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Synthesis of Mass Exchange Networks Involving Multiple Plants Using the Hub Layout Approach

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The synthesis of heat exchanger networks (HENs) has received significant attention in the last four decades. On the other hand, mass exchanger networks (MENs), whose synthesis methods have been based on analogies drawn from HEN synthesis, has received relatively less attention. This paper presents a new synthesis method for interplant MENs synthesis by drawing analogies from the interplant synthesis methods developed for its HENs counterpart. The approach adopted in this paper entails the utility hub concept where the plants that are participating in the integrated network are connected through external mass separating agents located at the utility hub. The integrated network of this paper is modelled using a modified version of the stage-wise superstructure synthesis method for MENs. The newly developed method is applied to a case study involving two plants and one utility hub. The solution obtained involves two mass exchangers in plant 1, two mass exchangers in plant 2 and four mass exchangers at the utility hub. A 21 % reduction in cost was obtained when the same external mass separating agent is used to absorb multiple components from rich streams at the utility hub when compared to the case where different external mass separating agents are used.

1. Introduction

To achieve sustainable designs, process plants must not only design energy efficient networks but also networks that are resource efficient. The concept of mass exchange network synthesis (MENS), which was first presented by El-Halwagi and Manousiouthakis (1989), has been used to achieve efficient resource utilisation in process plants considering operating and capital costs. Most of the synthesis methods that have been used in MENS have been based on analogies drawn from heat exchanger network synthesis (HENS). In HENS, the optimisation goal is to design networks that have the minimum annual operating and minimum annual capital costs. This has been achieved using sequential synthesis approaches. Chief among the sequential based approaches is Pinch Technology where the minimum operating and minimum capital costs are first targeted, after which designs that meet the targets are established (Smith, 2005). For MENS, the application of Pinch Technology aims at determining a target for the minimum operating costs, which is based on establishing the minimum mass separating agent (MSA) flows, as done by El-Halwagi and Manousiouthakis (1989). It also involves determining a target for the minimum capital cost, which is based on the mass exchanger column sizes, as presented by Hallale and Fraser (1998). The final step of the application of Pinch Technology to MENS entails designing networks that meet the operating and capital costs targets as presented by Hallale and Fraser (2000).

The other optimisation approach that has found wide usage in MENS is deterministic mathematical programming. Chief among the mathematical programming is the stage-wise superstructure (SWS), which was first developed for HENS by Yee and Grossmann (1990). In the SWS model for MENS presented by Szitkai, et al. (2006), along the superstructure, rich streams run from left to right while lean streams (which are the MSAs) run in the opposite direction. In the SWS for MENS, all streams are present in every stage of the superstructure. This is unlike the interval based mixed integer non-linear program superstructure for MENS developed by Isafiade and Fraser (2008) where the stages of the superstructure are defined by the supply and target compositions of either the rich or lean streams. In each stage of the SWS for MENS, streams can split into the number of streams of the opposite kinds present in the superstructure for the purpose of mass exchange.

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The SWS for MENS was updated by Azeez, et al. (2013) by defining the participation of streams in the superstructure using the supply compositions of both the rich and lean streams. Short and Isafiade (2020) developed an open-source package in Python to include detailed packed bed designs in mass absorbers in MENS. Isafiade and Short (2019) presented a mini review of the methodologies that have been adopted in MENS. The authors found that despite the fewer papers that have been published compared to its HENS counterpart, there are still several challenges within MENS that need to be addressed. The authors further stated that MENS problems involving many rich and many lean streams should be investigated as it may be useful for problems involving interplant mass integration which is the focus of this paper. With the growing interest in achieving sustainable resource utilisation by the process industry, the implementation of interplant mass integration can help in attaining optimal resource sharing among co-located plants, which may then help in achieving a circular economy. Interplant mass integration has received sizable attention in the literature especially for systems such as interplant water networks, where Wang et al. (2019) used the concentration potential concept for the synthesis of water networks involving multiple contaminants, and interplant hydrogen networks where Gai et al. (2022) adapted the multiple-level resource Pinch Technology framework for systems involving supply of fresh hydrogen sources having varying quality levels. However, the problem addressed in this paper differs from the interplant mass integration studies found in the literature in that a hub layout synthesis approach is adopted in the formulation of the superstructure to reduce the quantity of external MSA required by the integrated network. Also, the system considered in this paper is such that requires the simultaneous design of the gas-liquid mass exchange units involved in the integrated network.

2. Problem statement

Given a set of co-located process plants *P* where each plant has a set of streams *R*, with flowrate *G*, that are rich in certain species of supply and target compositions y^s and y^t. The compositions of the rich streams are to be decreased from supply to target values through mass exchange, with lean streams having supply and target compositions x^s and x^t. Two kinds of lean streams are available, process lean streams and external lean streams. The process leans streams are available within the process at a maximum flowrate L^u while the external lean streams are to be purchased, so their flowrate is unknown. Given also are unit costs for the lean streams and unit costs for the mass exchange columns. The goal is to design a network with minimum total annual cost (TAC) that optimally allocates the lean streams, including the external lean streams, in optimally sized mass exchangers, among the various rich streams within the co-located set of plants.

3. Methodology

The superstructure of the modelling approach adopted is illustrated in Figure 1 for two co-located process plants plant 1 (P1) and plant 2 (P2). In the figure, R1P1 represents rich stream 1 in plant 1, R2P1 represents rich stream 2 in plant 1, R1P2 represents rich stream 1 in plant 2 and R2P2 represents rich stream 2 in plant 2. For the lean streams, S1P1 represents process lean stream 1 in plant 1, S1P2 represents process lean stream 1 in plant 2, S1hub and S2hub are the external lean streams at the utility hub which is also located close to plants 1 and 2.

Figure 1 comprises three layers. Layer 1 comprises plant 1, layer 2 comprises plant 2 while layer 3 comprises the utility hub. In layer 1, the rich streams can only exchange mass with the process MSAs present in plant 1. The balance of mass load not absorbed by the process MSAs can only be removed in layer 3, i.e., the utility hub, using external MSAs S1hub and/or S2hub. The mass exchange profile of layer 2 is the same as that of layer 1, i.e., only process MSA is available for mass exchange while the balance of unabsorbed mass is removed in layer 3 using the external MSAs available at the utility hub. This profile of mass exchange between rich streams and external MSAs at the hub implies that the rich streams must be transported to the hub and back to their respective plants for the process to be feasible. This implies that the utility hub serves as waste/contaminant treatment plant.

The obvious alternative layout compared to the superstructure shown in Figure 1 is to just have both process and external MSAs in the individual plants to avoid piping and pumping costs. The downside of this alternative superstructure is that for problems involving MSAs that are expensive and require regeneration, it may be beneficial for co-located plants to outsource the regeneration process to another company that will be located at the 'utility hub' where an integrated regeneration of the external MSAs can take place. Also, if there are co-located plants, which is the scenario considered in this paper, that involve the separation of species that can be accomplished using the same external MSA as other plants present within an industrial park, then again, the layout of Figure 1 will be beneficial since the external MSA can be optimally shared among the rich streams of the participating plants at the utility hub. Such sharing is still possible and will potentially lead to overall cost reduction even if the species to be removed from the rich streams of the plants differ. As an example, if the specie to be removed from the rich streams of plant 1 is H_2S, while the specie to be removed from the rich streams of plant 2 is CO_2, the same external MSA, such as water or chilled methanol, can be used for the removal of both components at the utility hub. This is possible for problems involving both compatible components and incompatible components. An example of a problem that involves compatible components is the coke oven gas sweetening problem of El-Halwagi and Manousiouthakis (1989) where H_2S and CO_2 are to be removed from gaseous rich streams.

The superstructure shown in Figure 1 is modelled using a modified version of the SWS model for MENS presented by Szitkai, et al. (2006). The model comprises overall mass balance over every rich and every lean stream in the problem, including the external MSAs at the hub, mass balances over each stage of the superstructure for plant 1, plant 2, and the utility hub, equations depicting monotonicity of compositions from the rich ends of the superstructures to the lean ends, equations depicting approach compositions at the rich and lean ends of each mass exchanger, and the objective function. The objective function is shown in Eq(1). In the equation, AF is annualization factor, CF (\$/y) is fixed charges for mass exchanger installation, $y_{r,s,k,p}$ is a binary variable that indicates whether a match is selected between rich stream r and lean stream s in stage k of the superstructure and plant p. Note that the utility hub is also included in the set of plants. ACN (4,552 \$/kg·y) in Eq(1) is cost per stage for the columns as presented by Papalexandri et al. (1994), $AC_{s,p}$ (117,360 (\$/y)/(kg/s) for S1P1 and S1P2, and 176,040 (\$/y)/(kg/s) for S1hub and S2hub) is the cost per unit of lean stream s in plant p, $L_{s,p}$ is the flowrate of lean stream s in plant p. The costing parameters used in this paper are taken from Papalexandri et al. (1994) where AF and CF are both zero. Hallale and Fraser (2000), who solved the same example as this paper, but for a single plant scenario, used the same costing parameters.

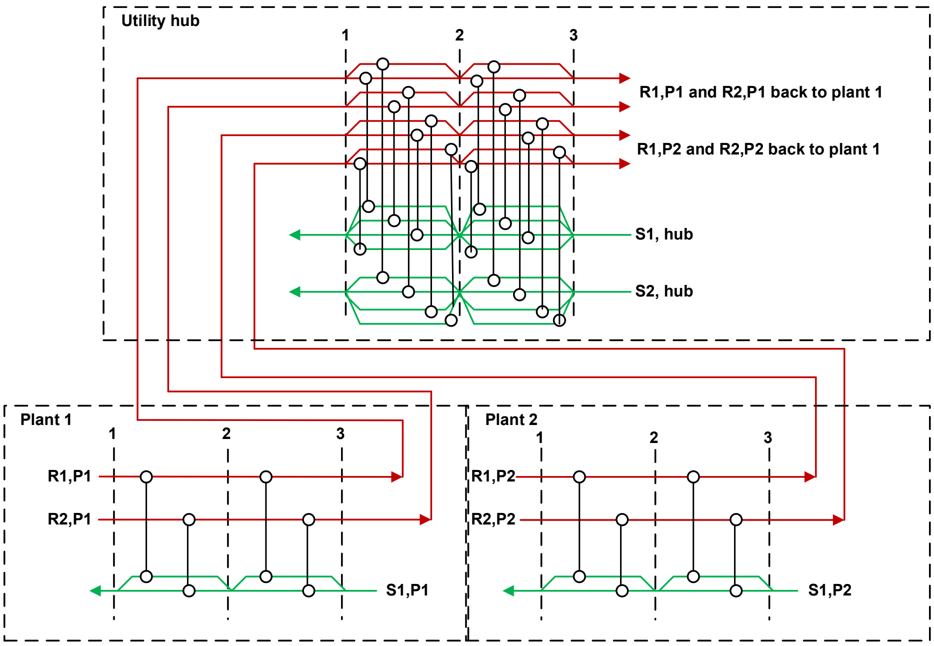

Figure 1: Superstructure of interplant mass integration

$$\mathrm{Min}\, TAC = AF\left\{CF\sum_{r\in R}\sum_{s\in S}\sum_{k\in K}\sum_{p\in P} y_{r,s,k,p} + ACN\sum_{r\in R}\sum_{s\in S}\sum_{k\in K}\sum_{p\in P} N_{r,s,k,p}\right\} + \left\{\sum_{s\in S}\sum_{p\in P} AC_{s,p}\cdot L_{s,p}\right\} \tag{1}$$

In Eq(1), $N_{r,s,k,p}$ is the number of stages in the column that exchange mass between rich stream *r*, lean stream *l*, in stage *k* and plant *p*, and is defined in Eq(2) by Shenoy and Fraser (2004).

$$N_{r,s,k,p} = \left(\frac{\Delta y^n + \Delta y^{*n}}{\Delta y_1^n + \Delta y_2^2}\right)^{1/n} \tag{2}$$

In Eq(2), Δy is the concentration difference in the rich streams, Δy^* is the equilibrium concentration difference for the lean streams, Δy_1 is the driving force at the rich end of the mass exchanger while Δy_2 is the driving force at the lean end, *n* is 0.3275 as presented by Chen (1987).

A two-step approach was adopted in solving the model of the case study of this paper because of the non-convexities involved in the model. Also, since the goal is to use as little as possible quantities of external MSA to absorb all components in all rich streams at the utility hub, then the problem involves a multi-component model which is not trivial to solve especially for a multi-plant scenario as addressed in this paper.

4. Case study

The case investigated is a modified version of the coke-oven gas sweetening problem presented by El-Halwagi and Manousiouthakis (1989). The problem data are shown in Tables 1, 2 and 3. As indicated in Table 1, the two rich streams in plant 1 are to be stripped of H_2S while the two rich streams in plant 2 are to be stripped of CO_2. The equilibrium constant m for process lean stream S1 in plant 1 (S1P1) is 1.45 while that of S1 in plant 2 (S1P2) is 0.35. m for the external lean stream, S1hub, that will initially serve plant 1 is 0.26 while m for S2hub that will initially serve plant 2 is 0.58.
In the first step, external lean stream S1hub was used, alongside S1P1, to only absorb H_2S from the rich streams of plant 1 while external lean stream S2hub was used, alongside S1P2, to only absorb CO_2 from the rich streams of plant 2. S1P1 and S1P2, which are process lean streams as indicated in Table 2, were used only in their respective plants. The superstructures used for the model of the first step involves 3 stages for plant 1, 3 stages for plant 2, and 2 stages for the superstructure at the utility hub. The model, which was developed in General Algebraic Modelling Systems (GAMS) as a mixed integer nonlinear programming (MINLP) model, was solved simultaneously using the SCIP solver (GAMS Development Corporation, 2013) for steps 1 and 2.
The model of the first step involves 513 equations, 583 variables of which 80 are discrete variables. The solution for this step, which was obtained in 18 minutes of computer processing unit (CPU) time, has a TAC of $ 1,112,772. This cost comprises an annual capital cost (ACC) of $ 559,896 and an annual operating cost (AOC) of $ 552,876. The solution, which is shown in Figure 2, involves 2 units in plant 1, 2 units in plant 2, and 4 units at the utility hub. The purpose of the first step of the solution method is to determine the quantity of the process lean streams that can be used for each of plants 1 and 2, and the quantity of mass, from the rich streams of each plant, that must be transported to the hub for removal by the external lean streams. This information is necessary because it will be used to define the supply compositions of the rich streams going into the superstructure of the utility hub in the second step of the synthesis procedure.

Table 1: Rich stream data for plant 1 and plant 2

Plant 1 (H_2S)				Plant 2 (SO_2)			
Rich streams	*R* (kg/s)	y^s	y^t	Rich streams	*R* (kg/s)	y^s	y^t
R1	1.0	0.070	0.0003	R1	0.40	0.051	0.0001
R2	0.6	0.060	0.0005	R2	0.20	0.115	0.0100

Table 2: Process lean stream data for plant 1 and plant 2

Plant 1 (H_2S)				Plant 2 (SO_2)			
Lean stream	L^u (kg/s)	x^s	x^t	Lean stream	L^u (kg/s)	y^s	y^t
$L1^u$	3.75	0.0006	0.031	$L1^u$	2.3	0	0.171

Table 3: External lean stream data at the utility hub

Lean stream				Lean stream			
	L (kg/s)	x^s	x^t		*L* (kg/s)	y^s	y^t
L1	∞	0.0002	0.00312	*L2*	∞	0	0.103

In the second step, only the utility hub superstructure model was solved. This was done by generating a 3-stage superstructure using R1P1, R2P1, and R2P2 as the rich streams participating in the superstructure. Since the mass load of R1P2 is fully absorbed in plant 2 by S1P2, the stream will not have to be transported to the utility hub which is why it is not included in the superstructure of step 2. The inlet composition of R1P1 to the superstructure in step 2 is 0.00087 and this is defined by the exit composition of the rich stream from stage 3 of plant 1's superstructure shown in Figure 2. Supply compositions for R2P1 and R2P2 as shown in Figure 3 were determined in the same way. The model of this step involves 282 equations, 211 variables of which 18 are discrete variables. The model was solved using SCIP and a solution was obtained in 19.42 minutes of CPU time. The solution obtained is like the network structure for the hub shown in Figure 2 with the difference being that the match that pairs R2P2 and S2hub for this solution is in the last stage of the superstructure whereas the match is in the first stage of the hub network in Figure 2. According to El-Halwagi and Manousiouthakis (1989), this problem involves compatible targets, so the approach of Hallale and Fraser (2000) is adopted to determine which of S1hub and S2hub will be used as external lean stream to absorb the two components which are H_2S and CO_2. The approach involves selecting the component that requires the larger external lean stream flowrate. Based on the solution network of the second step, H_2S requires the larger flowrate (1.042 kg/s), so S2hub which requires a flowrate of 0.1665 kg/s in a column with 46 trays was discarded from the utility hub network. The hub network structure was then sequentially redesigned so that S1hub will first absorb H_2S from R1P1 and R2P2 in columns 7 and 8 as indicated in stage 3 of the hub superstructure in Figure 3. The split branches in stage 3 will then mix to have a composition of 0.0031 and flow into column 6 to absorb more H_2S from R1P1. The S1hub stream that exits column 6 will then flow into column 5, which has been redesigned from requiring 46 trays to requiring 1 tray, to absorb CO_2 from R2P2. This implies that S1hub exits the hub superstructure with compositions of 0.00312 for H_2S and 0.0164 for CO_2 as the new target composition.

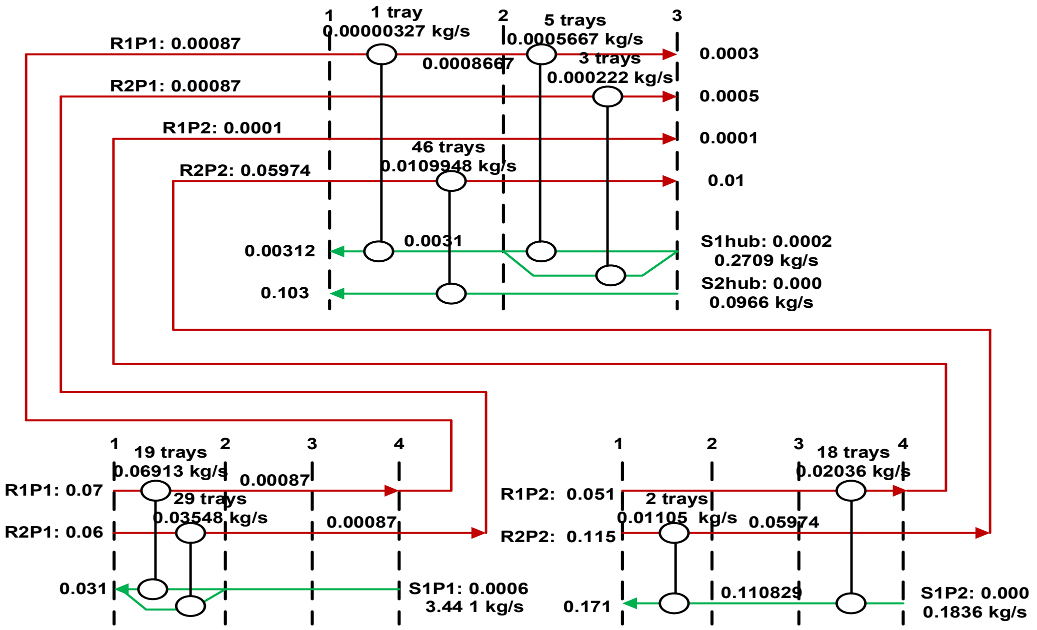

Figure 2: Network structure for step 1

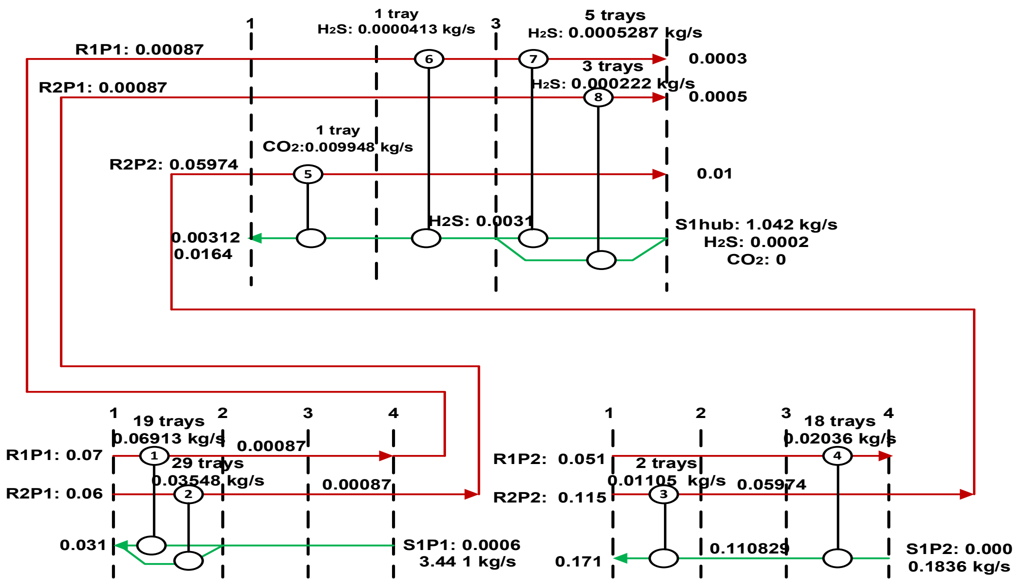

Figure 3: Final network structure.

The TAC for the final network of Figure 3 is $ 878,616. This cost comprises an ACC of $ 355,056 and an AOC of $ 523,560. The ACC decreased from the $ 559,896 obtained in Figure 2 to $ 355,056 obtained in Figure 3 mostly because the 46-tray column required by R2P2 was redesigned to a column that requires just 1 tray. The AOC decreased because only S1hub is now used in the final network. The TAC of the second step involves a 21 % reduction when compared with the solution network of the first step shown in Figure 2. This illustrates, in quantitative terms, the benefits of adopting an integrated simultaneous synthesis approach that is based on the concept of the utility hub.

5. Conclusions

This paper has presented a synthesis approach for interplant mass integration using a utility hub approach. The method of this paper can be used to achieve the concept of circular economy. The case study investigated has in quantitative terms illustrated the benefits of using the utility hub approach for interplant mass integration. However, the full benefits inherent in the newly presented concept of this paper can only be fully unpacked when issues such as the cost implications of pumping the rich streams to the utility hub, including the associated piping costs, are considered in the model. Also, the cost of regenerating the rich external MSA at the hub should be investigated. However, there may be opportunities to reduce the cost of regeneration, especially for a case where heat induced regeneration is required. Such opportunities would include integrating the heat duty of the regeneration with a combined heat power network at the hub. This will be considered in future studies.

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