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A methodology for the synthesis of heat exchanger networks having large numbers of uncertain parameters

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ABSTRACT

This paper presents a robust computational methodology for the synthesis and design of flexible HEN (Heat Exchanger Networks) having large numbers of uncertain parameters. This methodology combines several heuristic methods which progressively lead to a flexible HEN design at a specific level of confidence. During the first step, a HEN topology is generated under nominal conditions followed by determining those points critical for flexibility. A significantly reduced multi-scenario model for flexible HEN design is formulated at the nominal point with the flexibility constraints at the critical points. The optimal design obtained is tested by stochastic Monte Carlo optimization and the flexibility index through solving one-scenario problems within a loop.

This presented methodology is novel regarding the enormous reduction of scenarios in HEN design problems, and computational effort. Despite several simplifications, the capability of designing flexible HENs with large numbers of uncertain parameters, which are typical throughout industry, is not compromised. An illustrative case study is presented for flexible HEN synthesis comprising 42 uncertain parameters.

1. Introduction

HEN (Heat exchanger networks) are some of the more important systems within process industries because they enable rational utilization of energy and substantially improve the economic and environmental efficiencies of the production plants [1]. HEN design has been (and still is) one of the more studied fields within Process Systems Engineering. The methods for systematic HEN design have evolved from graphically-based pinch analysis [2] through the sequential approaches [3], and finally to simultaneous HEN synthesis [4]. A recent comparison between the main approaches [5] has confirmed that simultaneous methods show the best performances. However, the pinch methodology has made a remarkable progress through various extensions, like Power Pinch Analysis for determining minimum electricity targets [6] or carbon emission planning [7] and management [8]. The pinch technique has also been used within an optimization-based automated targeting model for Carbon Capture and Storage utilization in order to meet the carbon emission limits [9]. Nowadays, a retrofit of HENs has attracted a lot of attention among researchers for improving the energy efficiencies of the existing heat transfer systems [10]. These approaches may be based on the pinch technology, like in Smith et al. [11], or on the optimization models, like in Pan et al. [12] who developed a MILP (mixed integer linear programming) iterative method for HEN retrofit problems.

Throughout industry, several input data for HEN design fluctuate significantly, like the flowrates and the temperatures of process and utility streams. These parameters are often defined within ranges of values rather than as one single value. HEN should therefore be designed in such a way as to operate feasibly over the whole range of fluctuating input parameters, thus leading to a flexible HEN design.

The flexibilities of HENs are presently dealt with using both approaches. Pinch based sensitivity tables are applied for generating flexible HENs at maximum energy savings [13]. Operational issues especially controllability of HENs were addresses by combining targeting and Aspen Hysys simulation [14]. Regarding the mathematical programming, multi-period models and two-stage strategies are applied, by considering the flexibility and economics of the networks simultaneously and systematically. Papalexandri and Pistikopoulos [15] developed a large MINLP (Mixed Integer Nonlinear Programming) problem for the synthesis and retrofitting of flexible and

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controllable HENs based on a multi-period hyperstructure network. Aaltola [16] developed a multi-period MINLP model for synthesizing flexible HEN configurations. He considered a nominal- and three other periods for changing temperatures and flowrates within an application example. The maximum area approach was applied within a simultaneous MINLP model for designing flexible HEN in multi-period operation [17]. Escobar et al. [18] proposed a framework for the synthesis of flexible and controllable HENs, and presented several examples containing up to 14 uncertain parameters. Zheng et al. [19] proposed an approach to flexible HEN synthesis based on Probability Bounds Analysis, and utilized an Aspen Energy Analyzer for HEN design with 3 uncertain parameters. The Lagrangean decomposition has been used for solving multi-period models for flexible HENs, as shown by Escobar et al. [20], who solved examples with up to 15 process streams under variable inlet temperatures and heat capacity flowrates. Li et al. [21] solved a HEN with 11 uncertain parameters by applying a stepwise optimization method also suitable for nonconvex network problems. A general MINLP strategy based on a two-stage stochastic formulation was developed for the syntheses of flexible processes [22], which transforms a two-stage stochastic model into its deterministic multiscenario equivalent. This strategy was illustrated by a small HEN design problem with 3 uncertain parameters. As the number of scenarios increases exponentially with uncertain parameters, some authors have proposed methods for reducing scenarios in discretized two-stage stochastic models, e.g. a heuristic method [23], and a sensitivity analysis method [24].

Several authors have studied the influences of various disturbances on optimal HEN designs, for example the influences of changing temperatures and flowrates on the total exchanger area within a thermal power plant [25], and the influences of fluctuating energy prices over a network's entire lifetime [26]. Recently, increasing interest has been observed in integrating Total Sites including the renewables under varying supplies and demands [27].

The literature review revealed that a wide variety of approaches to flexible HEN design have been developed. Table 1 presents some types of these problems, and the solutions proposed. Although not exhaustive, this table illustrates the great diversities and complexities of the approaches and solutions within the area of flexible HEN design problems.

The existing approaches to flexible HEN design mostly deal with the limited number of uncertain parameters. Although the extensive progress within this area, designing flexible industrial networks or even the Total Sites with a greater number of uncertain parameters did not attract a lot of attention, and is still considered as a challenging task. There is a lack of reliable, straightforward, and fast techniques for designing flexible HENs. The main goal of this work was to fill this gap, and propose a robust methodology for flexible HEN synthesis potentially suitable for applications with several hundreds of uncertain parameters. In our previous work we developed different methods and approaches for designing flexible processes, for example, the approximate stochastic optimization [28], identification of critical points [29], and sensitivity analyses for the reductions of scenarios [24]. In the latter work, a bioethanol case study with around 70 uncertain parameters was carried out. In this work, however, those methods suitable for HEN synthesis have been identified and combined into a robust strategy that represents a firm basis for solving those HEN problems having larger numbers of uncertain parameters. Although heuristically-based, the benefit of this strategy is that it gradually develops a HEN from the synthesis of inflexible HEN structure at the nominal conditions, over the flexible HEN design, and finally to its validation by stochastic methods. It is based on the unique approaches of: a) influential uncertain parameters identification by sensitivity analysis, and b) critical points determination for drastically reducing the scenarios. The individual steps within the methodology include the solutions of smaller optimization problems, thus ensuring that the approach remains efficient and manageable. In this way it presents a novelty within the area of flexible HEN design, and demonstrates a potential for being applied hereafter to industrial HENs.

2. Problem statement and formulation

HEN design and synthesis are more often performed deterministically, i.e. at the fixed values of input parameters. In practice, however, many input parameters are subject to considerable fluctuations. Flexible designs should be capable of coping with input variations, and maintain feasible operations at the optimum expected economic criterion over a longer time horizon.

Table 1
Some approaches to flexible HEN design.

Type of problem	Solution methods
To calculate the responses of HEN's temperatures to variation of input parameters. To determine those exchangers that need to be increased and those that should be bypassed for desired flexibility.	Pinch-based sensitivity tables [13,30].
To determine the potential of heat matches to handle parameter variations.	Hypertarget method; iterative procedure for screening and targeting flexible HEN design [31].
To synthesize flexible and controllable HEN.	Multi-period hyperstructure network representation, synthesis/retrofit MINLP [15]. Two-stage procedure: design and operability stage, MINLP Synheat model [4,18].
Flexible HEN design and synthesis.	Multi-period MINLP model, LP and NLP search algorithms [16]. Multi-period MINLP model, maximum area approach [17]. Probability bounds analysis, double loop sampling, and Aspen Energy Analyzer [19]. Multi-period MINLP model, Lagrangean decomposition [20]. Stepwise procedure: MINLP nominal HEN structure, flexibility index, HEN structure at critical point, combination of topologies [21]. Reduction of scenarios in two-stage stochastic problem: • Multi-level MINLP methodology [22]. • MILP heuristic method [23]. • Sensitivity analyses [24]. • Karush-Kuhn-Tucker formulation, Iterative two-level method, Approximate one-level method [29].
Variations: • of temperatures and flowrates. • of energy prices in HEN and Total Sites. • in supply and demand in renewable Total Sites.	MINLP synthesis of HEN structures for different cases in thermal power plant [25]. Stochastic multi-period MINLP [26,32]. Total Site Profiles and cascading of utilities [27].