A MULTI SCALE METHODOLOGY FOR ORC INTEGRATION OPTIMIZATION IN AN INDUSTRIAL PROCESS

Cong-Toan Tran[1], Assaad Zoughaib[2]*

MINES ParisTech, PSL Research University, CES - Centre for energy efficiency of systems,
Z.I. Les Glaizes – 5 rue Léon Blum 91120 Palaiseau, France

[1] cong-toan.tran@mines-paristech.fr

[2] assaad.zoughaib@mines-paristech.fr

* Corresponding Author

ABSTRACT

In industrial processes, a large amount of energy is usually lost as waste heat. This waste source reduces not only the energy efficiency of industrial processes but also contributes to greenhouse gases emissions and thermal pollution. In this context, The CERES-2 project (CERES denotes “Energy paths for energy recovery in industrial systems”), supported by the French National Research Agency, aims at developing a decision-making tool to identify the optimal solutions of industrial waste heat recovery. This platform leans on energy integration and multi-objectives optimization to identify and design the best waste heat recovery solutions, according to technical and economic criteria, for a given industrial process. The solutions gather direct heat recovery, heat pumping and electricity production technologies.

This paper presents how the developed multi scale methodology helps optimizing the integration and the architecture of an ORC in an industrial process.

On the process scale, CERES platform uses a MILP algorithm that uses Grand Composite Curve of the industrial process to specify the best integration location of the ORC in a systematic manner. The algorithm is based on exergy criteria and a simplified modeling of the ORC. This algorithm tests every possible couple of temperature level and chooses the best ones for the location of the heat recovery systems.

Once the ORC operating conditions defined, its detailed design and optimization is performed thanks to a model developed in Modelica language permitting to design the working fluid and the heat exchangers. The multi-objectives optimization of the cycle is performed by using self-adaptive version of Strength Pareto Evolutionary Algorithms 2 (SPEA2) implemented in CERES platform.

The methodology is successfully used in an industrial case where an ORC is integrated to the process.

1 INTRODUCTION

In France, the annual energy consumption in industry sector is about 456 TWh, of which 70 % is related to heating requirements. Although energy efficiency in France is one of the highest in the world, there are still significant sources of energy savings (Terrien 2008), especially via heat recovery (Center for Process Integration 2006). A number of studies show that it is theoretically possible to recover 10-25% of the energy consumption related to boiler fumes, ovens and driers (US Department of Energy 2000), that represents between 35 and 85 TWh per year for France (Dupont and Sapora 2009). The difficulties encountered by manufacturers to optimize their energy consumption can be divided into 3 groups:

- the variety of waste heat sources (nature, temperature ...);
- the variety of available production and recovery technologies;
- the different criteria to be considered for optimization: economic, energy, and environment.

Among the existing heat recovery methodologies, the method based on the pinch analysis, developed by Linnhoff (Linnhoff and Hindmarsh 1983), is considered as the most basic one. Other works have established the general rules for selection of appropriate utilities for a process (Bagajewicz and Barbaro 2003). The method has been successfully applied to a large number of process projects over the world. However, it requires a manual calculation procedure, so difficult to be used for a large system. In addition, there is no way to ensure that the found solution is the optimal one. These limitations require to develop alternative methodologies, such as mathematical programming approaches.

It should be noted that an adapted methodology has to be able to deal with a complex problem with many parameters and design variables (discrete or continuous) and result in technologically reliable solutions. The calculation time has to be also compatible with industrial requirements.

This paper presents a multi scale methodology allowing to integrate thermodynamic systems into an industrial process. This methodology is tested via a case study in which an integration of organic Rankine cycles (ORC) in an oil refinery process will be shown. In this case study, the results are obtained from CERES software, an open source tool developed by MINES ParisTech with supports of ANR and their 11 academia and industry partners (MINES ParisTech 2015).

2 METHODOLOGY

The methodology is composed of 3 sequential steps:

- The first step aims to identify waste sources and quantify heat recovery potential of the process. The pinch analysis is used in this step.
- Utilities are necessary to respond to the process energy requirements. So, the second step is to identify the most appropriate technologies (among the production and recovery technologies available, such as ORC system, heat pump, combined heat and power system) to be integrated in the process. The preliminary design of the identified systems is also investigated. An exegetic analysis is performed in this step.
- Finally, an optimal design of the selected system is performed thanks to optimization algorithms and mathematical solvers.

If the recovery potential analysis (first step) has been developed over decades, the identification of the most appropriate technologies (second step) and the optimal design (final step) are original since they combine the exergy analysis and the pinch method. In what follows, these two steps will be described.

2.1 Identification of the most appropriate technologies

The main challenge of an energy integration problem is to design a heat exchanger (HEN) network. There are a number of algorithms to design HEN. For minimizing the global cost (HEN and utilities), the algorithm picks up utilities in a set defined by the user. If too many utilities are available in the set, algorithm may crash down because of large number of combinatory possibilities. Moreover, potential relevant utilities that are not proposed will never be chosen. For this reason, it is necessary to carry out a preliminary phase aiming to select relevant utilities before the HEN design.

The algorithm developed in (Thibault, Zoughaib, and Pelloux-Prayer 2015) makes in one step automatic utility identification and pre-design. This algorithm is based on the Grand Composite Curve (GCC) utilization and a simplified exergy definition. Independently from their economical cost, utilities will be identified according to their energy efficiency, based on exergy criteria. The operating temperature levels of each selected utility are also specified.

To do so, the algorithm minimizes the exergy consumption / destruction of the process by selecting and sizing the appropriate utilities. It thus quantifies the available exergy flux (cooling at above ambient temperature) and the needs of exergy (heating above the temperature of the pinch point and cooling below the ambient temperature). In this analysis, a priori exergetic efficiency for the utilities is used, allowing to approach the performance of real energy conversion systems. The algorithm considers the following technologies: chiller, heat pump, ORC and CHP systems.

2.2 Design optimization

The previous step specifies the relevant utilities to recovery heat waste. This specification results in the temperature levels of hot and cold sources, and the powers of the utilities. In the next step, the utilities must be designed and optimized to achieve at least the exergy efficiency assumed previously. It is also necessary to check that the systems proposed are technically acceptable.

Among the variety of available production and recovery technologies, in this paper we focus on ORC system. In order to design an ORC system we first identify the appropriate refrigerant. According to (Ayachi et al. 2014), there is a strong correlation between the global exergy efficiency of the entire system (process and ORC) and the critical temperature of the refrigerant used in ORC system. As shown in Figure 1, an optimal critical temperature (for a heat source at 150°C) can be read from the hot source temperature and the pinch value (minimum temperature difference of heat exchanger). In particular, it appears a correlation for the optimal critical temperature of the refrigerant allowing to obtain a maximal exergy efficiency:

$$T_C \approx TIT_{\max} - 33\,K \tag{1}$$

where $TIT_{\max}$ represents the highest turbine inlet temperature which can be reached for a given hot source temperature and a given pinch value of heat exchanger.

This correlation allows to identify the most appropriate refrigerant.

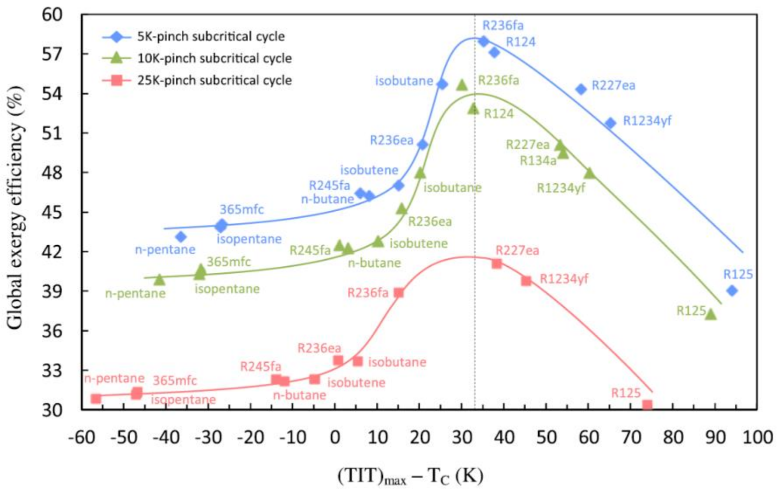

Figure 1: Refrigerant selection according to the temperature levels and the pinch of heat exchanger (Ayachi et al. 2014)

Once the refrigerant is identified, a multi-criteria optimization is performed for an ORC model (Figure 2). According to (Thieriot et al. 2011), optimization algorithms can be divided into two families: Gradient algorithms and Meta-heuristics algorithms. Meta-heuristic algorithms present a common characteristic: they combine rules and randomness to imitate natural phenomena. Within such methods, derivative computation is unnecessary. Most developed methods are evolutionary algorithms, genetic algorithms and simulated annealing. In this study we use Strength Pareto Evolutionary Algorithms 2 (SPEA2), one of the most common evolutionary algorithms.

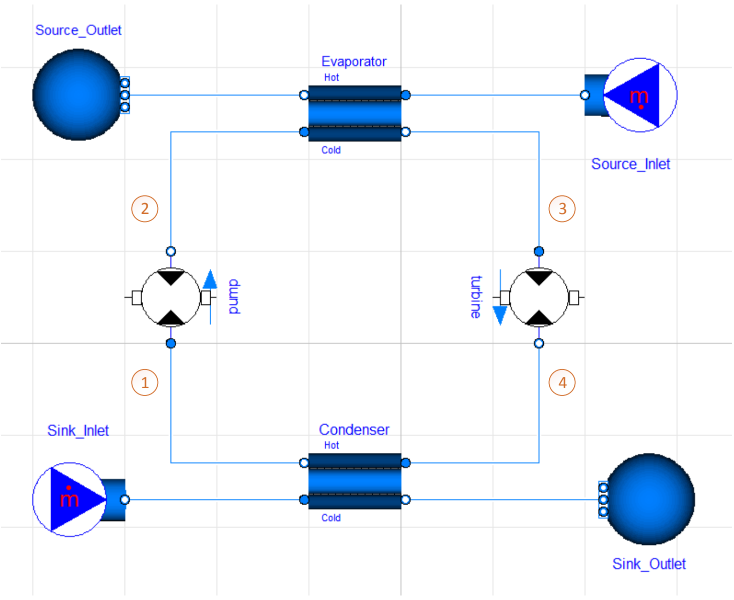

Figure 2. ORC model used in the optimization step

In what follows, we present the ORC model which will be used in the optimization step (Figure 2). The model is composed of 4 components defined via the following equations.

Pump:

$$\eta_{is,p} = \frac{h_{2,is} - h_1}{h_2 - h_1} \tag{2}$$

$$\dot{W}_p = \dot{m}_r \left(h_2 - h_1 \right)$$

Turbine:

$$\eta_{is,t} = \frac{h_3 - h_4}{h_3 - h_{4,is}} \qquad (3)$$

$$\dot{W}_t = \dot{m}_r \left(h_4 - h_1 \right)$$

Evaporator and condenser:

$$\dot{Q}_h = \dot{m}_r \left(h_3 - h_2 \right) \qquad (4)$$

$$\dot{Q}_c = \dot{m}_r \left(h_4 - h_1 \right)$$

Since no detailed heat exchanger design is done at this level, additional equations are used to take into account the pinch values set by the user.

Performances of the system:

$$\dot{E}x_h = \dot{m}_h \left[\left(h_{h,in} - T_a s_{h,in} \right) - \left(h_{h,out} - T_a s_{h,out} \right) \right]$$

$$\dot{W}_{ORC} = \dot{W}_t - \dot{W}_p$$

$$\eta_{En} = \frac{\dot{W}_{ORC}}{\dot{Q}_h} \qquad (5)$$

$$\eta_{Ex} = \frac{\dot{W}_{ORC}}{\dot{E}x_h}$$

3 CASE STUDY

We apply the presented methodology on a crude oil preheating process. The stream data (inlet and outlet temperatures, heating/cooling requirement) can be found in (Kemp 2006). For energy targeting an overall minimum temperature difference admissible ΔT_{min} = 20 K is considered. The grand composite curve (GCC) drawn from these streams is presented in red in Figure 3. Reading the GCC indicates that below the pinch temperature the process requires cooling needs of about 40 MW in a temperature range between 150 °C and 100 °C. We also observe a self-sufficient pocket of about 10 MW, situated between 100 °C and the ambient temperature.

The technology identification algorithm (the second step of the methodology presented) indicates how to use an ORC to fit the GCC, allowing to recover heat waste and produce maximum electricity. The algorithm is run by assuming a priori exergy efficiency of 50 % for the ORC unit. The following figures show the obtained results where the green line is the GCC of ORC units. The number of ORC units is limited to 1 (**Error! Reference source not found.**), then to 2 in cascade (Figure 4).

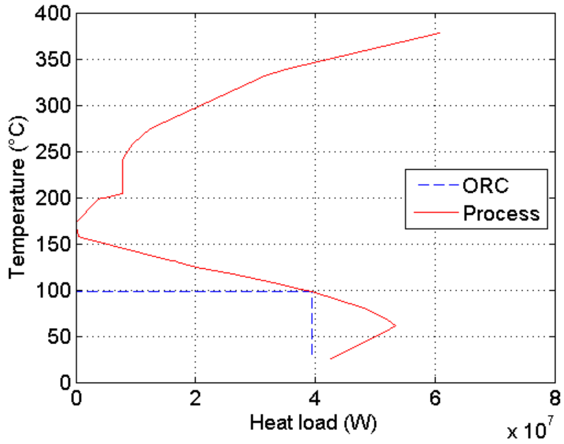

Figure 3: Integration of an ORC into the process

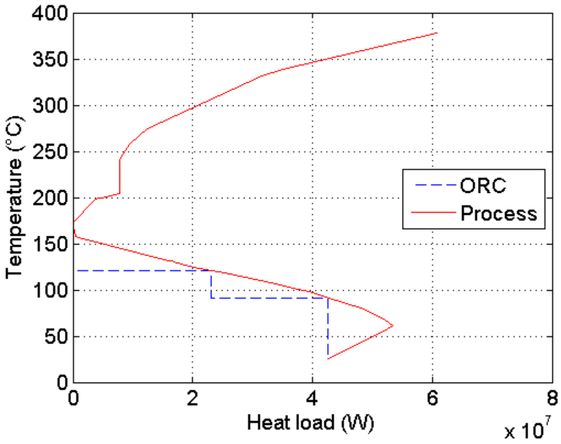

Figure 4: Integration of two ORC into the process

When the number of ORCs is limited to 1, the algorithm proposes to use an ORC at an average temperature of 100 °C. The ORC recovers a thermal power of 39 MW and produces 3.7 MW of electricity. When the use of 2 ORC is allowed, it is possible to cover all the available heat of the process. The two ORCs work at temperatures of 120 °C and 90 °C. In total they produce 4.3 MW of electricity. The small difference of the electric productions suggests using only one ORC, due to important investment costs of the ORC technology. For this reason, in what follows we focus to optimize a design of an ORC. As shown in (**Error! Reference source not found.**), the ORC have to work with a hot source whose temperature varies from 150 °C to 100 °C.

In this optimization study, the ORC model described in section 2.2 is used. In particular, the parameters of the model are shown in Table 1. These parameters are fixed.

Parameter	***Value***	***Unit***
Source	hot water	
Sink	cold water	
Ambient temperature	20	°C
Condensation temperature	25	°C
Pinch value of the evaporator	10	K
Pinch value of the condenser	3	K
Inlet hot source temperature	150	°C
Outlet target hot source temperature	100	°C
Isentropic efficiency of the pump and turbine	0,8	

Table 1: Parameters of the ORC model

First, according to Eq. (1), and after eliminating the candidates that does not fit safety and environmental requirements, we can determine that the optimal refrigerant is R1234yf. Then, we apply the SPEA2 algorithm to optimize the model. In particular, the evaporation pressure is varied, and the energy efficiency and exergy efficiency of the ORC are set as objective functions.

The multi-criteria optimization results are presented via a Pareto curve (Figure 5). Each point on the Pareto curve is a potential optimum. In this study, the ideal point is a hypothetical point at which two objective functions have their maximum values. However this point does not exist on the Pareto curve. So, the selection of the optimal point depends on the priority of the objectives and on the experience of the user. As an example, we can choose the closest point to the ideal point.

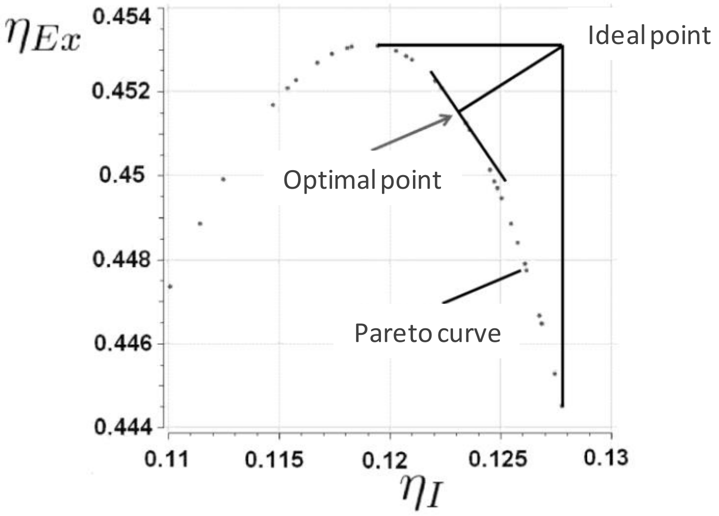

Figure 5: Optimization results (Pareto curve as functions of energy efficiency η_I and exergy efficiency η_{Ex})

It should be noted that the ORC model obtained by the optimization has an exergy efficiency of about 45 %, which is lower but close to the assumption of an exergy efficiency of 50 % used in the technology identification algorithm (the previous step).

It can therefore be concluded that the optimization results validate the technological relevance and the benefit on energy of an ORC integration solution for the crude oil preheating process. In further work, heat exchanger network design and utility selection based on economic criteria will assess the final profitability of such solution.

4 CONCLUSION

In conclusion, this paper has presented an approach for ORC integration in an industrial energy process. The method is based on energy and exergy analysis, aiming to offer the most appropriate solution to recover heat waste. The method is divided in different sequential steps such as process energy integration, selection, sizing and optimization of the utilities. It has been successfully used in an industrial case where an ORC is integrated to the process.

The method is a multi-scale approach going from a quick analysis of energy recovery potential to an identification of required utilities and, finally, to optimal design of the identified utilities. Therefore, the method provides a comprehensive analysis of energy integration problem.

5 NOMENCLATURE

Variable			**Subscript**	
			a	ambient
η	efficiency		*c*	cold side
$\dot{Ex}$	exergy	J	*en*	energetic
h	specific enthalpy	J/kg	*ex*	exergetic
$\dot{m}$	flow rate	kg/s	*h*	hot side
$\dot{Q}$	thermal power	W	*in*	inlet
s	specific entropy	J/(K.kg)	*is*	isentropic
TIT	turbine inlet temperature	°C	*out*	outlet
$\dot{W}$	electric power	W	*p*	pump
			r	refrigerant
			t	turbine

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