FME HighEFF

Centre for an Energy Efficient and Competitive Industry for the Future

Deliverable D1.2_2019.06

A Novel Methodology for Cogeneration Targeting with Optimum Steam Level Placements

Delivery date: 2019-06-15

Organisation name of lead beneficiary for this deliverable:

University of Manchester

HighEFF- Centre for an Energy Efficient and Competitive Industry for the Future is one of Norway's Centre for Environment-friendly Energy Research (FME).
Project co-funded by the Research Council of Norway and Industry partners.
Host institution is SINTEF Energi AS.

Dissemination Level		
PU	Public	x
RE	Restricted to a group specified by the consortium	

Deliverable number:	D1.2_2019.06
ISBN number:	
Deliverable title:	A Novel Methodology for Cogeneration Targeting with Optimum Steam Level Placement
Work package:	WP 1.2
Deliverable type:	JP
Lead participant:	University of Manchester

Quality Assurance, status of deliverable		
Action	Performed by	Date
Verified (WP leader)	Sigurd Skogestad	
Reviewed (RA leader)	Egil Skybakmoen	
Approved (dependent on nature of deliverable)*)	External delivery without industry partner contributions – Subject to peer review process	

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Abstract

This study aims to develop a novel method to synthesise site-wide heat recovery, distribution, cogeneration systems with optimum operating conditions of the steam mains. Previous approaches have simplified the problem to the extent that many important practical issues have been neglected and restricted the scope of the options included. The proposed methodology uses a combination of total site analysis and mathematical programming for a holistic approach to the steam system, which accounts for interactions between site utility system and processes. The optimisation problem involves the selection of more realistic operating conditions of the steam mains (superheating and pressure). The model will also account for water preheating, and superheating and desuperheating for process steam generation and use. Deaerators and let-down stations are also included in the analysis. The application of this methodology to a case study yielded a 7.6 % reduction in total energy requirement, compared to conventional utility system design method. The proposed approach addresses severe shortcomings in previous research on this topic and provides a foundation for future work to explore the next generation of sustainable utility systems.

Anton A. Kiss, Edwin Zondervan, Richard Lakerveld, Leyla Özkan (Eds.)
Proceedings of the 29th European Symposium on Computer Aided Process Engineering
June 16th to 19th, 2019, Eindhoven, The Netherlands.

Novel Methodology for Cogeneration Targeting with Optimum Steam Level Placement

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Abstract

This study aims to develop a novel method to synthesise site-wide heat recovery, distribution, cogeneration systems with optimum operating conditions of the steam mains. Previous approaches have simplified the problem to the extent that many important practical issues have been neglected and restricted the scope of the options included. The proposed methodology uses a combination of total site analysis and mathematical programming for a holistic approach to the steam system, which accounts for interactions between site utility system and processes. The optimisation problem involves the selection of more realistic operating conditions of the steam mains (superheating and pressure). The model will also account for water preheating, and superheating and desuperheating for process steam generation and use. Deaerators and let-down stations are also included in the analysis. The application of this methodology to a case study yielded a 7.6 % reduction in total energy requirement, compared to conventional utility system design method. The proposed approach addresses severe shortcomings in previous research on this topic and provides a foundation for future work to explore the next generation of sustainable utility systems.

Keywords: Cogeneration targeting, heat and power integration, total site integration, steam level optimization, mathematical programming.

1. Introduction

Sustainable development, as one of the most significant challenges faced by society, is closely related to the rational generation and use of energy. For this reason, in the process industries it is important to place a focus on the synthesis of energy-efficient sustainable utility systems and how this can shape energy use patterns. The energy transition of existing systems to meet future demands needs to be directed to be on a sustainable basis (Broberg Viklund, 2015). In the future, process utility systems will need to incorporate a much greater contribution from renewable energy sources. This will create a paradigm shift in the way such utility systems are designed and operated.

One of the key performance indicators for the synthesis of utility systems is cogeneration potential, which establishes objectives on heat and power generation as well as steam distribution and boiler fuel requirement (Ghannadzadeh et al., 2012). Steam mains pressures and superheating play an essential role in the performance of both heat and power generation at the site. Research has analyzed the influence of the steam levels on the energy targets in total site heat integration (Mavromatis and Kokossis, 1998; Shang and Kokossis, 2004; Beangstrom and Majozi, 2016). However, previous methods do not consider the degree of superheat and its effect on the potential shaft power generated by steam expansion.

In addition to these models, Kundra (2005) and Ghannadzadeh et al. (2012) presented targeting approaches, in which both sensible and latent heat of steam has been considered. However, previous methodologies have been based on the assumption of fixed steam mains pressure, usually based on heuristics. This neglects the close interrelation between the processes and the system and its subsequent implications. Moreover, the superheat for both the steam generation and use has been assumed to be the same. This premise might lead to thermodynamically infeasible solutions or difficulty to be achieved in practice, due to limitations of the materials of construction or design complexity.

Sun et al. (2015) proposed a graphical approach to overcome the shortcomings assessing cogeneration potential and enhancing site-wide heat recovery methodically. Whilst the proposed methodology by Sun et al. (2015) gives useful thermodynamically and physical insights for understanding some of the interactions within the system. It does not provide a systematic decision-making approach to determine the optimum utility system performance since it does not allow the analysis of the trade-off between the cost of the additional steam generation and the profit from power generation.

Though there is extensive literature for cogeneration targeting in utility systems, the conventional concepts present a number of limitations and drawbacks for the selection of optimum site operating conditions. This study aims to offer the basis for a systematic approach to explore the next generation of sustainable utility systems. For the first time, a study in this area combines an extended transshipment method based on Shang and Kokossis (2004) with total site analysis and more realistic site conditions. In turn, this determines the total site heat and mass flow and ensures that the total operating cost is minimized.

The novelty of this work is derived from the requirement of increased practical and realistic conditions for both steam generation and usage. This is used in combination with an evaluation of the interactions between steam mains conditions (pressure and superheat) and system performance. The effect of process steam generation at a different temperature from the steam mains, as well as the efficiency and the exhaust temperature of the steam turbines based on steam conditions (superheating) and load, is also explored to provide a more realistic and accurate heat recovery. Ultimately, this methodology allows for power targeting of utility systems operating at optimum conditions. In essence, the study provides a framework for the analysis of sustainable steam systems.

2. Methodology

Cogeneration targeting with simultaneous steam mains selection requires making continues and discrete decisions, where non-linear energy terms are involved. Thus, to produce a linear model and avoid convergence and robustness issues, some properties are fixed during the optimization. Every optimization step is succeeded by a rigorous simulation, as shown in Figure 1. The following subsections provide a summary of these steps.

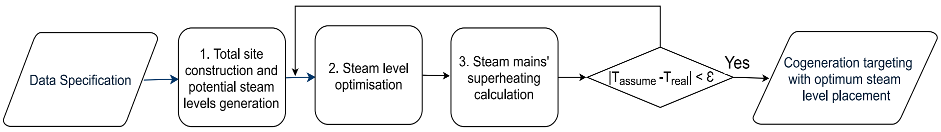


Figure 1. Schematic representation of optimization approach

Step 1 Total site construction and potential steam levels generation

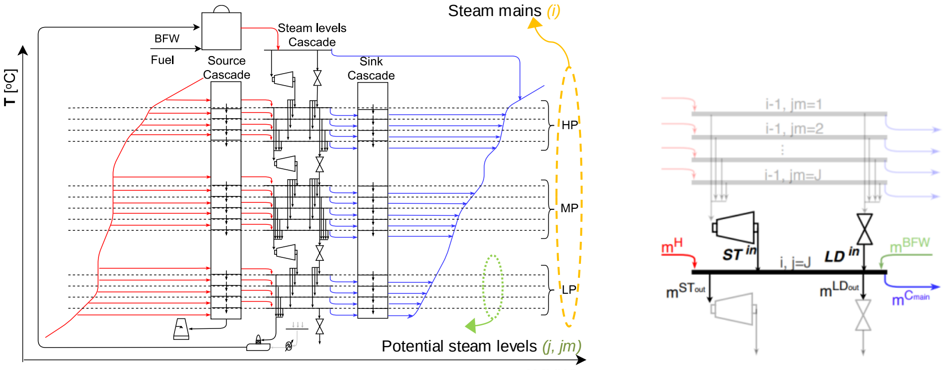
The extended Total Site Profile (TSP) concept of Varbanov et al. (2012) is adopted to obtain the potential steam levels required for the heat recovery and power generation via the utility system. Apart from the stream data specification - i.e. number of processes involved, number of stream of each process, parameters including supply and target temperatures, as well as the heat capacity- the specific minimum approach temperature (ΔT_{min}^{PU}) is used to avoid misleading energy targets that can result from the use of inaccurate global minimum temperature difference (ΔT_{min}) values between process streams.

Saturated temperature (pressure) denotes the potential steam levels. The temperatures are obtained by partitioning the site-wide temperature range into intervals. Since the sink profile defines the quantity and quality of heat required, steam intervals are based on its temperature range. Operational constraints are also taken into account, such as minimum/maximum temperature for process and utility steam generation. Additionally, minimum temperature and pressure difference between each potential level are set by the designer, to guarantee a representative number of options and avoid unnecessary levels. Once generated the potential steam levels, they are classified based on the number of steam main required and the pressure ranges for each header.

Step 2 Steam level optimization

The MILP formulation is based on Total Site Heat and Mass Cascades (TSHMC) employing a transshipment model. An extension of Shang and Kokossis (2004) model enables recording energy and mass balances among process source/sink streams and potential steam levels. The TSHMC are formulated by the temperature intervals (defined by the steam levels) and comprise three cascades: source, steam and sink, as illustrated in Figure 2(a) Process streams act as steam sources or sinks, where the (residual) heat that cannot be used in the interval for either steam generation or use is going to the next lower temperature level, at the respective cascade. Heat flows from the process sources to sinks through steam. Utility steam is raised at boiler house at VHP conditions and distributed to the different headers by either passing through steam turbines or let down stations.

In the source cascade, the heat from process sources is used to raise steam at the steam level pressure, from BFW conditions to superheating. The latter is a designer variable and is restricted by the source profile and the heat exchanger equipment. Regarding sink cascade, heat flows from steam level to process sinks via steam desuperheated. Steam is desuperheated prior its use by BFW injection. For the development of the TSHMC, let m^{H}, m^{ST}, m^{LD}, m^{Cmain}, m^{BFW} be the steam mass flowrates of the process steam generation, steam turbines, let-down stations, process sinks and BFW injected, respectively.



(a) Total site heat and mass cascade

(b) Mass balance for i-th steam main

Figure 2. Schematic representation of optimization approach

The MILP formulation is based on the minimum annualised utility cost as the objective function, where the steam flows, heat loads, fuel consumption, electricity generation and cooling water requirement are continuous variables. Binary variables are associated to whether a steam main (defined as *i*) exists at a given condition, denoted by the set of potential steam levels *j* or *jm*. Binary variables are also related to the steam turbines operation between steam mains (*i,j*) and (*i+1,jm*) and the operating status of boilers at VHP conditions.

Energy and mass balance, as well as the electricity balance are the main equality constraints. While equipment size constraints -- that avoid equipment operating at lower efficiency -- are inequality constraints. Power generation and fuel consumption are estimated employing the linear models of Sun and Smith (2015) and Shang (2000), respectively. Both models accounts for full and part-load operating performance.

Step 3 Calculation of steam mains' superheating

Once the optimum steam level placement (saturated temperature/pressure) has been obtained, the actual superheating temperature of the header is calculated. The superheating is defined through a material and energy balance in each steam main. This is determined by the enthalpy and flow rate of the process steam generation, turbine exhausts, steam passing through let-down valves, and any BFW injected in the steam main. The calculations require top-down iterations that start with the utility steam and work down through the cascade from high to low pressure until superheating constraint is satisfied by all the steam mains. Turbine exhaust properties are obtained using the Willan's linear model presented in the Sun and Smith (2015) research, based on the inlet steam conditions and the steam main pressures. The steam is expanded through letdown valves at isenthalpic conditions. Finally, Step 2 and 3 are repeated until achieving convergence (usually 3-4 iterations).

3. Case Study

Site data was adapted from an example available in the literature (Sun et al., 2015). Number of streams and ΔT_{min}^{PU} for each process are detailed in Table 1. Power site demand is 40 MW. The site energy requirement is satisfied using a steam system comprising a natural gas boiler, three distribution steam mains, a deaerator, expansion valves, steam turbines and a single cold utility (cooling water). The utility steam is generated in the boiler house at the very high pressure (VHP) main conditions (100 bar). The inlet temperature of the cooling water is 20 °C. Electricity is generated by single back-pressure steam turbines allocated between each level. The HP, MP and LP steam mains operating conditions are estimated to minimize the total operating cost.

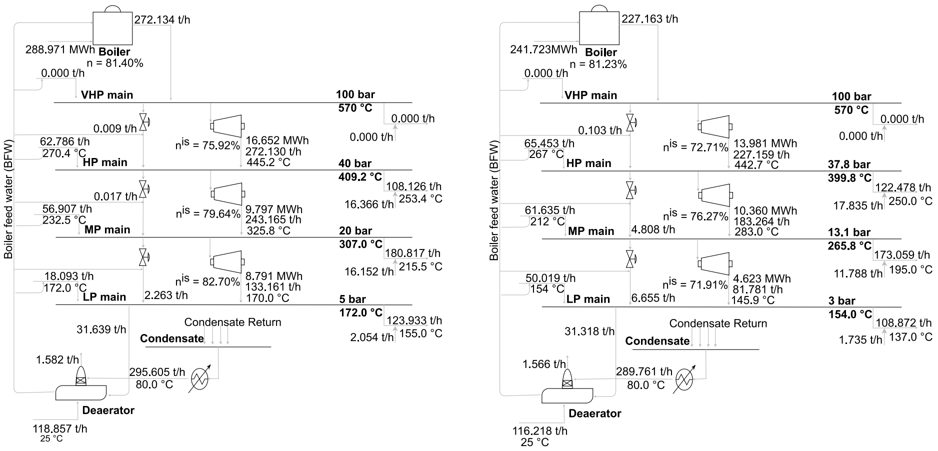
Table 1. Summary of the stream data for case study

	Process A	*Process B*	*Process C*	*Process D*	*Process E*
No. of streams	4	8	9	6	9
ΔT_{min} (°C)	15	5	5	10	15

In order to assess the benefit of the methodology, the optimized system configuration is compared against a conventional design based on heuristics, where the HP, MP and LP mains pressure are 40, 20 and 5 bar, respectively. Figure 3 compares the two steam system configurations. Both systems were obtained based on the temperature specifications presented in Table 2. For the optimization, the present case study has considered 65 potential steam levels, based on the specifications and the sink profile temperature. The potential steam levels has been classified in 15 levels for HP ($\geq$ 30 bar), 42 levels for MP (6 – 30 bar) and 8 levels for LP (3 - 6 bar).

Table 2. Temperature specifications for the steam system

Constraints	*Temperature [°C]*
Maximum boiler steam temperature	570
Minimum process steam generation temperature (saturation)	134
Minimum steam main superheating	20
Degree of superheating for process steam generation	20
Degree of superheating for process steam usage	3



(a) "Conventional" design *(b) Optimized Design*

Figure 3. Steam system configuration

The steam main pressures for the optimized system configuration are 37.8, 13.1 and 3 bar; respectively.The manipulation of steam main conditions affects site operational performance. Steam mains selection is affected by several factors i.e. process steam generation, turbine exhausts and let-down flows. Steam passing through let-downs is required to achieve steam balance and more important to maintain the minimum superheat of 20 °C in each steam main. However, this may result in a reduction in the power generation as it is observed in Table 3. Compared with conventional design cost, the proposed design diminishes the fuel and CW consumption by 16.35 % and 10.61 %, respectively. Even though the power generation is less than the traditional design, the total utility cost decreases 7.61 %.

Table 3. Comparison of steam system designs

Parameter	*Conventional*	*Optimization*	*Difference in units*
Fuel consumption [MWh]	288.97	241.72	- 47.25
Power Generation [MWh]	35.20	28.96	+ 6.24
Cooling Utility [MWh]	237.54	212.33	- 25.21
Fuel Cost [M£ y^{-1}]	51.19	42.82	- 8.37
Power Cost [M£ y^{-1}]	3.62	8.38	+ 4.76
Cooling Cost [M£ y^{-1}]	10.21	9.13	- 1.08
Operating Cost [M£ y^{-1}]	**65.02**	**60.33**	**- 4.69**

4. Conclusions

A new methodology has been developed to provide increased realism and accuracy in utility systems synthesis, operating at optimum conditions for future utility systems. The study shows the close relation between steam level selection and heat recovery and power generation enhancement. In an illustrative example, the new model presents a significant reduction of the total energy requirement at the site compared to a conventional design method (7.61 %). This proves that the energy requirement can be further reduced by holistically optimizing the steam mains operating conditions and the site heat recovery and cogeneration.

5. Acknowledgements

This publication has been funded by HighEFF-Centre for an Energy Efficient and Competitive Industry for the Future. The authors gratefully acknowledge the financial support from the Research Council of Norway and user partners of HighEFF.

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