Recycling in a Separation Process Structure

Z. Kovacs, F. Friedler, and L. T. Fan
Dept. of Chemical Engineering, Kansas State University, Manhattan, KS 66506

Separation sequencing or network synthesis is a subfield of process synthesis that is of mathematical interest as well as industrial significance; various methods have been proposed for it (Hendry and Hughes, 1972; Thompson and King, 1972; Westerberg and Stephanopoulos, 1975; Seader and Westerberg, 1977; Nath and Motard, 1981; Floudas, 1987; Wehe and Westerberg, 1987; Mocsny and Govind, 1989; Huang and Fan, 1990). For either a heuristic or mathematical programming method of separation sequencing or network synthesis, it is of vital importance to identify the class of structures that may possibly be optimal. A heuristic method generates a separation process structure that can be deduced from its rules, and a mathematical programming method determines a structure embedded in the "superstructure." If the heuristic rules or initial superstructure is not sufficiently complete, an appreciable fraction of potentially optimal structures might be excluded from consideration. Whether the optimal structure of a separation network synthesis problem may contain loops remains an open question. Resolving this question is pertinent both theoretically and practically, since a validated mathematical model has been hitherto unavailable for this important class of synthesis problems.

For the extremely simple case, that is, for the production of pure products from one feed stream by simple and sharp separators, it has always been assumed, but never rigorously proved, that the optimal structure of a separation network cannot contain loops (see, for example, Nishida et al., 1981). While the assumption has probably been satisfied for such a simple case, it may be invalid for some separation problems of practical importance, such as the case of multiple feeds or multicomponent products.

In examining the mathematical programming formulation of separation sequencing, Floudas (1987) has introduced a theorem stating that for a relatively simple problem involving only one three-component feed stream and two three-component product streams, the structure involving recycling or that containing a loop cannot be optimal. While the theorem should be valid for this simple problem, the proof given does not appear to be sufficiently rigorous even for the simple system considered (Csallner, 1992). Obviously, therefore, it is extremely difficult, if not impossible, to generalize the theorem and the approach for its proof to include more complex classes of problems, such as those involving multiple feeds.

In general, an algorithmic method excludes loops directly by imposing an assumption (see, for example, Wehe and Westerberg, 1987), and a heuristic method excludes loops indirectly by adopting heuristic rules that generate only loopless structures (Nishida et al., 1981). Because of its nature, a heuristic method cannot be expected to generally yield the optimal solution for any arbitrary problem. Nevertheless, it is obvious that any effective heuristic method should not exclude the optimal solution from consideration for any problem, and thus, the incorporation of loops should also be of concern to a heuristic method.

The objective of this note is to demonstrate with an example that the optimal structure of a separation system may contain a loop. Specifically, it is numerically illustrated that recycling should be allowed in the minimum cost separation system.

Example of an Optimal Structure Involving Recycling

Suppose that three product streams are to be generated from two three-component feed streams as indicated in Table 1. In this example, both feed streams contain components A, B, and C; product stream 1 contains component A; product stream 3, component C; and product stream 2, components A and B. These product streams are to be produced by simple and sharp separators, dividers, and mixers. The components in a stream forming a ranked list are arranged in the descending order of a certain chemical or physical property, such as relative volatility and particle size, on which the separation is based. Moreover, the order in this list remains invariant and is un-

Table 1. Pertinent Data for the Example

	Component Flow Rate		
	A	B	C
Feed stream 1	80	9	12
Feed stream 2	3	3	90
Product stream 1	81	0	0
Product stream 2	2	12	0
Product stream 3	0	0	102
Deg. of difficulty of sep.		1	1

Correspondence concerning this article should be addressed to L. T. Fan.
Z. Kovacs is with the Dept. of Comp. Sci., JGYTF, Szeged, Hungary.
F. Friedler is on leave from the Dept. of Systems Eng., Research Inst. Tech. Chem., Hungarian Academy of Sciences, Veszprém, Hungary.

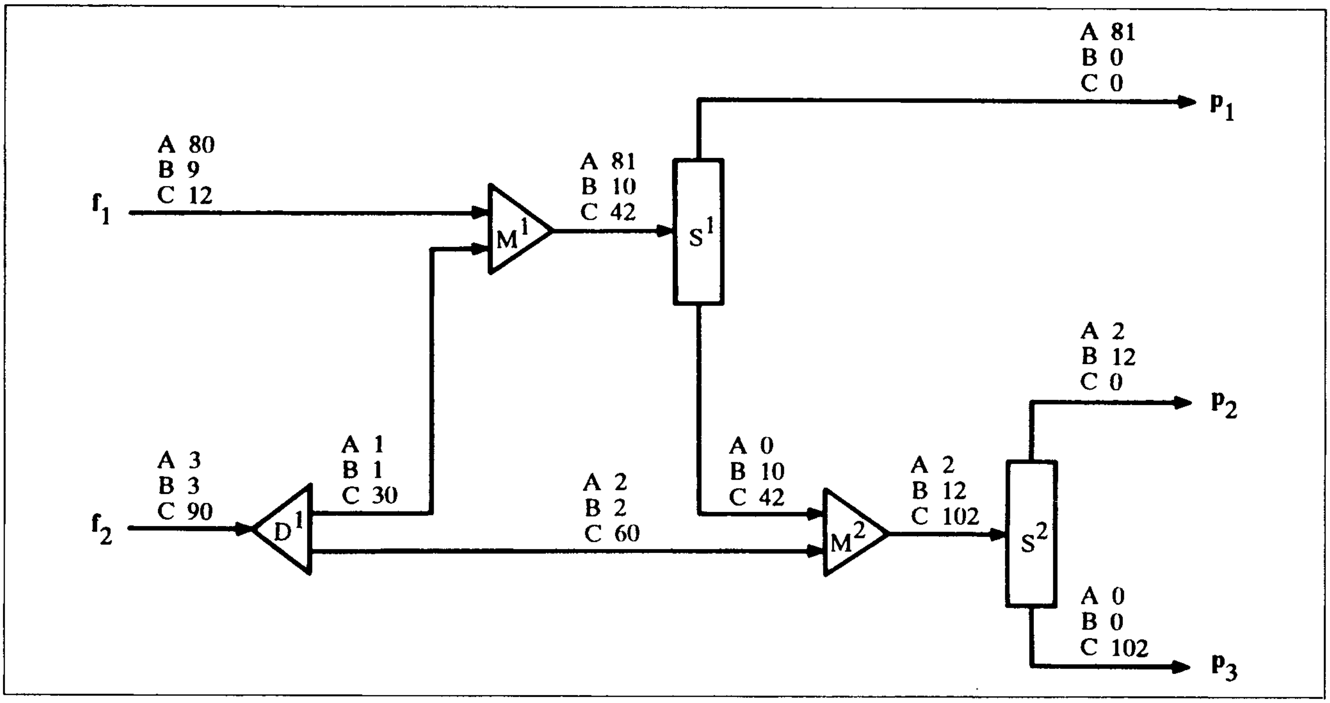

Figure 1. Separation structure costing 36.13.

affected by elimination of any component from the stream during the separation. When two sublists are generated from the list by a separator, any component in the higher ranked sublist will stay higher than any component in the lower ranked sublist. The cost of each separator, c_i, is calculated by the expression:

$$c_i = (f_i D_i)^b$$

where f_i is the massload of the ith separator, D_i is the degree of difficulty of the ith separation, and b is a constant between 0 and 1, whose value here is taken to be 0.6. The cost of the

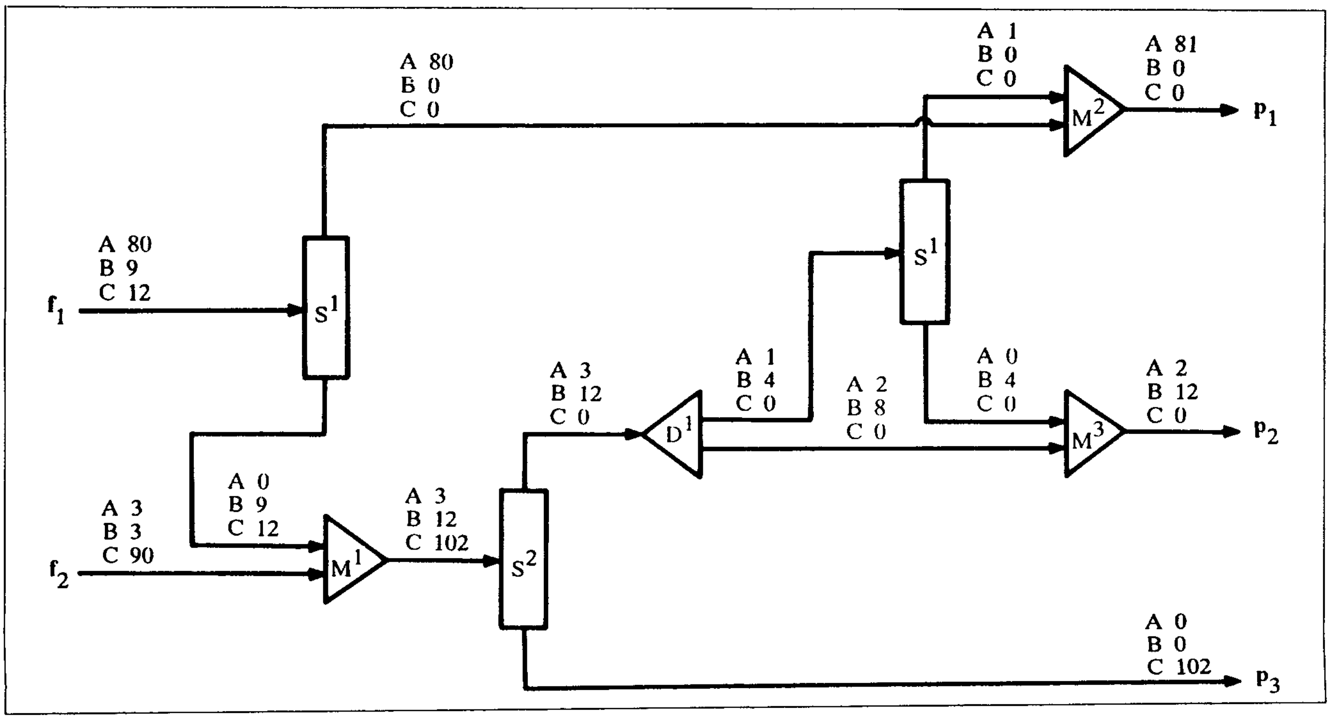

Figure 2. Optimal loopless separation structure costing 35.98.

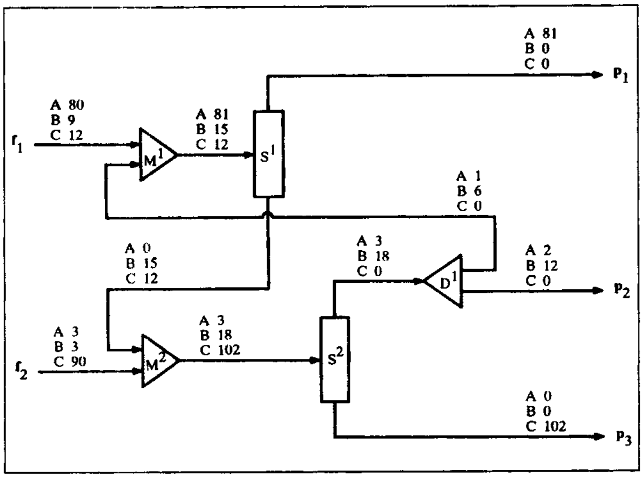

Figure 3. Optimal separation structure containing a loop and costing 34.54.

resultant separation system is the sum of the costs of individual separators in the network.

Minimization has been carried out by resorting to an available global optimization algorithm (Csendes, 1990), with and without excluding redundancy and/or recycling. The optimal structure of Figure 1 has been obtained if both redundancy and recycling are excluded; it costs 36.13. The optimal structure of Figure 2 has been obtained if only recycling is excluded; it costs 35.98. Nevertheless, the optimal structure of Figure 3 has been obtained if neither is excluded; it costs 34.54. Obviously, it is superior to the structures of Figures 1 and 2. Note that although all the costs have been calculated with $b=0.6$, the above statement has been numerically verified for other values of b, for example, $0.4<b<0.7$. This example belongs to the class of problems, which is the simplest and yet involves recycling in their optimal solutions. Recycling, however, is not involved with an even simpler class of problems, such as the one in which each has one feed stream or two component feed streams. Since the present example may be embedded in more complex problems, the occurrence of recycling should also be of concern to these complex problems.

Concluding Remarks

This note unequivocally demonstrates that incorporation of a loop can enhance the optimality of a separation sequence or network. The numerical example given may constitute a definitive example countering a prevailing heuristic rule adopted or invalidating a major assumption imposed in separation sequencing or network synthesis. Such a heuristic rule or assumption asserts that a structure with a loop cannot be optimal. This implies that in the detailed design of a separation process, incorporation of recycling should be taken into account. Nevertheless, it should be cautioned that a variety of practical considerations, such as costs of mixers and dividers, piping complexity, pumping energy, maintainability, and controllability, may overshadow the desirability of recycling in an actual separation network.

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