CHEMICAL ENGINEERING TRANSACTIONS
VOL.103, 2023
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

ISBN 979-12-81206-02-1; **ISSN** 2283-9216
DOI: 10.3303/CET23103087

Interplant Heat Integration Involving Multiple Periods of Operations with Unequal Durations

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This paper presents a synthesis method for interplant heat integration where the participating plants have multiple periods of operations with unequal durations. The method adopted is the energy hub approach where interplant heat integration and heat exchange with hot and cold utilities occur at the energy hub while intra-plant heat integration occurs at the individual plant level. The example considered involves three plants that are co-located with each plant having a 2-period operational profile involving daytime and night-time. The multiperiod profile for plant 1 spans 12 hours for the daytime period and 12 hours for the night-time period. That of plant 2 spans 10 hours for the daytime and 14 hours for the night-time while that of plant 3 spans 8 hours for the daytime and 16 hours for the night-time. The unequal periodic durations across the three plants were synchronised using a newly developed operational period mapping approach that gave rise to 4 periods for the interplant heat integration. The solution obtained from the example considered involves 14 heat exchangers of which 6 are intra-plant heat exchangers, 5 are utility exchangers while 3 are interplant process heat exchanger at the energy hub.

1. Introduction

To combat greenhouse gas emissions in a more holistic manner, one of the approaches adopted by the process industry is heat integration. However, most of the works that have been published on process heat integration have been based on Heat Exchanger Network (HEN) synthesis of individual plants involving single period operations. Multiple period operations, which is a more realistic process scenario has not received much attention. Multiple period operations in process plants may be due to plant start-ups, shut-downs, process upsets, change in feedstock quality, change in plant throughput, etc. Accommodating multiperiod operations in HEN synthesis may require designing heat exchangers to be large enough to optimally transfer heat in all periods of operations. One of the first studies to adopt a simultaneous synthesis approach for multiperiod HENs is the work of Aaltola (2002) where an average representative area sizing approach was used in the objective function. This was later improved on by Verheyen and Zhang (2006) using the maximum representative area sizing approach in the objective function. Isafiade and Short (2016) also adopted the maximum area approach in the objective function, but included scenarios where period durations are unequal and uncertain. Beyond, HEN synthesis of individual plants, process integration has been extended to energy sharing among multiple plants in what is known as interplant heat integration (IPHI). In the work of Song et al. (2017), which addressed IPHI, a screening algorithm and the potential theoretical maximum heat recovery within the interplant network was adopted. Chang et al. (2018) adopted the energy hub design technique for IPHI. In this method, the energy hub is reserved for only interplant process-to-process heat exchange while intra-plant process-to-process heat exchange and heat exchange with utilities can only take place at individual plant level.
It is worth stating that most of the studies on IPHI have involved single period HENs with only few studies devoted to multiperiod HENs. Ma et al. (2018) addressed IPHI involving multiperiod HEN synthesis by connecting the participating plants with one another through a central utility system using economics and environmental impacts as objective functions. Čuček et al. (2015) investigated retrofit and large-scale networks in IPHI problems involving multiperiod operations.

Paper Received: 12 March 2023; Revised: 29 June 2023; Accepted: 26 July 2023
Please cite this article as: Isafiade A.J., 2023, Interplant Heat Integration Involving Multiple Periods of Operations with Unequal Durations, Chemical Engineering Transactions, 103, 517-522 DOI:10.3303/CET23103087

The work of Cowen et al. (2019), which although did not directly involve IPHI involves three plants, whose operations are multiperiod, having their heat demand integrated with utilities supplied by a bioenergy supply chain network. This work was improved on by Isafiade et al. (2022), which directly addressed IPHI involving multiperiod operations, by adopting the energy hub approach where intra plant process-to-process heat exchange can only occur at individual plant levels while interplant process-to-process heat exchange can only occur at the energy hub. Also, the exchange of heat between a process stream and a utility can only occur at the energy hub. The method of Isafiade et al. (2022) also included the integration of a bioenergy supply chain network with the energy hub of the integrated model. One of the key benefits of the energy hub approach of Isafiade et al. (2022) is that various utility sources can be shipped, through supply chain network optimisation, to the energy hub for integration with the heat demand of the individual plants in the IPHI network. Another key benefit is that if a process stream participating in process-to-process heat exchange at the energy hub is unavailable, it can readily be replaced by a utility. However, the methods of Ma et al. (2018) and Isafiade et al. (2022) assumed that the participating plants in the interplant network will all have the same number of periods with equal durations. This may not always be the case in practical scenarios where the number of periods in one plant may differ from the number of periods in other plants. The implication of this difference is that heat exchangers may not be optimally matched between streams in different plants for interplant heat exchange and the quantity of utility consumed per period in each plant may not be optimally allocated in computing the integrated network's total cost. Therefore, this paper aims to address this shortcoming by adopting a systematic integrated time slice based periodic mapping approach that accommodates IPHI at an energy hub for multiple plants having varying periodic durations.

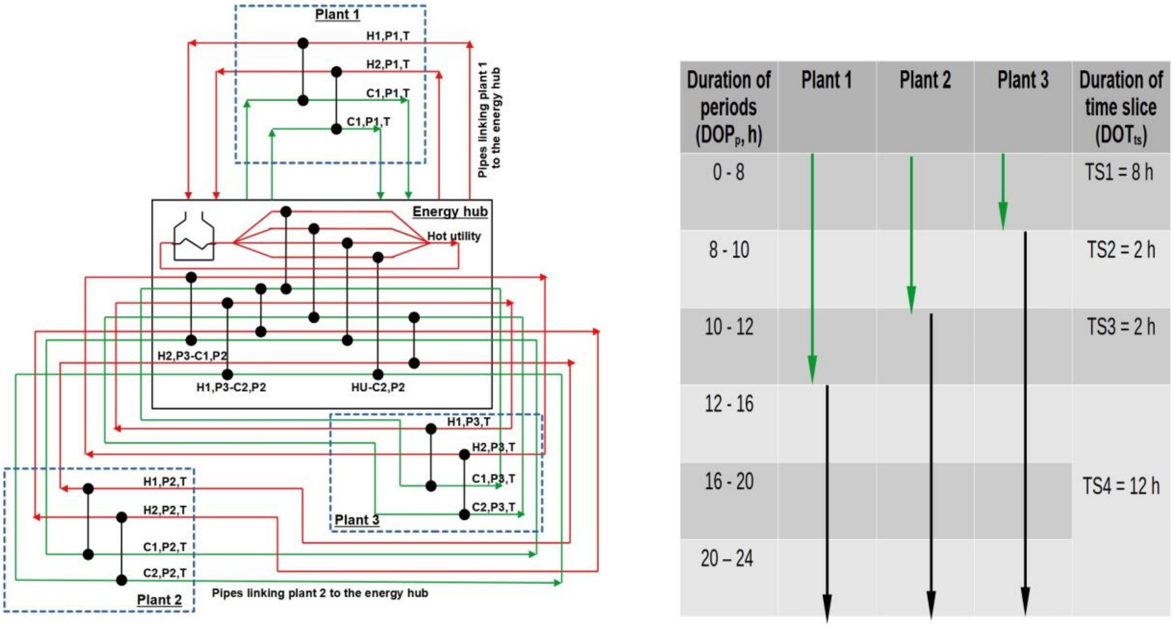
2. Problem statement

Given a set of process plants *P*, with each plant having a set of hot streams *H* with supply and target temperatures T^s and T^t and heat capacity flowrate *FCPH*, and a set of cold streams *C* also having supply and target temperatures T^s and T^t and heat capacity flowrate *FCPC*. Each plant also has multiple periods of operations *T* whose durations differ from those of other plants. Other parameters given are interplant distances and distances between each plant and the energy hub, stream heat transfer coefficients, cost functions for heat exchangers and an energy hub where hot and cold utilities are available. The goal is to synthesize a minimum total annual cost (TAC) interplant heat exchange network where energy is optimally transferred among process streams and utilities both at the intra-plant and interplant levels considering the varying periodic durations among plants.

3. Methodology

The method adopted in this paper is an extension of the IPHI synthesis technique presented by Isafiade et al. (2022) whose superstructure is shown in Figure 1a. The superstructure comprises three hypothetical process plants (P1, P2, P3), with varying daytime/night-time periodic durations, that are co-located within the neighbourhood of an energy hub where hot and cold utilities are available. To illustrate the stream matching profile available in the superstructure shown in Figure 1a, H1, P2, T, which represents process hot stream 1 in plant 2 and operational period T, can be paired through intra-plant heat exchange with any of C1, P2, T and C2,P2,T, with the same possible pairing profile available to H1, P2, T. The same pattern of intra-plant heat exchange is also available in Plants 1 and 3. In terms of heat exchange with hot or cold utilities, any of the hot and cold process streams, from any of the three plants, and in any period of operation T, can be transported to the energy hub through pipes for heat exchange with hot or cold utilities. Interplant heat exchange can only occur at the energy hub. As an example, in Figure 1a, exchanger H2,P3 – C1,P2 is a match between process hot stream 2 in plant 3 and process cold stream 1 in plant 2. Exchanger H1,P3 – C2,P2 in Figure 1a is a match between process hot stream 1 in plant 3 and process cold stream 2 in plant 2. It should be known that the representation of each process stream in each plant in Figure 1a is such that they are piped back to their respective plants to undergo subsequent processes after exchanging heat at the hub. If the subsequent processes result in the streams being heated or cooled, then the circuit is closed, otherwise, it is open. However, the overall process of this paper is a continuous process. In the work of Isafiade et al. (2022), it is assumed that the periodic durations in each of the plants are equal. The illustration of this assumption is explained as follows. For the interplant heat exchanger H2,P3 – C1,P2, the duration of the operational period in which H2 is available in plant 3 is the same as the duration in which C1 is available in plant 2. However, in practical designs such assumptions may not hold. So, in this paper, a new periodic duration mapping approach for interplant heat exchange at the energy hub is proposed. The new method is demonstrated through the case study investigated in this paper. The objective function of the newly developed method, which is illustrated in Eq.(1), comprises annual operating costs (AOC) of hot and cold utilities, installed annual capital costs (ACC) of process and utility exchangers and pipes that connect each plant to the energy hub. A simplified cost law expression is used in the objective function to compute the installed capital cost of heat exchangers. In Eq(1), AF (0.2/y) is the annualization factor for heat exchangers and pipes, CF (5,500 \$) is the installation cost for heat exchangers, $y_{p,i,j,k}$ is the binary variable that indicates the existence of a match between streams i and j in plant p or at the energy hub, AC (700 \$/m^2) is the cost per unit area of heat exchanger, AE is the area cost exponent of the heat exchangers, $Dist_{i,j}$ (m) is the average distance between plants and the energy hub, $PC_{p,i}$ (\$/m) and $PC_{p,j}$ (\$/m) are the units costs of pipes transporting hot and cold process streams to and from their respective plants to the energy hub (parameters were taken from Chang et al. (2018)), DOT_{ts} is duration of periodic time slice ts, NOP is the number of periodic time slices, CUC (\$/(kW·y)) and HUC (\$/(kW·y)) are the units costs for cold and hot utilities, $q_{p,I,j,k,ts}$ (kW) is heat exchanger heat load. It is worth stating that since the weighting terms that multiply the annual operating costs of hot and cold utilities in Eq(1) are summed over the time slices, then the fractional contributions of utility consumption per period and per plant will be adequately accounted for in the objective function.

$$\begin{aligned}\operatorname{Min} TAC = AF\Bigg\{ & CF.\sum_{p\in P}\sum_{i\in H}\sum_{j\in C}\sum_{k\in K} y_{p,i,j,k} + AC.\sum_{p\in P}\sum_{i\in H}\sum_{j\in C}\sum_{k\in K}\left[A_{p,i,j,k}\right]^{AE} \\ & + \sum_{p\in P}\sum_{i\in H}\sum_{j\in C}\sum_{k\in K}\left(y_{p,i,j,k}\cdot\left(Dist_{i,j}\cdot PC_{p,i} + Dist_{i,j}\cdot PC_{p,j}\right)\right)\Bigg\} \\ & + \sum_{ts\in TS}\left(\frac{DOT_{ts}}{\sum_{ts=1}^{NOP} DOT_{ts}}\cdot\sum_{p\in P}\sum_{i\in H}\sum_{j\in C}\sum_{k\in K} CUC\cdot q_{p,i,j,k,ts}\right) \\ & + \sum_{ts\in TS}\left(\frac{DOT_{ts}}{\sum_{ts=1}^{NOP} DOT_{ts}}\cdot\sum_{p\in P}\sum_{i\in H}\sum_{j\in C}\sum_{k\in K} HUC\cdot q_{p,i,j,k,ts}\right)\end{aligned} \quad (1)$$



(a) (b)

Figure 1: (a) Interplant heat integration superstructure, (b) Duration of time slices for case study investigated

4. Case study

The case study investigated in this paper is adapted from Isafiade et al. (2022). The problem involves three process plants and an energy hub. Table 1 illustrates the distances between plants and the energy hub. Tables 2 and 3 illustrate the stream data for the hot process streams in the three plants for daytime and night-time periods, while Tables 4 and 5 illustrate the equivalent data for the cold process streams. Table 6 shows stream data for hot and cold utilities. It should be known that the bioenergy supply chain component included by Isafiade et al. (2022) in the problem is excluded in this paper. This means that the cost of hot utilities used in this paper are different from those of Isafiade et al. (2022). Also, as shown in Tables 2, 3, 4 and 5, this paper considers the case where duration of periods (DOP_p) is unequal. This is unlike Isafiade et el. (2022) that assumed equal periodic durations. In this paper, for plant 1, the DOP for daytime is 12 h while that of plant 2 is 10 h and 8 h for plant 3. This implies that interplant heat exchange between process streams from different plants at the energy hub will result in a mismatch as far as duration of periods is concerned. As an example, if H1 in plant 3 at daytime period is matched with C1 in plant 1, which is also present at daytime period, at the end of the 8th hour, stream H1 in plant 3 will switch to the night-time period with the stream parameters for H1 changing from the values in Table 2 to the values in Table 3, while C1 in plant 1 will still be operating at its daytime stream parameters. This approach, which was adopted by Isafiade et al. (2022) has the tendency to result in suboptimal networks. Also, the contributions of utility consumption, and the attendant environmental impact, for each period of operation will be difficult to identify for the purpose of computing the annual operating cost in the objective function. To accommodate the stated unequal periodic durations among plants, the time slice approach shown in Figure 1b was developed in this paper. The workings of the periodic time slice approach are as follows. The first column in Figure 1b represents the actual periodic durations for each plant. The periodic interval of the availability of each plant in the daytime is mapped against the time intervals in the first column using the green arrows, while the equivalent for the night-time is mapped using the black arrows.

Table 1: Average distances between plants and the energy hub (Isafiade et al., 2022)

Process plants	Energy hub (m)	Plant 1 (m)	Plant 2 (m)	Plant 3 (m)
Plant 1	150	-	110	100
Plant 2	120	110	-	130
Plant 3	140	100	130	-

Table 2: Process hot stream data for plants 1, 2 and 3 in daytime period (Isafiade et al., 2022)

Plants	Streams	T^s (K)	T^t (K)	FCPH (kg/s)	h (kW/(m^2·K))	Cp (kJ/(kg·K))	ρ (kg/m^3)	DOP_p (h)
Plant 1	H1	660	370	2.0	1.0	3.2	780	12
	H2	590	320	1.6	1.0	3.5	820	
Plant 2	H1	553	333	2.0	1.6	3.7	790	10
	H2	493	310	2.5	1.6	3.3	810	
Plant 3	H1	520	390	2.0	2.1	3.2	782	8
	H2	473	370	1.0	4.1	3.0	760	

Table 3: Process hot stream data for plants 1, 2 and 3 in night-time period (Isafiade et al., 2022)

Plants	Streams	T^s (K)	T^t (K)	FCPH (kg/s)	h (kW/(m^2·K))	Cp (kJ/(kg·K))	ρ (kg/m^3)	DOP_p (h)
Plant 1	H1	640	350	2.1	1.0	3.2	780	12
	H2	600	310	1.8	1.0	3.5	820	
Plant 2	H1	543	333	1.9	1.6	3.7	790	14
	H2	483	300	2.4	1.6	3.3	810	
Plant 3	H1	522	395	2.1	2.1	3.2	782	16
	H2	479	380	1.8	4.1	3.0	760	

To overcome the shortcomings identified with the energy hub stream matching approach of Isafiade et al. (2022), the fifth column is created so that each time slice in the column will then correspond to a period of operation in the IPHI multiperiod model. So, instead of just having 2 periods of operations (i.e., daytime and night-time), the integrated time slice approach results in 4 periods which correspond to column 5 in Figure 1b. The 4 periods of operations are then included in the IPHI multiperiod model. In Figure 1b, the starting time and ending time for each time slice corresponds to one or more of the starting/ending time of the periodic duration of one or more plants. Solving the model produces an interplant heat integrated network having a TAC of $ 418,348. The model, which was set up as an MINLP in General Algebraic Modelling Systems (GAMS development corporation, 2015), has 27 blocks of equations, 2,425 single equations, 15 blocks of variables, 3,115 single variables and 405 discrete variables. The model was solved using CONOPT for the NLP and CPLEX for the MILP. The solution was obtained in about 60 s of CPU time. The TAC comprises hot utility AOC of $ 260,020, cold utility AOC of $ 1,451, pipe ACC of $ 90,973 and heat exchanger ACC of $ 65,903.

Table 4: Process cold stream data for plants 1, 2 and 3 in daytime period (Isafiade et al., 2022)

Plants	Streams	T^s (K)	T^t (K)	FCPC (kg/s)	h (kW/(m²·K))	Cp (kJ/(kg·K))	ρ (kg/m³)	DOP_p (h)
Plant 1	C1	320	650	3.5	2.0	4.0	790	12
	C2	360	500	3.3	2.0	3.3	770	
Plant 2	C1	303	430	2.0	2.6	4.1	810	10
	C2	363	413	2.5	2.6	3.4	790	
Plant 3	C1	303	398	3.5	2.1	3.9	790	8
	C2	308	373	3.9	2.1	3.3	780	

Table 5: Process cold stream data for plants 1, 2 and 3 in night-time period (Isafiade et al., 2022)

Plants	Streams	T^s (K)	T^t (K)	FCPC (kg/s)	h (kW/(m²·K))	Cp (kJ/(kg·K))	ρ (kg/m³)	DOP_p (h)
Plant 1	C1	310	640	3.4	2.0	4.0	790	12
	C2	350	500	3.5	2.0	3.3	770	
Plant 2	C1	293	420	2.1	2.6	4.1	810	14
	C2	353	415	2.2	2.6	3.4	790	
Plant 3	C1	299	390	3.4	2.1	3.9	790	16
	C2	296	373	3.9	2.1	3.3	780	

Table 6: Data for hot and cold utilities (adapted from Isafiade et al., 2022)

Utilities	T^s (K)	T^t (K)	h (kW/(m²·K))	Cp (kJ/(kg·K))	ρ (kg/m³)	Cost ($/(kW·y))
HU1	680	680	5.0	2.1	314	150
HU2	580	580	3.8	2.0	367	110
HU3	453	453	2.5	1.98	491	170
CU1	300	300	1.0	3.2	800	15
CU2	293	293	1.0	3.2	800	20
CU3	283	283	1.0	3.2	800	25

Table 7: Intra-plant heat exchange

Plants	Exchanger	Area (m²)	Heat load (kW)			
			TS1	TS2	TS3	TS4
Plant 1	H1-C1	29.04	1,856	1,856	1,856	1,948.8
	H2-C1	87.84	1,496	1,496	1,496	1,762.5
Plant 2	H1-C1	34.72	540.9	385	348.8	140.9
	H2-C1	43.59	213	303.1	242.7	242.7
Plant 3	H1-C2	5.08	334.5	456.4	456.4	456.4
	H2-C2	7.85	309	534.6	534.6	534.6

Table 8: Heat exchange with hot and cold utilities at the energy hub

Exchanger	Area (m²)	Heat load (kW)			
		TS1	TS2	TS3	TS4
HU1-C1,P1	29.95	1,268	1,268	1,268	776.7
H2,P1-CU3	1.09	16	16	16	64.5
HU2-C1,P2	5.53	287.5	353.3	502	709.9
HU2-C2,P2	3.68	425	425	463.8	463.8
H1,P2-CU1	2.31	60	115.5	-	-

Table 7 shows the heat exchanger areas for the intra-plant heat exchange in each of the plants. The table also shows the heat load for each time slice in each heat exchanger. Table 8 shows the profile of heat exchanged, including heat exchanger areas, for process streams transported to the energy hub.

No plant 3 stream is in the table which implies that they did not exchange heat with either hot or cold utilities. Table 9 shows process streams transported from the various plants to the energy hub for heat exchange with process streams from other plants, i.e., interplant heat exchange. H1,P2 is on Tables 8 and 9 which is an indication that the stream was involved in exchange of heat with both cold utility and a process cold stream at the energy hub. However, heat exchange with cold utility only took place in time slices 1 and 2 which both fall within the daytime period for plant 2.

Table 9: Interplant heat exchange at the energy hub

Exchanger	Area (m^2)	Heat load (kW)			
		TS1	TS2	TS3	TS4
H1,P2-C2,P1	82.3	1027	1127.6	1127.6	1335.5
H2,P2-C1,P3	20.2	1296.8	1206.7	1206.7	1206.7
H1,P3-C2,P1	11.6	497.5	397	397	397

5. Conclusions

This paper has presented a new methodology for synchronising varying duration of periods among multiple plants for implementation in IPHI. The developed method considers both intra-plant and interplant heat integration using the energy hub layout approach. Time slicing is used to divide the total operational durations of all plants so that process streams across plants and across operational periods can be matched for heat exchange at the energy hub. One of the key advantages of the developed method is that the multiperiod stagewise superstructure model of Verheyen and Zhang (2006) can readily be extended to multiperiod IPHI problems using the energy hub approach. Identifying the fractional contribution of utility consumption, and the attendant environmental impact, of each operational period in each plant in the IPHI network is also relatively easier through the time slicing approach. Although some of the data used in this paper are hypothetical data, the newly developed method can be applied to practical designs. However, such implementation must include other design considerations such as detailed individual heat exchanger design, fouling in heat exchangers, cost of pumping process streams from their respective plants to the energy hub, heat losses along the length of pipelines and the use of game theory to optimally share the integrated interplant network's TAC among the participating plants.

Acknowledgments

The support of the National Research Foundation of South Africa (Grant numbers: 119140 and 149309) and the Research Office at the University of Cape Town, are acknowledged.

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