Process Safety and Environmental Protection xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Simultaneous synthesis of flexible heat exchanger networks for unequal multi-period operations

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ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form 14 April 2016
Accepted 23 April 2016
Available online xxx

Keywords:
Multi-period
Flexible
Synthesis
Mathematical programming
Heat exchanger network
Optimisation

ABSTRACT

The synthesis of heat exchanger networks has received significant attention in the last four decades due to the rising cost of fossil based energy sources and their attendant green-house gas emissions potential. However, most of the methods presented in the literature for heat exchanger network synthesis (HENS) have assumed that plants' process stream parameters, such as supply/target temperatures and stream flowrates, are fixed, hence having a single period of operation. In reality, process parameters vary within certain ranges due to changes in environmental conditions, changes in product quality demand, plant start-ups/shut-downs, and other disturbances which may upset the system. This implies that plants need to be designed to accommodate the aforementioned potential variations in operating parameters. This paper presents a new 3-step approach for the synthesis of flexible heat exchanger networks for multi-period operations with unequal period durations. The first step entails optimising a representative single period network of the multi-period problem. The solution to the representative network is then used to initialise the multi-period network in the second step. In the third step, the resulting network from the second step is redesigned/evaluated to handle unforeseen changes in lengths of periods. The solutions obtained from the newly presented method compare favourably with those in the literature.

1. Introduction

The world's attention is shifting significantly towards the need to reduce emissions of green-house gases. Key energy-using industries, such as chemical plants, have embraced the use of heat exchanger network synthesis (HENS) to achieve a reduction in additional energy through efficient recovery of process heat within their operations. Methods of HENS that have been used are sequential based (e.g. pinch technology, Smith, 2005) and mathematical programming based (e.g. stage-wise superstructure of Yee and Grossmann, 1990). Most of these methods are, however, developed for single period plant operations. In reality process plant operations are multi-period in nature, hence the heat exchanger network has to be flexible and resilient in order to accomplish the required heat duty.

2. Literature review

The term "multi-period" implies that plants' process parameters such as supply and target temperatures, as well as flowrates, fluctuate around some fixed values due to issues such as varying environmental conditions, plant start-ups and shut downs, changing process feed quality, changing product quality demand, etc. In some cases, the degree to which these parameters fluctuate around the average value, and the length of time of such variations are known upfront. Scenarios of this nature are usually called multi-period operations. In some other cases, the fluctuation of these operating parameters may be random around a set of nominal values, and there may not be clearly defined sets of periods. The extent to which a heat exchanger network is able to handle these two scenarios

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http://dx.doi.org/10.1016/j.psep.2016.04.021
0957-5820/

Please cite this article in press as: Isafiade, A.J., Short, M., Simultaneous synthesis of flexible heat exchanger networks for unequal multi-period operations. Process Safety and Environmental Protection (2016), http://dx.doi.org/10.1016/j.psep.2016.04.021

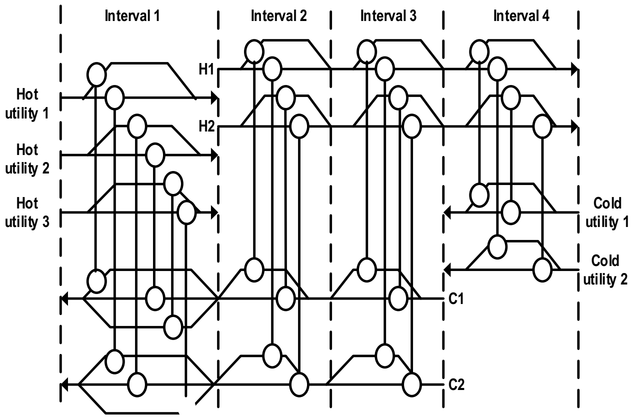

Fig. 1 – Stage-wise superstructure of Yee and Grossmann (1990) as used in this work.

is dependent on its degree of flexibility. However, network designs for these two scenarios need to be flexible such that the heat exchanger areas are large enough to transfer whatever quantity of heat needs to be transferred efficiently.

The work of Floudas and Grossmann (1986, 1987a), Aaltola (2003), Verheyen and Zhang (2006) and Isafiade and Fraser (2010), amongst others, addressed the multi-period scenario. The models of Floudas and Grossmann (1986, 1987a), are the multi-period versions of the linear programme (LP), mixed integer linear programme (MILP) and non-linear programme (NLP) of Papoulias and Grossmann (1983) and Floudas et al. (1986) respectively. While those of Aaltola (2003), Verheyen and Zhang (2006) and Isafiade and Fraser (2010), which are simultaneous in nature, are the multi-period version of the stage-wise superstructure (SWS) model of Yee and Grossmann (1990) and the interval based mixed integer non-linear programme (MINLP) superstructure synthesis of Isafiade and Fraser (2008). The SWS model as presented by Yee and Grossmann (1990) is shown in Fig. 1. In the model of Aaltola (2003), an average area approach was used. This implies that for stream pairs that exist in more than one period and in the same stage of the multi-period SWS, the average heat exchanger area requirement of all the matches is used as the representative heat exchanger area in the objective function. The model of Verheyen and Zhang (2006) extended this average area approach through the introduction of the maximum area approach. In this technique, instead of using the average of all the areas in all periods where the same stream pairs are matched, the maximum of these areas is used as the representative area in the objective function. However, in these two methods, the length of the periods have to be equal, which is not always the case in reality. Isafiade and Fraser (2010), further extended the maximum area method of Verheyen and Zhang (2006) using the multi-period interval based mixed integer non-linear programming superstructure (IBMS). The authors modified the objective function of Verheyen and Zhang (2006) to handle unequal period durations so that the correct weighting for utility contribution to the annual operating cost of participating periods can be adequately taken into account.

Even though the multi-period IBMS of Isafiade and Fraser (2010) is able to handle multi-period problems with unequal durations, two major shortcomings associated with this method and those of Aaltola (2003) and Verheyen and Zhang (2006), were identified by Jiang and Chang (2013). These shortcomings are that the representative exchangers may be overdesigned for some periods of operation, i.e. for periods having small heat capacity flowrate compared with other periods, and that the resulting networks are tailored towards one set of period durations. For this second shortcoming, it implies that if the length of periods change, then the designs may have to be changed or the utility requirements would change. Hence Jiang and Chang (2013) used the timesharing mechanism of Sadeli and Chang (2012) for flexible multi-period HENs to overcome the aforementioned drawbacks of the other methods. The methodology for this timesharing approach is that single period networks are designed for each of the periods participating in the problem using the traditional SWS model of Yee and Grossmann (1990). A set of algorithms is then used to select a set of heat exchangers from the resulting individual networks that would participate in the flexible network. The mode of operation of the flexible network is that in one period of operation, the exchangers in the flexible network would be used to exchange the required heat duties. However, if a change in period occurs, instead of already paired streams still exchanging heat in their usual exchangers, as is the case with the approaches of Aaltola (2003), Verheyen and Zhang (2006), Isafiade and Fraser (2010) and Isafiade et al. (2015), they will be made to swap or switch exchangers with some other stream pairs in what is known as the timesharing mechanism.

It is worth mentioning that even though the time sharing mechanism of Jiang and Chang (2013) has some advantages over the other SWS based models, the method still contains some notable weaknesses. One of these drawbacks is that changing from one period to another would require cleaning of the heat exchangers to avoid stream contamination. This is because according to the timesharing mechanism, another pair of stream match may need to use an exchanger previously used by some other stream pair. Apart from the time and operational cost that would be expended on the cleaning, the resulting designs from the time sharing mechanism would be more complex than designs from conventional SWS based multi-period synthesis methods due to the need for additional piping and associated instrumentations for by-passes and rerouting of streams, and this would be more problematic in larger problems.

Other methods presented in the literature for the synthesis of heat exchanger networks for multi-period operations are those of El-Temtamy and Gabr (2012), Isafiade et al. (2015), Sadeli and Chang (2012), Kang et al. (2015), Jiang and Chang (2015) and Escobar et al. (2014). El-Temtamy and Gabr (2012) extended the multi-period models of Floudas and Grossmann (1986, 1987a) through a procedure whereby the models are solved in a random manner iteratively. However, it cannot be said that these models are simultaneous in nature because they are based on the automated sequential approach of HENS (i.e. they involve LP, MILP and subsequent NLP models), hence each step is dependent on solutions obtained in the previous steps. Isafiade et al. (2015) extended the multi-period SWS model of Verheyen and Zhang (2006) to handle problems involving multiple options of utilities. The authors used a solution approach whereby the multi-period model is solved a number of times, and the matches which are common to two or three of the solution networks are used to initialise a reduced superstructure. The reduced superstructure is then solved as an MINLP model. However, as mentioned previously, the solution obtained is restricted to pre-determined set of period durations. Sadeli and Chang (2012) used mathematical model time sharing heuristics to bypass the issue of

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