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物質およびエネルギーの変換を考慮したバッチプラントの運転操作手順生成手法

Synthesis of Operating Procedures for Material and Energy Conversions in a Batch Plant

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Abstract

The problem of operating procedure synthesis for process plants is investigated. Knowledge about plant structure and material-conversion procedures was represented by directed graphs and the subgraph-isomorphism algorithm was utilized to solve the problem. The concept of heat-resources is introduced here as an extension of usual equipments. A mechanism to have multiple outputs for a material conversion is also proposed. These extensions provide the method to deal with the operation of heat exchange and separation for the synthesis of operating procedures in our subgraph-isomorphism framework. The method is successfully applied to a double effect evaporator.

1. Introduction

A sequence of unit operation is required to produce target products in a given batch plant. The synthesis of the sequence can be defined as searching allowable sets of sequential operations and an initial state to realize a given final state without violating constraints. This problem is a complex problem and usually designed by human expert. In these days, small quantity and multi-purpose production become popular and the generation or changes of operating procedures become frequent. Operating procedures are usually generated by human experts and it requires considerable amount of time and efforts. The requirement of automatic generation of operating procedures is get-

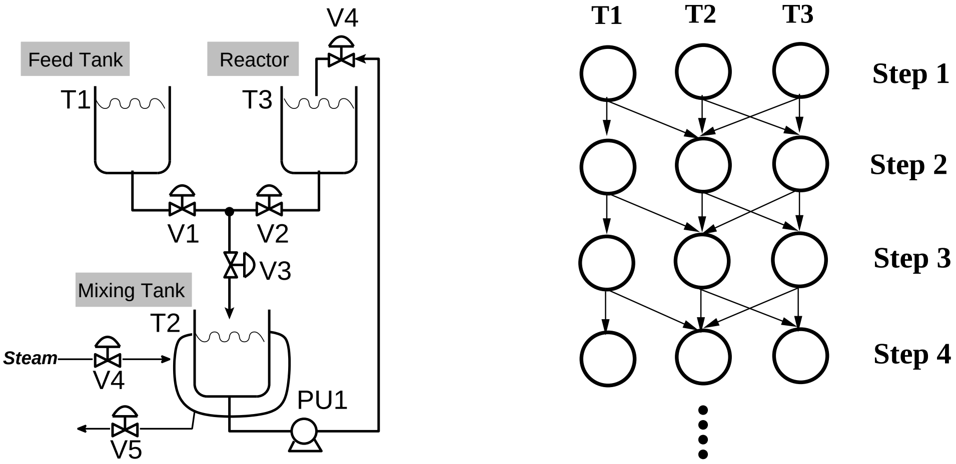


Fig. 1 The example plant and corresponding sequential plant-structure graph

ting increased to improve the efficiency. It is also required to verify the generated operating procedures for the improvement of the reliability and the safety.

Several approaches have been investigated for the automatic synthesis of operating procedures of a chemical plant. Viswanathan *et al.* proposed a synthesis method based on the Grafset, a discrete event model concept[1]. Aylett *et al.* applied AI planning tool to the synthesis of operating procedures of a chemical plant[2]. We have proposed directed graph representations and recursive algorithm to solve this problem[3, 4]. Recently, we introduced a subgraph isomorphism framework to this problem domain[5]. Short summary of the subgraph isomorphism framework will be described in section 2.

In this paper, our subgraph isomorphism framework is extended so as to deal with heat exchanges and chemical separations. For these purposes, the concept of heat resources is introduced as the addition of material-conversion graph. Moreover, the output from one node is extended to have multiple materials in the material-conversion graph. Finally, the method is demonstrated on the double-effect evaporator plant to generate operating procedures.

2. Method

To generate a sequence of operating procedures for a production of a specific product by a given plant, the knowledge about connectivity of plant equipments and the knowledge about operations for material conversions and energy conversions are required at least.

2.1 Plant Structure

In this study, the connectivity of plant equipments is represented as a digraph named sequential plant-structure graph[3], which can also deal with state transitions of the plant. For example, a simple example plant shown in Fig. 1 is converted into the sequential structure-graph are shown in the right side of the figure. In this representation, each nodes represents process equipment and each directed arcs represents the direct connectivity between equipments. Here, valves and pumps are implicitly included in the arcs. For example, arcs from T1 to T2 include valves V1 and V3, and arcs

name	type	conversion procedures	equipment constraints
UP1	Reaction	$A \rightarrow B$	T2
UP2	Reaction	$C \rightarrow D$	T2
UP3	Mixing	$B + D \rightarrow E$	T1,T2,T3

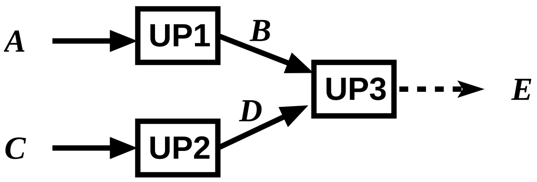
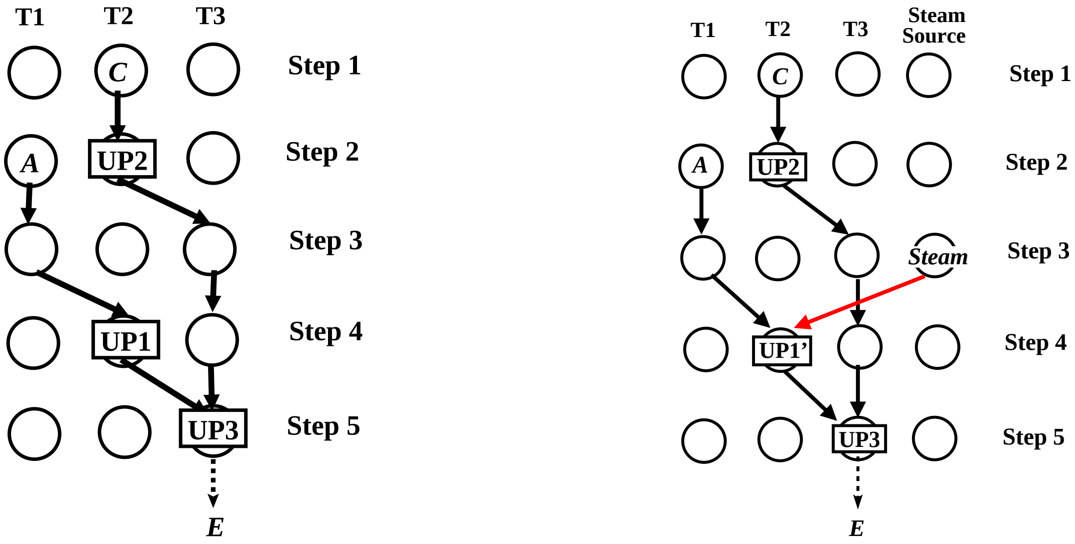


Fig. 2　Unit operations for material conversions and the material-conversions graph



(a) without heating

(b) with heating

Fig. 3　One of the feasible operating procedures to produce E in the example plant

from T2 to T3 include PU1 and V4. Each lines of the graph is corresponding to a time step, which duration of time is not constant. Nodes in the same column are the same equipments in different time steps. Each arcs represents a material flow between the connected equipments. Arcs connected to the same equipment represent the state of holding the contents in the same equipment.

2.2　Material Conversion Procedures

The knowledge about unit operating procedures and material conversions is represented by digraph named material-conversion graph1). For example, the knowledge about unit operating procedures and material conversions listed in the left side of Fig. 2 is converted into the material-conversion graph as shown in the right side. Here, the start points represent raw materials and the goal point is the target product E. Other nodes represent a sequence of unit operations to convert the connected materials. The materials B and D, those are produced by unit operations UP1 and UP2, are implicitly included in the arcs to the node UP3.

2.3　Synthesis by Subgraph Isomorphism

The synthesis of operating procedures to produce a target material is the task to find path of material conversions from raw materials to the target materials and to allocate the each conversion procedures on a specific equipment. This problem is to find out if the plant-structure graph contains a subgraph that is isomorphic to the material-conversion graph, or find all such isomorphic subgraphs. Cordella *et al.* have developed an efficient

name	type	procedures	equipment constraints
UP1’	Reaction & Heating	$A + \text{(Heat)} \rightarrow B$	T2

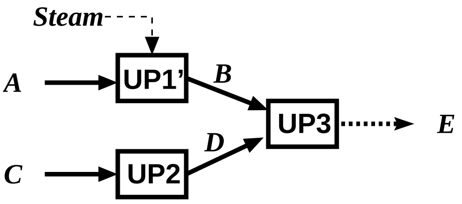


Fig. 4 A modified procedures for material and energy conversions

name	type	procedures	equipment constraints
UP4	separation	$X \rightarrow Y + Z$	T3

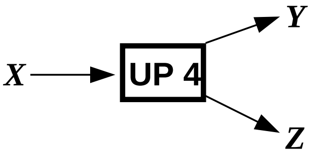


Fig. 5 Example of a separation operation

algorithm for graph-subgraph isomorphism[6]. We implemented the algorithm with special consideration to solve this problem[5].

Applying to the practical problem, many kinds of restrictions must be considered to get the appropriate procedures. Typical restrictions for chemical plants are avoidance of contaminations, possible equipments for a specific operation, and so on. In this study, these restrictions are treated as the constraints during the search of the solutions. Figure 3(a) shows one of the feasible solutions of the operating procedures to produce E.

2.4 Energy Conversion Procedures

To deal with unit operations such as the heat exchange, conversion and transfer of the energy must be considered. Let us consider about the jacket heating in Fig. 1. In this example, the first unit operation is replaced to a reaction with heating by considering about the heating (Fig. 4). The material conversion is the same but the term (Heat) in the conversion procedures is introduced here. This term means that the operation includes heat exchange, and requires a heat source. The source of utilities are also introduced, because most of the heat exchanges in process plants are using such utility lines as steam and water,

By using this definition, the subgraph isomorphism algorithm can be used to generate the operating procedures for a plant including energy conversions. An example of material-conversion graph including energy conversions is shown in Figure 4. Figure 3(b) shows an example of operating procedures for the example plant. In this figure, a line from *Steam* to UP1’ provides steam from the heat source to the tank T2, then the UP1’ operation convert the material A to B.

2.5 Separation Procedures

Separation operation did not treated in the previous study[5], because each nodes in the material-conversion graph has only one output arc. In this study, this restriction is removed to have multiple output arcs from one node. Implementation of the graph-subgraph matching was improved to satisfy this functionality. As the result, separation operation can be treated in the same framework. The node UP4 in Fig. 5 shows an simple example of the material conversion with separation operation.

3. Case Study

To demonstrate the ability of the proposed algorithm, the synthesis of operating procedures for the start-up of a double-effect evaporator$^{2)}$ is investigated here. Figure 6 shows the schematic flow of the target plant. The purpose of this plant is to remove water from a salt water solution. This plant is called double-effect, because the steam that is evaporated off from the salt-water solution in the first evaporation is used to supply the energy for the second evaporation.

In this plant, the salt water SW is fed from the feed tank FT, preheated in Glass Heater GH and heated in Heat Exchanger HE1, and evaporated in the first stage evaporator EV1. The steam ST generated by the first stage evaporator is used as a heat source in the second stage evaporator EV2. The separated liquid $LQ1$ in EV1 is heated in HE2, and evaporated in EV2. Finally, steam is collected by barometric condenser BC1, then water WT is obtained in tank TK2, and liquid product $LQ2$ is obtained in tank TK1.

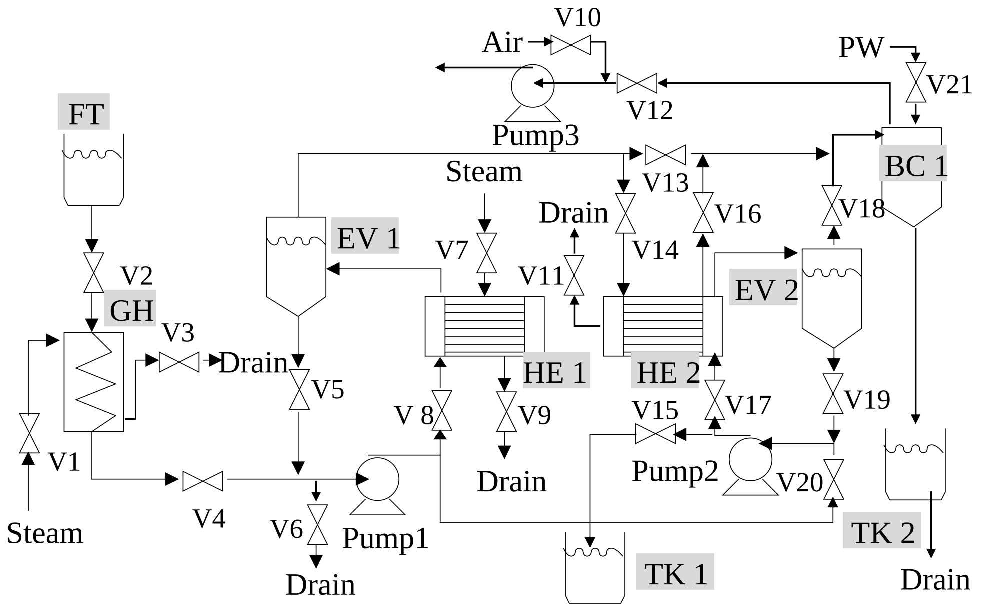
This plant includes heat exchangers and evaporators, which requires both the material flow and the energy flow. Material and energy conversion procedures for this plant is described in Table 1. In this table, UP1, UP2 and UP4 are the operation for heating, and UP6 are the operation for cooling.

By representing the plant structure as the structure graph (Fig. 7), material and energy conversion procedures as the conversion graph (Fig. 8), the proposed algorithm was applied to generate the operating procedures. Figure 9 shows an example of the generated matched graph representing the operating procedures to produce the target product $LQ2$ in TK1 and WT in TK2. Each arcs in the graph shows material transfer, where the operation of valves and pumps are implicitly included. The matched graph can be easily interpreted to a sequence of operations as shown in Table 2. In this table, operations such as evaporation and heating are corresponding to the nodes having the name of unit operations in the matched graph. Activation of valves and pumps are corresponding to the arcs in the graph. Initially, all the valves are supposed to be closed and no pumps are working. After completed operations in each steps, each valves must be closed to move to the next step, if it is opened again in the step. Final lines in steps 3, 5 and 8 do not require any valve operations, because the equipments are connected directly without any valves. The initiation time and condition of each operation steps are not considered.

By watching this operating procedures, the sequence of operations seems very reasonable. The operation of double effect is also realized by the transfer in step4. Although the algorithm could generate many possible solutions, the selection of appropriate solution will be the future work.

4. Conclusion

A subgraph-isomorphism framework for the synthesis of operating procedures for chemical plant is extended to deal with the operations of heat exchange and separation. This extension enables the consideration of operations related to the utilities such as steam and process water for various plants. The proposed method was demonstrated on the double-effect evaporator plant and confirmed that it generates very reasonable operating procedures automatically.



FT : Feed tank GH : Glass Heater HE : Heat Exchanger Ev : Evaporator
V : Valve TK : Tank BC : Braometric Condenser PW: Process Water

Fig. 6 The double-effect evaporator (DEE)

Table 1 Material and energy conversion procedures for the case study problem

name	type	conversion procedures	equipment constraints
UP1	Preheating	$SW + \text{(HEAT)} \longrightarrow SW'$	GH
UP2	Heating	$SW' + \text{(HEAT)} \longrightarrow SW''$	HE1, HE2
UP3	Evaporation	$SW'' \longrightarrow ST + LQ1$	EV1, EV2
UP4	Heating	$LQ1 + \text{(HEAT)} \longrightarrow LQ1'$	HE1, HE2
UP5	Evaporation	$LQ1' \longrightarrow ST' + LQ2$	EV1, EV2
UP6	Condensation	$ST - \text{(Heat)} \longrightarrow WT$	BC1
UP7	Condensation	$ST' - \text{(Heat)} \longrightarrow WT$	BC1

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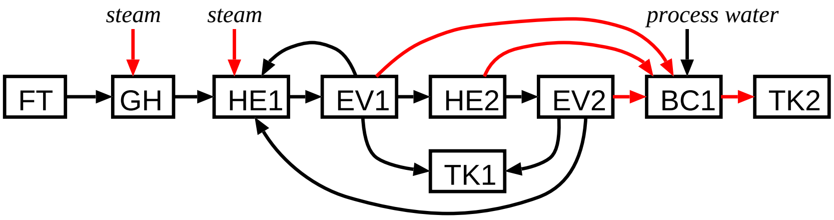

Fig. 7 Plant structure graph for the DEE plant

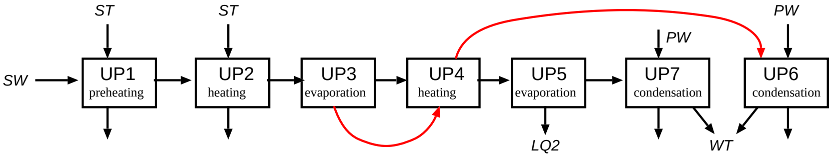

Fig. 8 Material and energy conversion graph for the DEE plant

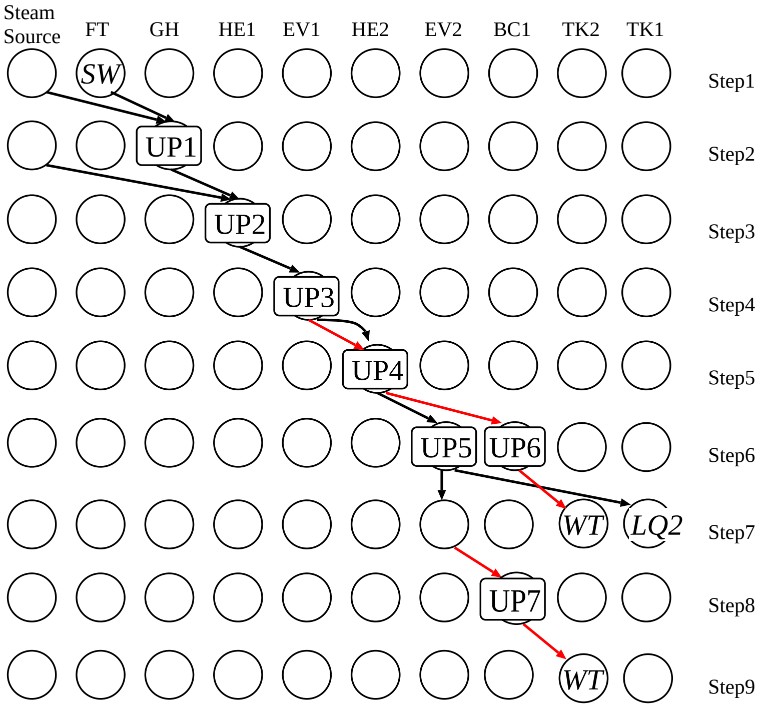

Fig. 9 An example of generated procedures for the DEE plant

Table 2 Interpretation of the generated procedures for the DEE plant

step	operation	activation of vales or pumps
step1	Prepare *salt water* in FT	
	Transfer the contents of FT to GH	by opening V2
	Transfer *steam* to GH	by opening V1
step2	Preheat in GH	
	Transfer the contents of GH to HE1	by activating Pump1, V4 and V8
	Transfer *steam* to HE1	by opening V7
step3	Heat in HE1	
	(Transfer the contents of HE1 to EV1)	
step4	Evaporation in EV1	
	Transfer the vapor from EV1 to HE2	by opening V14
	Transfer the liquid from EV1 to HE2	by activating Pump1, Pump2, V5 ,V20 and V17
step5	Heat in HE2	
	Transfer the vapor from HE2 to BC1	by opening V16
	(Transfer the liquid from HE2 to EV2)	
step6	Evaporation in EV2	
	Condensation in BC1	
	Transfer the vapor from EV2 to BC1, then TK2	by opening V18
	Transfer the liquid from EV2 to TK1	by opening V15
step8	Condensation in BC1	
	(Transfer the contents of BC1 to TK2)	