CHEMICAL ENGINEERING TRANSACTIONS
VOL. 70, 2018

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870186

Synthesis of Processing Systems Taking into Account Reliability

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Reliability is one of the most important properties of processing systems because of its high level direct effect on the investment and operational costs. Still there is no general method that is capable of simultaneously considering the reliability during the design procedure of processing systems. The main reason of the lack of general method is that the process systems design and the reliability engineering are based on different types of mathematical modeling tools. While process systems design is traditionally considered as mixed-integer optimization, reliability engineering is based on probability theory. The enumeration of the alternative feasible solutions of a redundant processing system is highly combinatorial, and, therefore, it is very difficult if possible to embed it into the widely used mixed-integer programming procedure.

For the simultaneous consideration of the costs and reliability in process systems design, general modeling tool is required that can conveniently cover the two areas. In the present work, it has been shown that the formerly developed axioms based combinatorial approach to process network synthesis (PNS), the so-called P-graph framework, can conveniently cover and integrate these two aspects. The interface between the synthesis and the reliability analysis steps of process systems design is established on the basis of the axioms of combinatorially feasible processing networks. Since the combinatorial feasibility and the structural operability are closely related terms, their simultaneous consideration hardly increases the complexity of the procedure.

The method for processing systems synthesis with simultaneous consideration of reliability is general and capable of effectively designing complex, highly interconnected processing networks with large number of redundant operations. The focus of the present work is on structures of processing systems, all statements and algorithms are general. The solutions of the synthesis of the HDA process have also been given.

1. Introduction

Process systems design has traditionally been performed by decomposing the overall problem into a sequence of subproblems. One of the original and best known approach was developed by Douglas (1985) called as hierarchical approach. The consecutively solved substeps of these design procedures are not independent, therefore, no guarantee can be given for the optimality of the result. In practice, the solution of these decomposition based sequential methods is frequently far from the optimal solution. Consequently, it is both conceptually and practically important to integrate these steps or at least few of them. For this reason, the integration of cost driven synthesis of processing systems and their reliability considerations is one step ahead in this direction. Then, the integrated method is capable of determining the optimal solution or the best solutions for the combined problem. Because of modelling difficulties, no general method has been developed that combines the cost related models with reliability models.

There are only few major contributions published that takes into account systems reliability in process design. Pistikopoulos et al. (1996) optimized the redundancy of the equipment units in designing a process. Terrazas-Moreno et al. (2010) considered both reliability and flexibility in optimizing the production capacities, the intermediate storages, and the redundancy on the production units. Goel et al. (2002) retrofitted a HDA process with additional structural options.

Please cite this article as: Orosz A., Kovacs Z., Friedler F., 2018, Synthesis of processing systems taking into account reliability , Chemical Engineering Transactions, 70, 1111-1116 DOI:10.3303/CET1870186

For the embedding of reliability consideration into process design, a general modeling technique is required that can appropriately describe the two areas. In the present work, the formerly developed axioms based process network synthesis (PNS) method, the P-graph framework (Friedler et al., 1992b) has been adapted for covering and integrating these two areas. The key point is the joint consideration of process feasibility of process design and process operability of reliability engineering. Since both items are highly structural, P-graph framework can conveniently represent them together in an integrated procedure.

Benjamin et al. (2016) have successfully applied the P-graph framework for risk based criticality analysis of a bioenergy park under an event of reduced production capacity. In Benjamin (2017), the criticality analysis of a bioenergy park has been performed under uncertain demand. Tan et al. (2015) minimized the dysfunction of a processing system because of inoperability of some operations.

P-graph framework is based on the fundamental structural properties of feasible processing networks. Since these structural properties are general and independent of the types of mathematical models of the operating units, the framework is also general. In the current work, linear mathematical models with fixed charge cost functions describe the operating units. Naturally, the method can simply be implemented for nonlinear mathematical models of the operating units.

The failures of operating units in a system are supposed to be independent and time invariant. Furthermore, an operating unit can either be functional or non-functional; the probability of the functionality of an operation is given as a parameter for its reliability.

2. Brief introduction to the P-graph framework

The P-graph framework represents a processing network by a directed bipartite graph of the operating units and the materials. A process network synthesis (PNS) problem is given by the sets of operating units, raw materials, and products. The optimal solution of the problem is to be given as a subset of the set of operating units that represents the related P-graph as the network of the process. Naturally, the set of operating units of a feasible process, including the optimal process, must satisfy certain structural (combinatorial) properties. For example, each product must be produced by at least one operating unit from this set of operating units. Also, if a material is consumed by at least one operating unit and not produced by any of them from this set, this material must be a raw material. In the P-graph framework, these types of combinatorial properties of the feasible process networks are collected and formally identified as set of five axioms (Friedler et al., 1992b). Networks of operating units satisfying the five axioms are called combinatorially feasible networks. Therefore, the network of each feasible process must be combinatorially feasible. Consequently, the search for the optimal network can be reduced to the set of combinatorially feasible networks. In practice, the set of combinatorially feasible networks is a small subset of all sets of networks (Peters et al., 2003). There are algorithms exploiting this property of networks resulting in a big acceleration in the search for the optimal network.

Algorithm MSG (Friedler et al., 1992a) is for generating the so-called maximal network (super-structure) that is the minimal among networks that include all combinatorially feasible networks. Algorithm SSG (Friedler et al., 1992a) is capable of generating the whole set of combinatorially feasible networks, while algorithm ABB (Friedler et al., 1996) is an accelerated branch-and-bound algorithm for generating the optimal network. These algorithms are the building blocks of process network synthesis simultaneously considering reliability constraints.

3. Reliability formula for a processing system

Though it is easy to determine the reliability of specific systems, e.g. for series or parallel systems (Birolini, 2007), no formula is known for general, highly interconnected processing systems with redundant operations that may include several loops. Now, a general formula is to be given for determining the reliability of any system that can be highly interconnected without any limitations on the network.

Suppose that there are n operating units on the maximal network, each of them has a binary state expressing its functionality. In binary vector $X=(x_1, x_2,\ldots,x_n)$, x_i is supposed to be 1 if unit i (i= 1, 2,…,n) is functional, otherwise it is 0. The network of the functional operating units given by X is a subnetwork of the maximal network. The operability of a subnetwork given by X is to be determined next. First, the structural operability of the networks will be defined. A network is defined to be structurally operational if it has a combinatorially feasible subnetwork. Then, the operability of the network can be determined by testing the feasibility of this network provided that this network is proved to be structurally operational.

The test whether a network is structurally operational can effectively be done by polynomial algorithm MSG. Algorithm MSG was originally developed for generating the maximal network of a PNS problem if the maximal network exists. Here, the network to be tested is considered as a PNS problem, then, the algorithm determines if there is a maximal network for this problem. If the answer is positive, i.e., the maximal network exists, the network is structurally operational, otherwise not. Therefore, set U of operational networks can be determined by selecting the operational subnetworks determined by all binary n-vectors.

The reliability of unit i is denoted by p_i, (i=1, 2,…, n). The probability of the occurrence of subnetwork given by binary vector (b_1, b_2,…,b_n) can easily be determined as given in Eq(1), where P denotes the probability of an event.

$$P((x_1, x_2,...,x_n) = (b_1, b_2,...,b_n)) = \prod_{i=1}^{n} p_i^{b_i} (1 - p_i)^{(1-b_i)} \tag{1}$$

A network described by an n-vector can be considered as an event in terms of probability theory. Since events described by two different binary n-vectors are exclusive, their joint probability is the sum of their probabilities. Therefore, the structural reliability of the network of operating units is the sum of the probabilities of its structurally operational subnetworks given in set U as shown by Eq(2).

$$P(U) = \sum_{(x_1, x_2,..., x_n) \in U} \prod_{i=1}^{n} p_i^{x_i} (1 - p_i)^{(1-x_i)} \tag{2}$$

Note that set U depends only on the process network, thus, the reliability formula gives the reliability of the process for any values of p_i, (i=1, 2,…, n). This formula is general, valid for any processing network.

4. Process synthesis taking into account reliability

In Section 3, the structural reliability of any system represented by the P-graph has algorithmically been determined. This algorithm can be integrated into the combinatorial algorithms of processing network synthesis. Consequently, the integrated method will be capable of synthesizing processing networks which simultaneously considers the structural reliability and the cost of the process.

The approach is primarily based on P-graph algorithms. The structural part of the synthesis problem is given as a P-graph, then algorithm MSG determines the maximal network. After that, algorithm SSG generates all combinatorially feasible subnetworks of this maximal network to evaluate them for both cost and reliability. The cost of a subnetwork is determined by known P-graph algorithms. The structural reliability is given by Eq(2). Then, the optimal solution or solutions can simply be selected.

The procedure given here is general, it is independent of the types of the mathematical models of the operating units. Since this procedure represents process networks explicitly, the procedure can simply be combined with simulation programs. Then, the feasibility of the process described by a combinatorially feasible network can directly be determined by the simulation program. Also, the feasible networks can automatically be evaluated by the simulation program for the selection of the optimal solution.

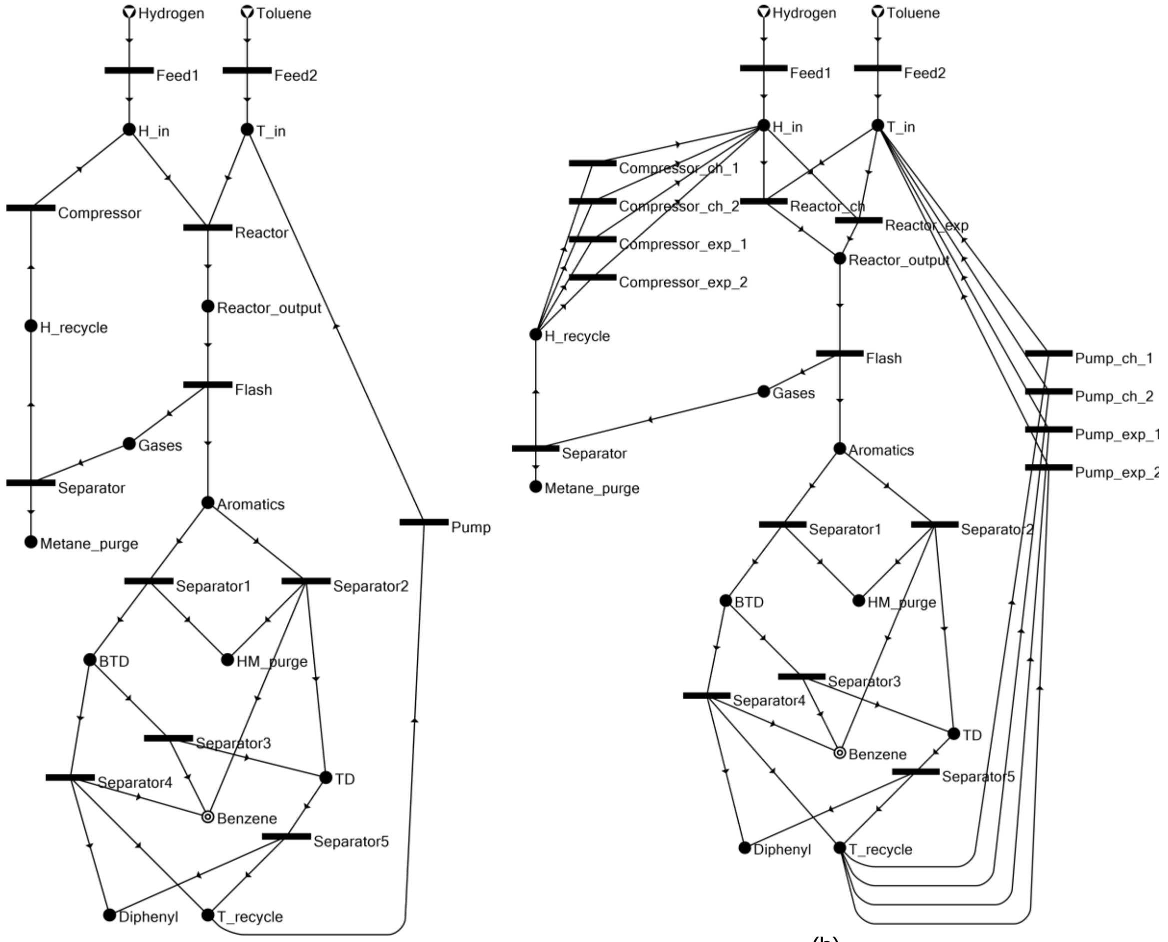
5. Case study

The well-known HDA process (Douglas, 1985) has been examined, the corresponding maximal network is shown on Figure 1(a). To satisfy the conditions on the systems reliability, redundant operations are considered on the maximal network, especially, for reactor, pump, and compressor units. The reliability and cost data of the operating units are given in Table 1. In general, there is no limitation on the possible combinations of the redundant units. For practical reasons, however, it is supposed here that only one reactor, at most two pumps, and at most two compressors may appear in a process to be synthesized. All cost data are given in Currency Unit (CU) for comparison.

The maximal network with redundant operations is shown on Figure 1(b). The operating units are described by linear models with fixed charge cost functions. There are 28551 combinatorially feasible networks of maximal network of Figure 1(b). Algorithm SSG is capable of generating and evaluating these 28551 networks in a few seconds on a regular notebook computer. The limitations on the number of redundant operations specified in the problem definition reduce the number of networks. Under these conditions, algorithm SSG generates 150 networks. 96 of the 150 networks satisfy the feasibility test on material constraints and operating unit capacities. The 96 feasible solutions are shown on Figure 2 as their costs vs. probabilities of failure. Both measures are important when selecting the most preferred solution or solutions. For this reason, the Pareto-solutions are highlighted on Figure 2. The process network of one of the Pareto solutions is given on Figure 3. There is only one redundant operation in this solution, it is the pumping. All Pareto solutions can be further examined by a simulation program for a more detailed design and further selection.

Table 1: Reliability and cost data of the operating units of the case study.

Unit	Fix cost (CU)	Proportional cost (CU)	Reliability	Probability of failure	Max flow rate
Flash	1500	0.3	0.99995	0.00005	
Feed1	0	0.0	0.99995	0.00005	
Feed2	0	0.0	0.99995	0.00005	
Compressor_ch	1325	0.9	0.99000	0.01000	41550
Compressor_exp	2150	1.6	0.99950	0.00050	41550
Pump_ch	2815	5.2	0.99000	0.01000	
Pump_exp	5050	9.8	0.99700	0.00300	
Reactor_ch	10400	1.3	0.99600	0.00400	14150
Reactor_exp	21500	1.9	0.99920	0.00080	14150
Separator	2300	0.2	0.99990	0.00010	41550
Separator1	2400	0.3	0.99995	0.00005	25000
Separator2	10500	0.9	0.99950	0.00050	
Separator3	9600	0.8	0.99990	0.00010	14150
Separator4	10500	0.9	0.99950	0.00050	
Separator5	1600	1.2	0.99995	0.00005	



(a) (b)

Figure 1: Maximal network for the synthesis of the HDA process. (a) Original network of operations; (b) Network with redundant operations.

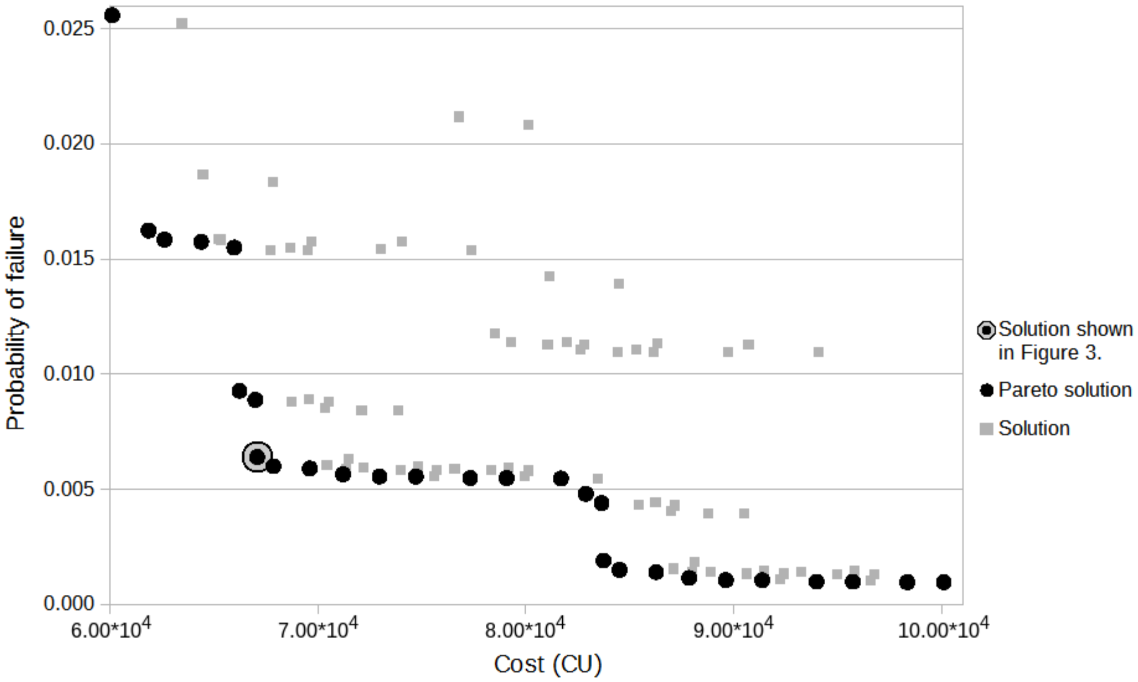


Figure 2: All combinatorially feasible solutions of the case study: probability of failures vs. cost.

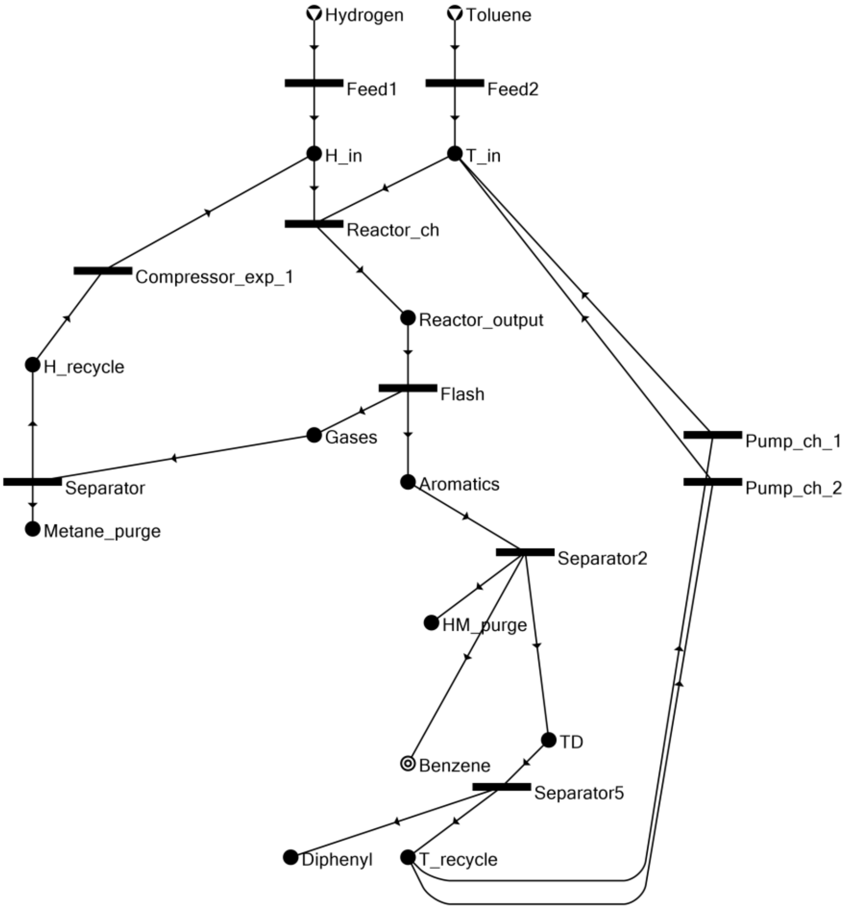


Figure 3: One of the Pareto optimal solutions identified on Figure 2.

6. Conclusions

A general procedure has been given to synthesize processing networks by simultaneously taking into account process reliability. This procedure is capable of effectively synthesizing complex, highly interconnected processing networks with large number of redundant operations. The procedure is general in terms of the mathematical models of the operating units, furthermore, it can be combined with simulation programs for automatic evaluation of processes during their synthesis. A formerly unavailable reliability formula of processing networks is also given for evaluating individual processing networks. The synthesis of the HDA process shows the practical impact of the proposed procedure.

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