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Indirect thermal integration for batch processes

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HIGHLIGHTS

- Algorithms to target minimum utility requirements for single as well as cyclic batch process are proposed.
- The proposed methodology accounts for indirect thermal integration between various different time intervals.
- The proposed methodology overcomes the limitations of existing methodologies.
- The proposed methodology guarantees the optimality as it is proved using rigorous mathematical arguments.

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ABSTRACT

Rigorous algorithms to target the minimum utility requirements for single as well as cyclic batch processes are proposed in this paper. Practically, heat integration between two different time intervals requires indirect integration through intermediate fluid. Targets, calculated via proposed methodology, account for indirect thermal integration in batch process. The proposed methodology overcomes limitations of existing methodologies and guarantees the optimality as it is proved to be optimum using rigorous mathematical arguments. This methodology is applicable to any fixed-scheduled batch process. Applicability of the proposed methodology is demonstrated through illustrative examples. In one of the illustrative examples, a reduction of 18.7% and 16.4% (in comparison to time slice model) is observed in hot and cold utility requirements, respectively.

1. Introduction

In recent years, heat integration has become an essential part of industrial process design due to increasing energy demands and increasing concerns about environmental sustainability. Techniques of pinch analysis, a branch of process integration, have been successfully applied to determine utility targets for continuous processes [1]. Apart from utility targeting, various other aspects of thermal integration have also been successfully explored for continuous processes: heat exchanger network synthesis [2–9], total site heat recovery [10–16], restricted matches utility targeting [17–19], utility system design [20], etc. Klemeš and Ptacnik [2] developed an interactive programming, based on thermodynamic analysis accompanied with optimization procedure, for designing heat exchanger networks (HENs). Klemeš and Ptacnik [3] analyzed HEN synthesis and explored possibilities of application of different mathematical methods. Yee and Grossmann [4] proposed a mixed integer nonlinear programming (MINLP) model to design networks which optimizes utility cost, exchanger areas, and selection of matches simultaneously. Zhu et al. [5] proposed conceptual methodology for HEN retrofit using heat transfer enhancement techniques. Aaltola [6] presented a framework using simultaneously MINLP model and search algorithms for generating flexible HENs with specified range of variations in the flow rates and temperatures of the streams. Sikos and Klemeš [7] presented a methodology to explore commercial software tools for HEN modeling and optimization with reliability. Soltani and Shafiei [8] developed a procedure using genetic algorithm (GA) combined with linear programming (LP) and mixed integer linear programming (MILP) to retrofit of HENs including pressure drops. Nemet et al. [9] presented deterministic and stochastic multi-period MINLP models for HEN synthesis to account future price projections. Extending the concept of pinch analysis, Dhole and Linnhoff [10] introduced procedure to set site-wide targets for fuel, cogeneration, emissions, and cooling before design. Bandyopadhyay et al. [11] developed the concept of site-level grand composite curve to calculate maximum possible indirect heat integration including assisted heat transfer. Bandyopadhyay et al.

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[11] proposed a methodology to estimate cogeneration potential at total site level. Varbanov and Klemeš [12] optimized energy demands, the local generation capacities, and the efficient integration of renewables into the corresponding total site energy systems. Alwi et al. [13] proposed a numerical method for total site heat integration (TSHI) involving variable supply and demand. Nemet et al. [14] evaluated the capital cost for the generation and use of site utilities (e.g., steam, hot water, cooling water, etc.), to study the trade-offs between heat recovery and capital cost targets for total sites. Varbanov et al. [15] developed a procedure for TSHI which allows specifying $\Delta T_{\min}$ values based on heat exchange contexts on a site (intra-process, process-to-utility and utility-to-process). Liew et al. [16] presented a systematic tool for TSHI that can be utilized for various design aspects such as, sizing of utility generation system, designing of backup generators, piping, etc. On the other hand, Cerda and Westerberg [17] presented an algorithm for the synthesis of HENs to incorporate restricted matches. Papoulias and Grossmann [18] proposed an MILP model for HEN involving stream splitting and selection of most preferred matches. Becker and Marechal [19] developed a targeting method, which considers restricted matches along with optimal integration of intermediate heat transfer units and the energy conversion system, such as, heat pumping and combined heat and power production. Maréchal and Kalitventzeff [20] presented a mathematical formulation for the optimal integration of the utility system of an industrial production site. These methods are not directly applicable to batch processes.

Modified approaches of pinch analysis have been developed to determine utility targets for batch processes as such processes are additionally constrained by the time of availability and requirements. Clayton [21,22] presented time average model (TAM) to determine utility targets in batch processes. In this methodology, utility targets are determined by averaging heat flows over the period of batch process. Utility targets, identified using TAM methodology, are under-estimated as the methodology bypasses the actual time constraints. To overcome this limitation, Linnhoff et al. [23] presented the time slice model (TSM). In this methodology, a batch process is divided into different time intervals and utility targets for each interval are determined by applying the problem table algorithm (PTA) [24]. TSM methodology does not consider the integration between the time intervals and therefore, over-estimates the utility targets for a batch process. Kemp and Deakin [25–27] developed an algebraic methodology, called time-dependent heat cascade analysis (TDHCA) to determine the minimum utility requirements for batch processes. TDHCA determines utility targets for batch processes by identifying the overall infeasibility when heat is cascaded on both time and temperature scales. Kemp and Deakin [25] proposed to pass heat on time scale as well as temperature scale to calculate overall infeasible cascade. However, how exactly to distribute heat among these scales was not suggested by Kemp and Deakin [25]. This may lead to multiple solution and hence, optimum cannot be guaranteed. It may be further noted that, this methodology is unable to capture the effect of indirect heat transfer which is more practical when heat transfers between different time intervals are involved. Pourali et al. [28] proposed a methodology which decomposes the entire time horizon of overall batch process into time intervals and then investigates the various combinations of different time intervals to attain the minimum total cost. Computational complexity of this methodology increases with increasing number of time intervals. Furthermore, combining time intervals is not feasible as a later time interval cannot supply heat to any prior time interval. Foo [29] proposed a hybrid approach that combines insight based and mathematical optimization techniques for determining utility targets for a batch process. Other than utility targeting several issues related to synthesis of batch HEN were addressed: design of thermal storage [30–32], number of heat exchangers [33–35] etc. Stoltze et al. [30] used TAM model to calculate waste heat recovery potential and presented a combinatorial method involving heat storage to achieve the energy targets. Sadr-Kazemi and Polley [31] investigated indirect heat recovery potential and heat storage design for batch process and reported that heat storage might provide a more flexible alternative compared to direct integration. Krummenacher and Auguste [32] carried out a comparative study and observed reduced heat recovery and the poorer economics when mixing of storage fluid is allowed. Krummenacher and Favrat [33] proposed guidelines to determine number of required intermediate heat storage units (HSUs) based on TSM. Krummenacher and Favrat [34] proposed a methodology for determination of the minimum number of HSUs based on TAM. Foo et al. [35] presented a minimum unit targeting technique for batch HEN problems utilizing TDHCA. Various techniques for batch HEN synthesis, based on mathematical optimization, were also reported in literature. Vaselenak et al. [36] addressed energy integration for a batch process based on heuristic rules and a mixed integer linear programming (MILP) formulation. They explored the possibility of heat recovery between vessels where temperatures vary during operations. They also investigated opportunity for rescheduling in their later work [37]. Papageorgiou et al. [38] presented mathematical formulation to determine trade-offs between heat integration and scheduling constraints. Zhao et al. [39] presented a mathematical formulation for process scheduling that involves heat integration without intermediate storage. Corominas et al. [40–42] addressed heat integration in multi-product batch processes. Krummenacher [43] studied direct and indirect heat integration of batch process and also proposed a methodology for HENS for batch processes using genetic algorithm method. Chen and Ciou [44] proposed a mixed integer nonlinear programming (MINLP) formulation to design an indirect heat recovery system (IDHS) for a batch process. Further, Chen and Ciou extended their work to include the associated variable temperature storage in a batch process and proposed an iterative method for designing an IDHS [45]. Chen and Chang [46] proposed a mathematical formulation to combine task scheduling and heat recovery into a single framework for batch process. Adonyi et al. [47] presented a procedure that considers heat integration and process scheduling simultaneously. Majozi [48] proposed a continuous time mathematical formulation to optimize the heat integrated batch process considering only direct heat integration. The methodology was further extended to include indirect heat integration and heat storage [49,50]. Halim and Srinivasan [51] incorporated heat integration with scheduling in sequential manner and later extended their work to incorporate water minimization [52]. A recent review by Fernandez et al. [53] covered various aspects related to batch HEN synthesis.

In this paper, an algebraic methodology is proposed to set the utility targets for a fixed-scheduled batch process. It should be noted that in a batch process, there are two forms of heat integration that can be explored: direct and indirect. Direct heat integration is only possible when heat integration is within same time interval. However, when heat integration between two different time intervals is involved, heat from hot process streams has to be first transferred to a heat transfer fluid, which is heated up and stored until heat is finally transferred to cold process streams whenever needed. The proposed methodology accounts for indirect thermal integration which is actually, more practical when heat integration between two different time intervals is involved. The proposed methodology overcomes the limitation of TDHCA and is proved to be optimal through rigorous mathematical arguments.

It is important to note that philosophically, pinch analysis sets targets for system level design prior to the detailed design