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A numerical technique for Total Site sensitivity analysis

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ABSTRACT

Total Site Heat Integration (TSHI) is a methodology for the integration of heat recovery among multiple processes and/or plants interconnected by common utilities on a site. Until now, it has not been used to analyze a site's overall sensitivity to plant maintenance shutdown and production changes. This feature is vital for allowing engineers to assess the sensitivity of a whole site with respect to operational changes, to determine the optimum utility generation system size, to assess the need for backup piping, to estimate the amount of external utilities that must be bought and stored, and to assess the impact of sensitivity changes on a cogeneration system. This study presents four new contributions: (1) Total Site Sensitivity Table (TSST), a tool for exploring the effects of plant shutdown or production changes on heat distribution and utility generation systems over a Total Site; (2) a new numerical tool for TSHI, the Total Site Problem Table Algorithm (TS-PTA), which extends the well-established Problem Table Algorithm (PTA) to Total Site analysis; (3) a simple new method for calculating multiple utility levels in both the PTA and TS-PTA; and (4) the Total Site Utility Distribution (TSUD) table, which can be used to design a Total Site utility distribution network. These key contributions are clearly highlighted via the application of the numerical technique to two Case studies.

1. Introduction

Pinch Analysis is an established technology for reducing energy consumption that has been widely applied in various industries for more than 30 years. Dhole and Linnhoff [1], Raissi [2] and Klemeš et al. [3] extended traditional heat integration, which focuses on direct heat transfer among process streams at a single site, to heat integration for multiple sites. This is known as Total Site Heat Integration (TSHI), sometimes called "site-wide integration". Direct heat transfer is not always suitable for inter-process heat recovery due to the required high degree of operational flexibility and the long-distance piping needed, which makes it very costly [4]. TSHI using indirect heat transfer utilising existing utility systems is typically more cost effective because the existing plant piping system can be used. TSHI heat integration is linked by a common central or sectional utility system.

Dhole and Linnhoff [1] have introduced Site Sink and Source Profiles (SSSP), a graphical tool that can be used to evaluate fuel consumption, cogeneration, emissions and cooling needs for an integrated site. A simple exergy model was proposed for cogeneration capacity estimation based on SSSP, and the model was further extended by Raissi [2] and Klemeš et al. [3]. Based on SSSP, Klemeš et al. [3] developed the Total Site Profile (TSP) and the Site Utility Grand Composite Curve, which can be used to evaluate Total Site potential heat recovery. Subsequently, Maréchal and Kalitventzeff [5] introduced a mathematical programming tool for minimising Total Site energy costs. Their work also included an integration of combined heat and power production using a steam network. Matzuda et al. [6] have successfully studied the heat recovery potential for a large steel plant using TSP analysis.

An advanced approach to these concepts, known as top-level analysis, is one that allows for "scoping", i.e., selecting site processes to target for heat integration improvements [7]. The utility system is first optimised for the current steam and power demands. This is followed by an assessment of the potential benefit of reducing steam demands at various levels by successively optimising the system in steps of steam demand reduction. This results in a set of curves for steam marginal prices for the system under consideration.

Perry et al. [8] extended the Total Site concept to a broader spectrum of processes in addition to the industrial process. A potential for the integration of renewable energy sources was introduced to reduce the carbon footprint of a Locally Integrated

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Energy Sector (LIES). In a LIES, heat sources and sinks can be derived from small-scale industrial plants, large building complexes (such as hotels and hospitals), offices and residential areas.

One of the major challenges in implementing the Total Site concept involving renewable energy is the variation of energy supply and demand with time and location. Therefore, Varbanov and Klemeš [9] suggested performing Total Site targeting in a set of time slices to maximise heat recovery within each time slice. Varbanov and Klemeš [10] then further extended the concept to heat storage, heat waste minimisation and carbon footprint reduction. A Total Site heat cascade is also introduced in this work to illustrate these concepts.

Bandyopadhyay et al. [11] proposed a modification of the Site Grand Composite Curve (SGCC) that incorporates assisted heat transfer. This type of heat transfer takes into account the non-monotonic parts or pockets of the process GCC, which were not considered by Dhole and Linnhoff [1], although this may not be practical for many integrated sites. The results of their study show that the modified SGCC tends to increase heat recovery potential, particularly those within each process, a feature which is not considered in the TSP. However, the economy of this design has to be explored, as an increased integration using nonstandard steam mains can be costly.

Kapil et al. [12] proposed the recovery and upgrading of low-grade heat from processes. The work has proposed a new methodology for estimating the cogeneration potential for a site utility system via bottom-up and top-down procedures. Ghannadzadeh et al. [13] presented Iterative Bottom-to-Top Model (IBTM) as a new shaftwork targeting model to estimate the cogeneration potential for site utility systems prior to the detailed design.

Fodor et al. [14] further developed a TSHI targeting method to allow for a variation of the minimum temperature difference (ΔT_{min}) among Total Site processes. Previous works by Dhole and Linnhoff [1] and Klemeš et al. [3] assumed a uniform ΔT_{min} on a Total Site. Fodor et al. [14] and Varbanov et al. [15] proposed the use of a utility and process-specific ΔT_{min} between utility and process streams, which is more realistic in practical applications.

The Total Site methodology and the concepts developed by Dhole and Linnhoff [1] and used in recent studies are based on a graphical method, with the typical advantages and disadvantages of such approaches. Numerical methodologies that provide similar benefits such as the Problem Table Algorithm (PTA) for heat pinch and the Water Cascade Analysis (WCA) for water pinch are therefore desirable.

The PTA is a numerical tool for intra-process heat integration proposed by Linnhoff and Flower [16]. This tool is the equivalent to the use of Composite Curves (CCs) and Grand Composite Curve (GCCs) in the graphical method and supports a more precise graphical construction by providing exact values for the crucial points. The algorithm was extended to multiple utility targeting by Costa and Queiroz [17]. The PTA was also recently extended to the Unified Targeting Algorithm (UTA) by Shenoy [18]. The UTA is a powerful tool for obtaining the maximum resource recovery for Process Integration problems including heat and mass exchange, water, hydrogen, carbon emissions and material reuse networks. However, the method proposed by Costa and Queiroz [17] involves rather complex calculations, whereas the UTA cannot be used for TSHI problems. To make the PTA a more powerful tool, simpler method for multiple utility targeting would be beneficial. Additionally, the PTA can also be extended to TSHI.

In the current study, a new numerical tool for targeting TSHI is proposed, known as the Total Site Problem Table Algorithm (TS-PTA). This numerical tool is an alternative to the graphical TSHI approach and is suitable for both the uniform and non-uniform ΔT_{min} methods proposed by Dhole and Linnhoff [1], Klemeš et al. [3], Fodor et al. [14] and Varbanov et al. [15]. Although graphical approaches are advantageous in terms of providing valuable visual insights, they are difficult to construct, especially for large problems, and may yield some inaccuracies inherent in the graphical nature of the method. The Problem Table Algorithm (PTA), which is a numerical tool introduced by Linnhoff and Flower [16] as an alternative to the Composite Curves, has been among the preferred analytical tools used to compensate for the limitations of the graphical approaches. In this work, the PTA method is extended to include TSHI analysis.

The previous works cited have generally not deeply studied the flexibility of integrated plants. A numerical tool therefore offers a good opportunity to evaluate the sensitivity of each plant in TS integration. The Total Site Sensitivity Table (TSST) can be used as a tool to explore site-wide sensitivities to various operational changes and variations. A typical case is when one site process must be closed down for regular maintenance or due to an accident. Using the TSST, the effect of a plant shutdown can be assessed, and suitable measures can be taken during the design and operational stages to ensure other site utility supplies are not disrupted.

2. Methodology

A summary of the procedure involving the four methodologies is described in the following.

2.1. Tool 1: Total Site Problem Table Algorithm (MU-PTA)

The initial steps follow the same procedure as the PTA for individual process. First, the shifted temperatures for the process streams in each individual process are calculated as described in Smith [19], Kemp [20] and Klemeš et al. [21]. The PTA is constructed as described by Linnhoff and Flower [16] and Smith [19]. The multiple utility cascade procedure for each individual plant is as follows:

a. Above the pinch region:
   i. Subtract half of the minimum temperature difference within each process, $\Delta T_{min,pp}/2$, from the shifted temperature to return it to a normal temperature, and then add the minimum temperature difference between the utility and process stream ($\Delta T_{min,up}$) [14,15].
   ii. Cascade the heat available in each temperature interval from the highest temperature to the pinch temperature. When a negative value results, an external heat enthalpy representing the utility is added immediately to the temperature interval during cascading.
   iii. The amount of each utility type required can be determined by summing the external heat enthalpies from below each utility temperature to the next utility temperature.
b. Below the pinch region:
   i. $\Delta T_{min,pp}/2$ is added, and $\Delta T_{min,up}$ is subtracted, to the shifted temperatures [14,15].
   ii. The heat available in each temperature interval is cascaded from the lowest temperature to the pinch temperature, and the external cooling utility required is immediately added to the temperature interval when there is positive value in the cascade.
   iii. The amount of each utility type to be generated is obtained by adding the external cooling utility above each utility temperature but below the next-highest temperature utility.

This tool also could be used for single process Heat Integration which has different temperature shifting at the beginning.