibility or their toxicity. In the literature correlations able to compute the flammability of mixed refrigerants and giving the order of magnitude of their global warming factor could be found and should be taken into account in the definition of the optimization problem.

5 Conclusions

During the period of this semester, a deep analysis of the integration of HPs has been carried on, with particular attention to industrial application. The Data Base resulting from previous works at LENI-EPFL has been tested in order to find the best approach of the Multi-Objective Optimization, with the final aim of finding optimal and realistic solutions in terms of HP integration.

Three different approaches have been tested in the frame of the Brewery process optimization, giving different results. The analysis of the results results in a trial and error approach in finding the best definition of the optimization method. The third approach finally gives the best results in terms of optimization but also realistic from the technical point of view.

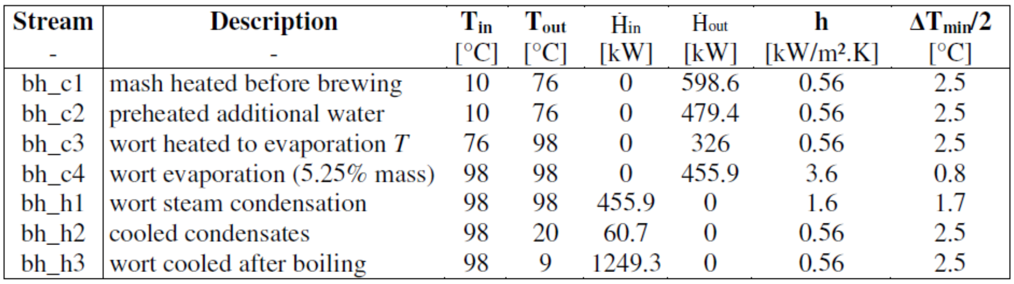
This latter is strictly connected to the pricing policies used in the estimation of the investment costs related to the purchase of the HP (mainly of the compressor). The engineer working with such tool has the possibility of implementing the cost correlations, obtaining at the end real improvement solutions for the process he wants to optimize.

Appendix 1

List of Process streams and thier properties

All the streams involved in the Brewery process are listed here below:

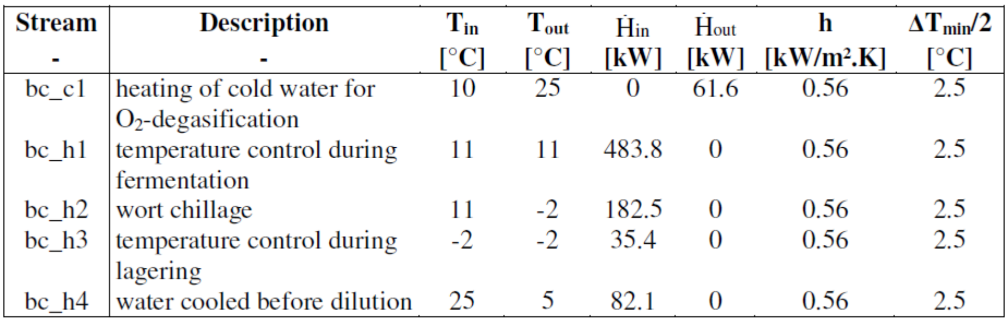
- Hot section streams:



Stream -	Description -	T_{in} [°C]	T_{out} [°C]	$\dot{H}_{in}$ [kW]	$\dot{H}_{out}$ [kW]	h [kW/m².K]	$\Delta T_{min}/2$ [°C]
bh_c1	mash heated before brewing	10	76	0	598.6	0.56	2.5
bh_c2	preheated additional water	10	76	0	479.4	0.56	2.5
bh_c3	wort heated to evaporation *T*	76	98	0	326	0.56	2.5
bh_c4	wort evaporation (5.25% mass)	98	98	0	455.9	3.6	0.8
bh_h1	wort steam condensation	98	98	455.9	0	1.6	1.7
bh_h2	cooled condensates	98	20	60.7	0	0.56	2.5
bh_h3	wort cooled after boiling	98	9	1249.3	0	0.56	2.5

Figure 22: Process Hot section - List of streams [4]

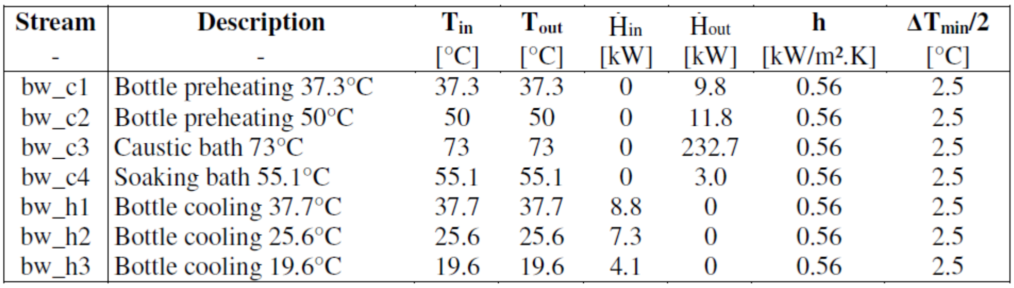
- Cold section streams:



Stream -	Description -	T_{in} [°C]	T_{out} [°C]	$\dot{H}_{in}$ [kW]	$\dot{H}_{out}$ [kW]	h [kW/m².K]	$\Delta T_{min}/2$ [°C]
bc_c1	heating of cold water for O_2-degasification	10	25	0	61.6	0.56	2.5
bc_h1	temperature control during fermentation	11	11	483.8	0	0.56	2.5
bc_h2	wort chillage	11	-2	182.5	0	0.56	2.5
bc_h3	temperature control during lagering	-2	-2	35.4	0	0.56	2.5
bc_h4	water cooled before dilution	25	5	82.1	0	0.56	2.5

Figure 23: Process cold section - List of streams [4]

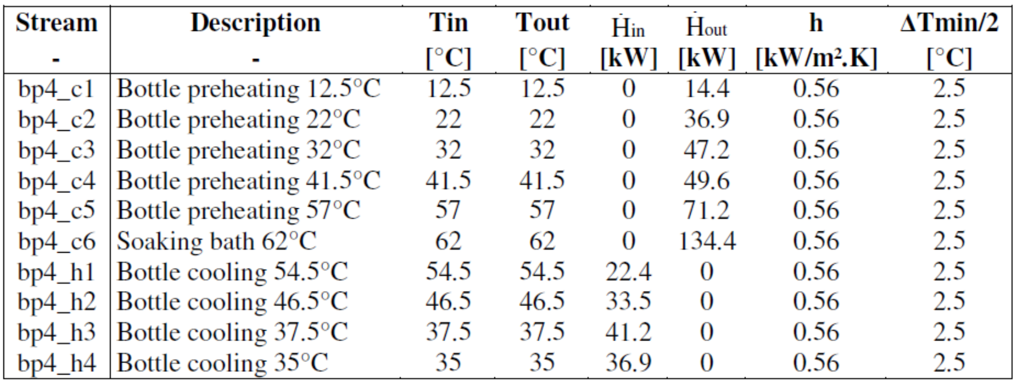
- Bottle washing section streams:



Stream -	Description -	T_{in} [°C]	T_{out} [°C]	$\dot{H}_{in}$ [kW]	$\dot{H}_{out}$ [kW]	h [kW/m².K]	$\Delta T_{min}/2$ [°C]
bw_c1	Bottle preheating 37.3°C	37.3	37.3	0	9.8	0.56	2.5
bw_c2	Bottle preheating 50°C	50	50	0	11.8	0.56	2.5
bw_c3	Caustic bath 73°C	73	73	0	232.7	0.56	2.5
bw_c4	Soaking bath 55.1°C	55.1	55.1	0	3.0	0.56	2.5
bw_h1	Bottle cooling 37.7°C	37.7	37.7	8.8	0	0.56	2.5
bw_h2	Bottle cooling 25.6°C	25.6	25.6	7.3	0	0.56	2.5
bw_h3	Bottle cooling 19.6°C	19.6	19.6	4.1	0	0.56	2.5

Figure 24: Process bottle washing - List of streams [4]

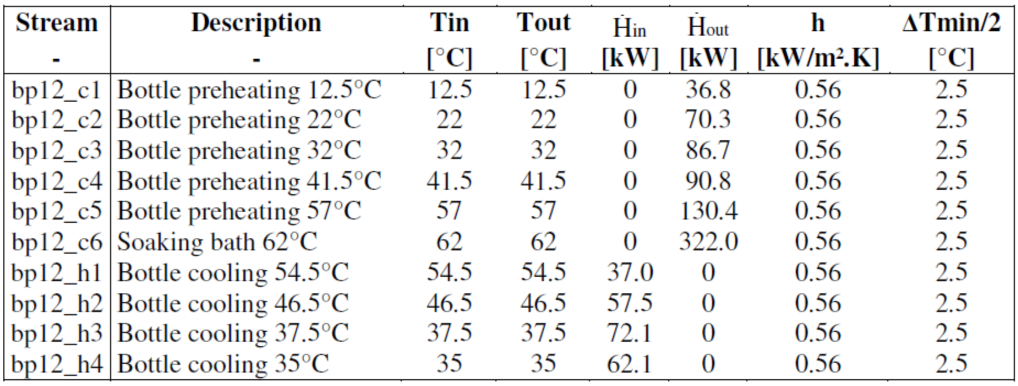
- Bottle pasteurization line 4 section streams:



Stream	Description	Tin	Tout	$\dot{H}_{in}$	$\dot{H}_{out}$	h	ΔTmin/2
-	-	[°C]	[°C]	[kW]	[kW]	[kW/m².K]	[°C]
bp4_c1	Bottle preheating 12.5°C	12.5	12.5	0	14.4	0.56	2.5
bp4_c2	Bottle preheating 22°C	22	22	0	36.9	0.56	2.5
bp4_c3	Bottle preheating 32°C	32	32	0	47.2	0.56	2.5
bp4_c4	Bottle preheating 41.5°C	41.5	41.5	0	49.6	0.56	2.5
bp4_c5	Bottle preheating 57°C	57	57	0	71.2	0.56	2.5
bp4_c6	Soaking bath 62°C	62	62	0	134.4	0.56	2.5
bp4_h1	Bottle cooling 54.5°C	54.5	54.5	22.4	0	0.56	2.5
bp4_h2	Bottle cooling 46.5°C	46.5	46.5	33.5	0	0.56	2.5
bp4_h3	Bottle cooling 37.5°C	37.5	37.5	41.2	0	0.56	2.5
bp4_h4	Bottle cooling 35°C	35	35	36.9	0	0.56	2.5

Figure 25: Bottle pasteurization section, line 4 - List of streams [4]

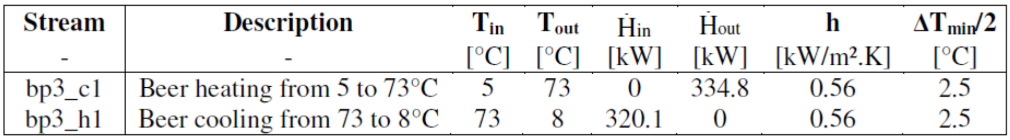
- Bottle pasteurization lines 1 and 2 section streams:



Stream	Description	Tin	Tout	$\dot{H}_{in}$	$\dot{H}_{out}$	h	ΔTmin/2
-	-	[°C]	[°C]	[kW]	[kW]	[kW/m².K]	[°C]
bp12_c1	Bottle preheating 12.5°C	12.5	12.5	0	36.8	0.56	2.5
bp12_c2	Bottle preheating 22°C	22	22	0	70.3	0.56	2.5
bp12_c3	Bottle preheating 32°C	32	32	0	86.7	0.56	2.5
bp12_c4	Bottle preheating 41.5°C	41.5	41.5	0	90.8	0.56	2.5
bp12_c5	Bottle preheating 57°C	57	57	0	130.4	0.56	2.5
bp12_c6	Soaking bath 62°C	62	62	0	322.0	0.56	2.5
bp12_h1	Bottle cooling 54.5°C	54.5	54.5	37.0	0	0.56	2.5
bp12_h2	Bottle cooling 46.5°C	46.5	46.5	57.5	0	0.56	2.5
bp12_h3	Bottle cooling 37.5°C	37.5	37.5	72.1	0	0.56	2.5
bp12_h4	Bottle cooling 35°C	35	35	62.1	0	0.56	2.5

Figure 26: Bottle pasteurization section, lines 1 and 2 - List of streams [4]

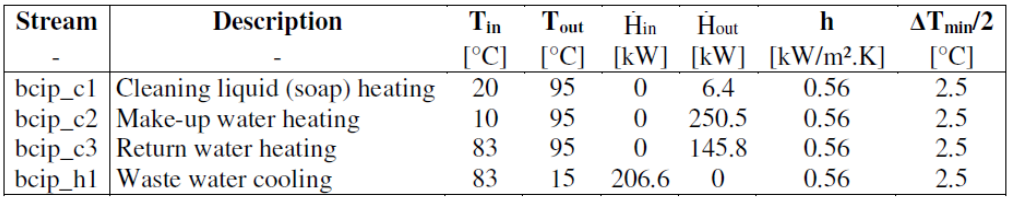
- Beer pasteurization section streams:



Stream	Description	T_{in}	T_{out}	$\dot{H}_{in}$	$\dot{H}_{out}$	h	$\Delta T_{min}/2$
-	-	[°C]	[°C]	[kW]	[kW]	[kW/m².K]	[°C]
bp3_c1	Beer heating from 5 to 73°C	5	73	0	334.8	0.56	2.5
bp3_h1	Beer cooling from 73 to 8°C	73	8	320.1	0	0.56	2.5

Figure 27: Beer pasteurization section - List of streams [4]

- Clean In Place section streams:

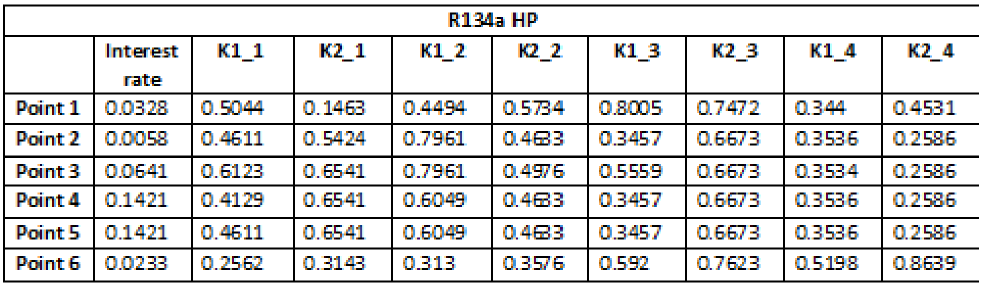


Stream	**Description**	$\mathbf{T_{in}}$	$\mathbf{T_{out}}$	$\dot{H}_{in}$	$\dot{H}_{out}$	**h**	$\mathbf{\Delta T_{min}/2}$
-	-	[°C]	[°C]	[kW]	[kW]	[kW/m²\.K]	[°C]
bcip_c1	Cleaning liquid (soap) heating	20	95	0	6.4	0.56	2.5
bcip_c2	Make-up water heating	10	95	0	250.5	0.56	2.5
bcip_c3	Return water heating	83	95	0	145.8	0.56	2.5
bcip_h1	Waste water cooling	83	15	206.6	0	0.56	2.5

Figure 28: Clean in Place section - List of streams [4]

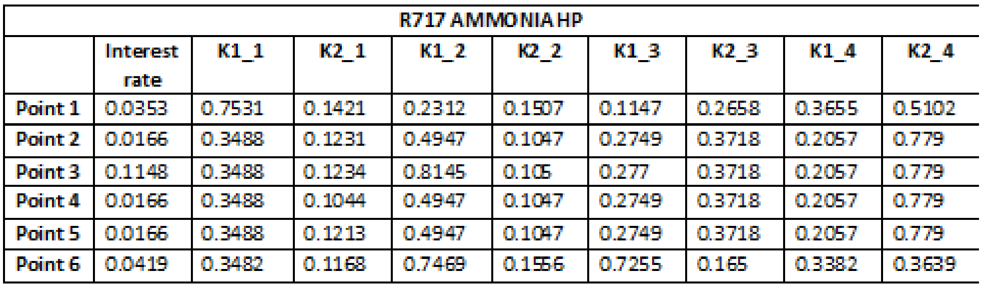
Appendix 2

Brewery optimization - Optimization Approach 3 - Decision Variables Point 1 - 6



R134a HP									
	Interest rate	K1_1	K2_1	K1_2	K2_2	K1_3	K2_3	K1_4	K2_4
Point 1	0.0328	0.5044	0.1463	0.4494	0.5734	0.8005	0.7472	0.344	0.4531
Point 2	0.0058	0.4611	0.5424	0.7961	0.4683	0.3457	0.6673	0.3536	0.2586
Point 3	0.0641	0.6123	0.6541	0.7961	0.4976	0.5559	0.6673	0.3534	0.2586
Point 4	0.1421	0.4129	0.6541	0.6049	0.4683	0.3457	0.6673	0.3536	0.2586
Point 5	0.1421	0.4611	0.6541	0.6049	0.4683	0.3457	0.6673	0.3536	0.2586
Point 6	0.0233	0.2562	0.3143	0.313	0.3576	0.592	0.7623	0.5198	0.8639

Figure 29: R134a HP Decision Variables



R717 AMMONIA HP									
	Interest rate	K1_1	K2_1	K1_2	K2_2	K1_3	K2_3	K1_4	K2_4
Point 1	0.0353	0.7531	0.1421	0.2312	0.1507	0.1147	0.2658	0.3655	0.5102
Point 2	0.0166	0.3488	0.1231	0.4947	0.1047	0.2749	0.3718	0.2057	0.779
Point 3	0.1148	0.3488	0.1234	0.8145	0.105	0.277	0.3718	0.2057	0.779
Point 4	0.0166	0.3488	0.1044	0.4947	0.1047	0.2749	0.3718	0.2057	0.779
Point 5	0.0166	0.3488	0.1213	0.4947	0.1047	0.2749	0.3718	0.2057	0.779
Point 6	0.0419	0.3482	0.1168	0.7469	0.1556	0.7255	0.165	0.3382	0.3639

Figure 30: R717 HP Decision Variables

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