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Multi-period analysis of heat integration measures in industrial clusters

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ABSTRACT

TSA (total site analysis) has shown to be an efficient tool for identifying heat integration measures in industrial clusters, leading to the optimal design of utility systems and energy bill reduction. In order to justify investments, any proposed utility system must be shown to be able to operate in all configurations that an industrial cluster can encounter, especially those relating to varying heat demand. Previous TSAs have generally been carried out using yearly means of heat exchange loads or using scenarios corresponding to specific operation modes of the sites. While these have been useful for designing systems under normal conditions, they are not fit for evaluating minima and peaks in utility demand. Carrying out a TSA on each possible configuration of a cluster is not feasible from a computational and results analysis point of view. A method is therefore proposed to represent the variability of data over long periods in a reduced form in order to carry out engineering studies.

A methodology is proposed to identify typical operating periods of an industrial cluster made up of several production units. This algorithm exploits a multi-objective optimisation to identify *n* periods that delimit typical operating modes or multiple profiles.

A TSA was previously carried out on the Stenungsund petrochemical cluster in Sweden, leading to the design of a utility system to significantly reduce the overall energy consumption of the cluster. The solution proposes that a common utility system would decrease the hot utility demand from 124 MW_{th} to 70 MW_{th}. The multi-period analysis methodology is demonstrated by application to this case study in order to identify the resilience of the proposed solution when faced with variations in heat production and consumption. The multi-period analysis of the proposed utility system leads to the identification of a peak utility demand of 88 MW_{th} rather than the previously identified 70 MW_{th}. A Total Site Sensitivity Analysis leads to a better understanding of the contribution of each of the clusters units and feasibility of investments.

1. Introduction

Industrial clusters are groups of related manufacturing companies in a concentrated geographical area, which can benefit from shared infrastructure and utilities. Clusters can be important regional actors, driving employment, research and development of local infrastructure [1]. Clusters can be major contributors to the European economy as well as major energy consumers. As such, they are currently the focus of attention for governments trying to reach energy reduction targets set by the European EED (Energy Efficiency Directive). The European Commission has set a target for the reduction of energy consumption by 30% and CO_2 emissions by 40% by 2030 [2].

This paper is separated into five sections. The problem is introduced in Section 1. A methodology is proposed for breaking down a year into typical periods in Section 2. A multi-period Total Site Analysis is carried out on a petrochemical site as a case study in

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Section 3. Section 4 briefly discusses sources of inaccuracy resulting from the applied methodology and Section 5 presents the conclusions and openings of this work.

1.1. Background

Increased energy efficiency in industry presents a major opportunity to improve companies' competitiveness, achieve expected environmental goals and improve energy security at the same time. The chemical and petrochemical industry are major consumers of fossil resources, as feedstock and as sources of heat and electricity. Globally the industry sector accounts for approximately 30% of energy use and 16% of direct CO_2 emissions [3]. The International Energy Agency estimates that as much as 18% overall energy consumption reduction could be achieved in the chemical and petrochemical industry. One important way to reach this savings potential is through PI (process integration).

Clusters of chemical plants offer large potential for efficiency improvements by site-wide heat integration. PI tools such as TSA (total site analysis) can be applied to determine the MER (minimum energy requirement) for the overall cluster. Common utility levels can then be determined enabling the optimal utilisation of process excess heat throughout the cluster, thus minimising the heating and cooling demand. The tools can be applied both in grass root design or retrofit of existing clusters. In practice, the latter is often the case. Recent works have shown the interest of implementing common utility systems to improve exergy efficiency in the oil industry [33] and to optimise the supply of cooling to processes in the petrochemical industry [34].

Retrofit of an entire cluster consisting of several processing plants is a complex task, which requires large investments and a great deal of collaboration between different companies or business units. Despite the availability of PI tools enabling the targeting of utility systems to achieve the site-wide MER there are additional barriers when heat integration is extended to a total site. Chew et al. [4] summarise many of these issues.

One of the main barriers for site-wide heat integration is plant interdependence. Variations in the heating and cooling demand as well as unexpected or planned process unit shutdowns can affect the surrounding processes when these are integrated. To minimise these effects additional equipment (back-up boilers and heat exchangers), advanced process control and careful planning is needed.

1.2. Existing work and literature review

The concept of TSA was first introduced by Dhole and Linnhoff [5] and further developed by Raissi [6]. The latest overview and recent developments of the methodology are presented in Refs. [7] and [8]. Matsuda et al. [9] first applied the methodology to one of the largest chemical clusters in Japan, which resulted in several heat integration projects within the Kashida industrial complex. Liew et al. developed an algorithmic approach to target large area heat integration considering variable heat supply (renewable sources) and demand (e.g. batch processes) in distinct periods [10].

Papalexandri and Pistikopoulos suggested a multi-period MINLP model to synthesise heat and mass exchange networks. The approach allows the operability requirements to be incorporated into the optimisation [11]. Hui and Natori demonstrated the use of multi-period mixed integer model to predict optimum operating conditions of plant utility systems for current and future periods and to develop production and operating strategies [12].

Becker and Maréchal developed a site-wide heat integration targeting approach enabling heat exchange across sites via intermediate heat transfer systems [13].

1.3. Extension to multiple periods

Process Integration studies have typically used historical data to plan future improvements. Using time averages [14] allows engineers to identify the annual energy consumption as well as the yearly minimum energy requirements of an industrial site but removes any information about the effects of variability on the solutions. In effect, variations of steam mass flows, chemical compositions and thermodynamic properties can significantly influence solutions. Furthermore, the peaks and minima in power demand cannot be identified through these studies.

In the case of a chemical cluster, variation of the thermodynamic properties of processes is an everyday reality, thus the assumption of steady state operations over extended timespans is rarely satisfactory. Variations in flow rates or temperatures can be caused by many factors. Economic factors can influence feedstock quantities and qualities, while adapting to varying market demand affects the quantities of specific output flows. Extreme weather conditions such as storms and heavy rainfall can lead to a rise in steam production in order to deal with increased condensation. Periods of exceptional heat can lead to a lack of cooling capacity and therefore the shutdown of certain plants while periods of prolonged cold can lead to increased steam consumption through tracing and steam hoses. Maintenance operations and turnarounds also greatly affect utility systems. Consumption of utilities in off-line units will be minimal, while their steam output will be nil. Lastly, to consider heat storage problems, operations optimisation and investment sizing must be done on a multi-period basis.

One consequence of conducting TSA studies based on yearly mean data sets is that the proposed solutions may be suboptimal, undersized and not adapted to each operating regime of an industrial cluster. Studies based on nominal or peak values provide feasible systems though they may lead to oversizing of utility systems and inaccurate economic evaluations of operations.

To address problems linked to undersized utility solutions, high capacity backup boilers in the case of steam or oversized transformers in the case of electricity may be required. The economic consequences can be important with rising capital investments.

A solution could be to evaluate a system for each available time step over an extended duration, which would establish the peak demands as well accurate operating costs. Given the complexity of industrial sites, this would result in challenging amount of data to handle. Pinch Analysis and Process Integration methods are not suited to such laborious studies. The use of computer aided optimisation tools to carry out studies on so many periods would be difficult as MILP (mixed integer linear programming) and MINLP (mixed integer non linear programming) solvers are not always able to solve such large problems [15].

The amount of data must therefore be reduced to a small number of representative periods, which capture the variations in thermodynamic properties of a chemical cluster. This data compression should allow solutions to properly take into consideration the effects of variability, production unit shutdowns and to better estimate peak demand of utility systems.

1.4. Interest and challenges

Several authors have addressed the problem of variability in Process Integration and TSA. The Time Slice concept [16] was developed in order to deal with the integration of batch processes and thermal storage. With Time Slices, the batch processes are cut up according to the batch cycle, so that each slice represents one temporal step of the overall process. Time Slices have also been used for the integration of renewable energy sources such as solar power.