CHEMICAL ENGINEERING TRANSACTIONS

VOL. 63, 2018

A publication of AIDIC

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

Guest Editors: Jeng Shiun Lim, Wai Shin Ho, Jiří J. Klemeš

ISBN 978-88-95608-61-7; **ISSN** 2283-9216

DOI: 10.3303/CET1863021

Systems Reliability, Footprints and Sustainability

Ákos Orosz[a], Ferenc Friedler[b,]*, Petar S. Varbanov[c], Jiří J. Klemeš[c]

[a]Department of Computer Science and Systems Technology, University of Pannonia, Veszprém, Hungary
[b]Institute of Process Systems Engineering & Sustainability, Pázmány Péter Catholic University, Budapest, Hungary
[c]Sustainable Process Integration Laboratory (SPIL), NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, Brno, Czech Republic
friedler.ferenc@ppke.hu

Systems reliability and availability are critical aspects that should be tackled simultaneously within process design, alongside the widely considered profit and environmental impacts affecting sustainability. In optimal process synthesis, the combination of process design with other aspects can be modeled by adding constraints to the problem formulation or by additional terms in the objective function. Independently of the formulation, the reliability and sustainability aspects have an adverse effect on the profitability of the process. Providing for sustainability in process design usually reduces the profit by increasing the cost. Reliability is considered in process design for improving the availability of the system. In this way, it acts in synergy with the other process factors to improve the profitability of the process. Improving process reliability, in addition to raising availability and direct profits, can also contribute significantly to reducing the risk of catastrophes, negative environmental impact and human injury. This contributes to the environmental and societal components of sustainability. Despite this potential advantage, the simultaneous optimization of reliability and sustainability improvement has not been considered. This work introduces a new method to consider reliability and sustainability in process design as an important extension of the basic process design. The result is illustrated by the design of a process considering profitability, sustainability and reliability simultaneously.

1. Introduction

Three main areas of research are related to the present work: process design, reliability engineering, and sustainability. Process design has five decades of history with an enormous number of publications and industrial applications. Our purpose is to extend process design to a simultaneous reliability and sustainability consideration. To make this extension, first, we have selected a process synthesis technology as a basis for the work. The selection of the synthesis technology has been very obvious. Since process synthesis and the two additional items are highly structural, a framework based on the structural properties of feasible processes is expected to be the most appropriate for the purpose. This is the P-graph framework established in 1992 (Friedler et al, 1992). It is based on a special bipartite graph representation of process structures (called as P-graph, see Figure 1a) and a set of axioms of combinatorially feasible process structures. The framework also includes effective algorithms. For example, algorithm MSG and SSG for the generation of the super-structure (called as maximal structure) and the feasible process structures (Friedler et al, 1995), and an accelerated branch and bound algorithm, algorithm ABB, for generating the optimal solution of a synthesis problem (Friedler et al, 1996). Additional tools have extended the framework to a wide range of applications from reaction engineering to supply chain management. The P-graph framework is also useful as an appropriate interface among the three areas covered by this paper.
The reliability of a processing system is usually defined as the probability that the system is able to perform its designated task at a sufficient level during a given time period. Many studies have been published on the reliability of binary coherent systems discussed by review studies (Birolini, 2007). Most deterministic methods consider problems with specific structures or use a method which requires an externally specified operability function for the system (Kim and Kang, 2013). When handling problems with complex structures, approximation or simulation methods are used (Praks et al., 2015).

Please cite this article as: Ákos Orosz, Ferenc Friedler, Petar S. Varbanov, Jiří Jaromír Klemeš, 2018, System reliability, footprints and sustainability, Chemical Engineering Transactions, 63, 121-126 DOI:10.3303/CET1863021

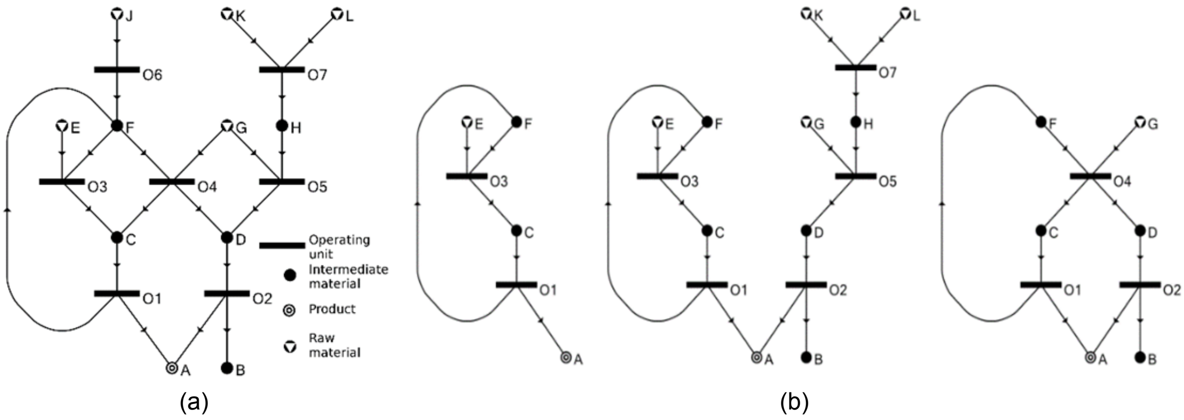

Figure 1: (a) P-graph - the maximal structure of the case study (b) *Three of the 19 combinatorially feasible structures of the maximal structure shown in (a)*

The consideration of sustainability in process design has received a high level of attention recently. Still, fundamental issues are to be solved. The most crucial question is how to consider profit and sustainability simultaneously. The P-graph framework offers theoretical background to answer this question. Varbanov and Friedler (2008) developed a synthesis method for fuel cell combined cycles taking into account both cost and carbon footprint. The book of Klemeš et al. (2010) gives an overall summary of process integration and sustainability also providing related P-graph applications. Cabezas et al. (2015) created a method on P-graphs for designing supply chain management focusing on sustainability. A useful tool for the decision makers is to illustrate the profitability of the alternative processes against sustainability on a so-called sustainability mapping. To do so, a systematic generation of all alternative solutions is needed, it can be done by one of the algorithms of the framework (Friedler et al., 1995).
No paper was found for considering all three parameters, the profitability, the sustainability, and the reliability concurrently. Using P-graph can be used as a binding modelling technique for evaluating these aspects simultaneously. The purpose of this paper is to provide a general procedure for designing a process by simultaneously taking into account its profitability, reliability and environmental footprint. The current paper provides the first step – the structural consideration. The data collection and evaluation procedure for the reliability levels and environmental impact assessment will be considered in a future work. The overall tool set development of the P-graph framework will need the full support of the P-graph user community (Varbanov et al., 2017). This new application will be supplied to the tool developers, in order to improve the pool of ideas and techniques, as well as to add to the pool of available case studies for community use.

2. Problem definition

The design problem is specified by the set of products to be produced, the set of available raw materials and utilities, and by the set of plausible operating units. The products are given together with the amounts to be produced in a certain period of time. The time period is considered throughout this paper as one year. The raw materials and the utilities are given by their unit price and their availability in the time period. Operating units transforms their inputs to their outputs by assigned equipment unit or units. In a process, one operating unit can be realised by one equipment unit or more than one equipment units simultaneously. Each equipment unit has its investment cost and an operating unit specific operating cost. Moreover, the maximal capacity, the reliability, and the environmental footprint for the maximal capacity are also assigned to each equipment unit. The process to be designed is selected on the basis of its profitability and environmental footprint while the process must satisfy the reliability requirement. The profit of a process is simply determined by deducting the cost of the process from the yearly income from selling the products. The cost of a process is the sum of the costs of the raw materials and utilities, furthermore, the cost related to the operating units. Finally, the cost of an operating unit in a process is determined by the costs of the assigned equipment units. The investment cost of an equipment unit is divided by the pay-out period, it is five years in this paper. The operating cost of an equipment unit is proportional to the realised capacity relative to its maximal capacity.
The reliability of the process to be designed is defined as the probability (on a 0 - 1 scale) that even after the failure of some equipment units, the remaining functional equipment units can produce all products.

3. Proposed method

Each component of the specified problem is highly structural and fits significantly to the algorithms of the P-graph framework. Since the common structural representation provides a basis for simultaneous consideration of all three of them, i.e., basic process design, reliability engineering, and sustainability consideration. The general policy in searching for the optimal solution or the best solutions is to eliminate the process structures from considerations that violate some combinatorial rules. For example, only those processes are examined during the basic process design that satisfies the five axioms of the P-graph framework. As an example, for an industrial process of 35 operating units, the search space of about 3.4 10^{10} structures is reduced to the set of 3,465 combinatorially feasible structures. Similarly, the set of the structures of the operable processes in the reliability examination is also reduced on the basis of combinatorial consequence. This enormous reduction makes it possible to evaluate the remaining process structures for sustainability by determining their sustainability mapping.

The proposed method first models the structure of the problem as a P-graph. This graph contains only the materials and operating units defined by the problem description. The maximal structure of the problem is determined by algorithm MSG (Friedler et al., 1993), which can be considered as superstructure including all potentially useful solutions. The maximal structure shown in Figure 1a includes 19 combinatorially feasible structures that satisfy the five axioms (Friedler et al, 1992). Three of the 19 structures are shown in Figure 1b. All combinatorially feasible structures can be generated by algorithm SSG (Friedler et al, 1995). Algorithm SSG is capable of generating each combinatorially feasible structure exactly once. Determining the reliability of a process of complex structure requires a special algorithm that is also based on the combinatorial tools of the P-graph framework. The result of the algorithm is the reliability formula of the process expressing its reliability depending on the reliabilities of the equipment units. For the structure shown in the centre of Figure 1b, suppose that each operating unit represents an equipment unit with reliability: p1, p2, p3, p5, and p7 for O1, O2, O3, O5, and O7.

First, the algorithm determines the structurally operational sub-structures. A sub-structure is structurally operational, if it has a combinatorially feasible substructure. A structurally operational structure is not necessarily combinatorially feasible. However, a combinatorially feasible structure is always structurally operational. Figure 2 shows two structurally operational substructures, the left is combinatorially feasible, while the right is not. Algorithm MSG of the framework is a proper tool for checking the property of being structurally operational. In process synthesis, it is important to note that not all structurally operational structures are capable of producing the products in the required amounts. The set of operational sub-structures is a collection of those structurally operational sub-structures that can generate products in the required amounts.

Since the system of the examined process is binary and coherent with independent failures, the probability of a given sub-structure can be easily determined. The probability assigned to the structure on the left side of Figure 2 is given by Eq(1), and the probability assigned to the structure on the right side of Figure 2 is given by Eq(2). The reliability function of a structure is determined as the sum of the probabilities of its operational sub-structures. The formula for determining the reliability of a process can be written as seen in Eq(3).

p1 x (1 - p2) x p3 x (1 - p5) x (1 - p7) (1)

p1 x p2 x p3 x (1 - p5) x (1 - p7) (2)

$$P(U) = \sum_{(x_1, x_2, \ldots, x_n) \in U} \prod_{i=1}^{n} p_i^{x_i} (1 - p_i)^{(1 - x_i)} \tag{3}$$

In Eq(3), U is the set of operational sub-structures, p_1, p_2, …, p_n are the reliabilities assigned to the operating units, and x_1, x_2, …, x_n are binary values determining whether an operating unit (via its equipment unit) is functional in the given sub-structure or not.

To include footprint in the model, a new type of node is introduced on the given P-graph. This node is connected to all operating units that have a footprint. The resultant P-graph is shown in Figure 3. The arcs from this node to an operating unit express the emission or other sustainability related parameter of the operating unit. When performing process network synthesis, the algorithms of the P-graph framework builds and runs linear programming models in this specific realisation to minimise the cost of a given structure. Since the new node of the footprint is also included in the model, the optimisation procedure also determines the footprint for a given solution.

Finally, in order to increase the reliability of the process, redundant equipment units can be included in the final design. To do so, an extended version of the SSG algorithm of the P-graph framework (Friedler et. al., 1992) was created. This algorithm first generates the combinatorially feasible structures of the maximal structure based on the operating units without redundancy in the equipment units. At the next step, it generates the solution structures by assigning a different number of redundant equipment units to an operating unit.

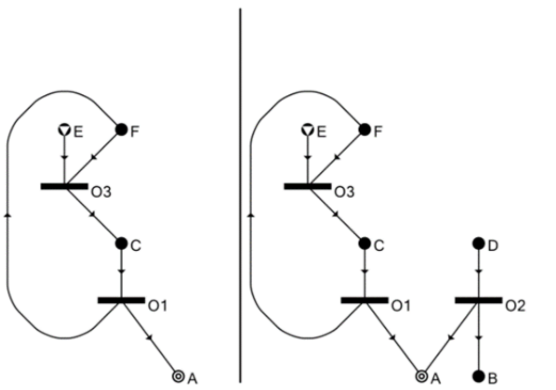

Figure 2: Two structurally operational sub-structures

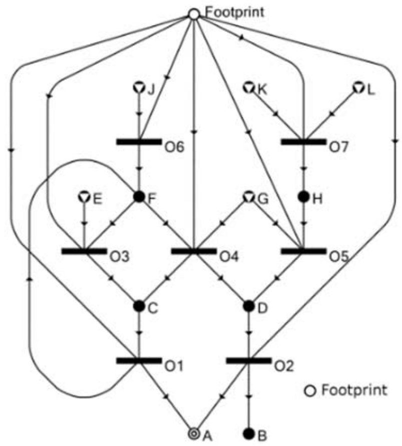

Figure 3: Sustainability is considered on the basis of the sum of the footprints of the individual activities

The algorithm to determine the set of solutions has the following steps:

1. The maximal structure is determined on the basis of input data by algorithm MSG.
2. The maximal structure is extended with a new node representing the footprint of each operating unit.
3. The set of combinatorially feasible structures is generated by the original SSG algorithm.
4. Single or multiple equipment units are assigned to each operating unit of the combinatorially feasible structures.
5. Feasibility test and optimisation for material flows and reliability: the cost and footprint are determined for each feasible structures of step 4 that satisfies the reliability constraints, these are the solutions of the problem.
6. The determination of the sustainability mapping for decision makers: each dot represents one solution.

4. Case study

The case study has been derived from the example in (Friedler et al, 1995). The maximal structure is given in Figure 1a. The process to be designed must produce one product from some of the 5 available raw materials. The process may include a subset of the 7 plausible operating units. The parameters of the operating units are collectively shown in Table 1. Each operating unit has two possible equipment units to select from during synthesis, each given in a separate row. From each equipment unit, a maximum of two can be installed in a process in parallel. For the 5 raw materials, there is a limited supply of 20 t/y, and each of them costs 4,000 €/t. The demand of the product is 40 t/y. While in the model the footprint is intentionally left abstract for flexibility, in the case study ecological footprint is given in the form of global hectares following the Sustainable Process Index (SPI) (Narodoslawsky and Krotscheck, 1995). The material flows and capacities are given in t/y, the costs are given in 1,000 €/y. The payout period for the investment is supposed to be 5 y. At the input and output materials of an operating unit, the material flow ratios are given in parenthesis. The reliability level values, specified in Table 1 are assumed in such a way, as to evaluate the efficiency and validity of the proposed model and algorithm. Figure 4 shows the solutions generated by the method, the reliability of each solution is at least 0.999. The vertical axis represents the realised profit (in 1,000 €/y) of the solution, the horizontal axis represents 1/Footprint (in 1/ha). A further solution from the origin is better in terms of profit or sustainability. The solutions represented by bold circles are the Pareto-optimal solutions. As it can be seen, numerous different processes can produce the products in the required amount with the assumed reliability, but only a few of them are to be considered during the decision making. Figure 5 shows the P-graph of one of the optimal solutions with 7.303 ha footprint, 409,225 € profit, and 0.9993 reliability. It is interesting to recognise that this process has a redundancy on the equipment unit level. Two identical equipment units are assigned to operating unit O1, they are O1/1 and O1/2 on Figure 5.

Table 1: Parameters of the operating units for the case study

Operating unit	Capacity (t/y)	Investment cost (1,000 €)	Operational cost (1,000 €)	Footprint (ha)	Reliability (1)	Inputs	Outputs
O1	25	16	0.6	0.15	0.9999	C(2)	A(1.5), F(0.5)
	15	10	1	0.1	0.9995		
O2	25	14	0.4	0.2	0.999	D(2)	A(1), B(1)
	20	20	0.5	0.1	0.9995		
O3	15	13	0.75	0.1	0.999	E(1), F(1)	C(2)
	12	12	0.3	0.15	0.999		
O4	7	10	0.6	0.05	0.995	F(1), G(1)	C(1), D(1)
	10	17	0.5	0.08	0.999		
O5	8	12	0.6	0.05	0.995	G(1), H(1)	D(2)
	5	15	0.3	0.1	0.999		
O6	15	15	1	0.08	0.999	J(1)	F(1)
	12	10	0.8	0.05	0.9995		
O7	10	18	1	0.07	0.9999	K(1), L(1)	H(2)
	20	23	0.8	0.05	0.999		

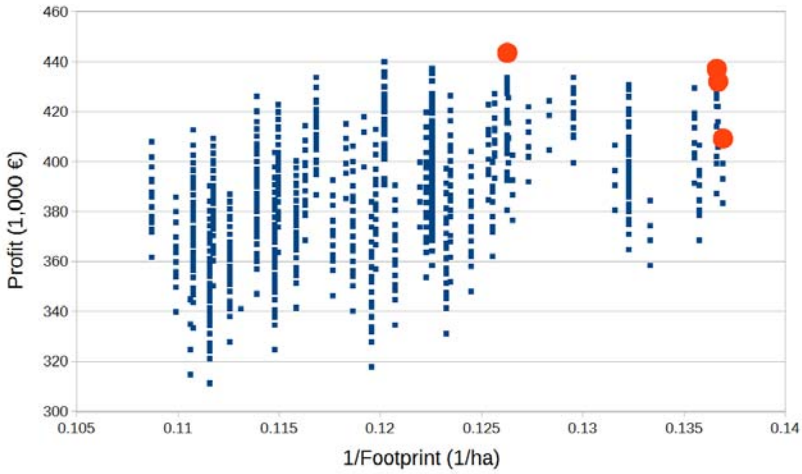

Figure 4: Sustainability mapping of the case study: each dot represents a solution for the design problem, bold dots are to be considered for selection

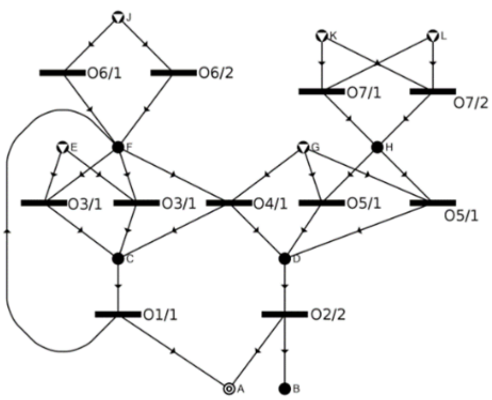

Figure 5: One of the optimal processes satisfying the reliability constraint

5. Conclusions

Process design has been extended to simultaneous consideration of profit, reliability, and sustainability. The proposed method is based on the P-graph framework that provides appropriate interfaces among the three areas. The new method generates all processes that satisfy the constraints on products, operating units, raw materials, and reliability. For each of these processes, the profit and footprint are determined. The sustainability mapping shows each solution as profit against 1/footprint for selecting the best solution that takes into accounts both profit and environmental impacts. As far as the case study illustrates, it is crucial to generate and analyse all solutions for selecting the best solution. It is also important to emphasise that processes with identical or similar profit may have a big difference in their environmental impact.
The provided case study is based on a hypothetical example, having mainly structural features – with the main goal to outline the key method features and set up the concepts. More concrete case studies should be developed in the follow up developments. Other key directions for improvement will be the identification of the footprint components for the SPI, as well as integrating the reliability and cost-benefit dimensions.

Acknowledgments

The project "Sustainable Process Integration Laboratory – SPIL", project No. CZ.02.1.01/0.0/0.0/ 15_003/0000456 funded by EU "CZ Operational Programme Research and Development, Education", Priority 1: Strengthening capacity for quality research supported by the collaboration agreement with Pázmány Péter Catholic University in Budapest, Hungary, has been acknowledged. The support of KAP project of Pázmány Péter Catholic University is also acknowledged.

References

Birolini A., 2007, Reliability Engineering, Springer, Heidelberg, Germany.
Cabezas H., Heckl I., Bertok B., Friedler F., 2015, Use the P-graph framework to design supply chains for sustainability, Chemical Engineering Progress, 111, 41-47.
Friedler F., Tarjan K., Huang Y.W., Fan L.T., 1992, Graph-theoretic approach to process synthesis: Axioms and theorems, Chemical Engineering Science, 47, 1973-1988.
Friedler F., Tarjan K., Huang Y.W., Fan L.T., 1993, Graph-theoretic approach to process synthesis: Polynomial algorithm for maximal structure generation, Computers & Chemical Engineering, 17, 929-942.
Friedler F., Varga J.B., Fan L.T., 1995, Decision-mapping: A tool for consistent and complete decisions in process synthesis, Chemical Engineering Science, 50, 1755-1768.
Friedler F., Varga J.B., Feher E., Fan L.T., 1996, Combinatorially accelerated branch-and-bound method for solving the MIP model of process network synthesis. Chapter. In: Floudas C.A., Pardalos P.M (Eds.), State of the Art in Global Optimization, Springer, Boston, MA, ISBN: 978-1-4613-3439-2, 609-626,
Kim Y., Kang W.H., 2013, Network reliability analysis of complex systems using a non-simulation-based method, Reliability Engineering & System Safety, 110, 80-88.
Klemeš J., Friedler F., Bulatov I., Varbanov P., 2010, Sustainability in the Process Industry, Integration and Optimization, McGraw-Hill, New York, United States.
Narodoslawsky M., Krotscheck C., 1995, The sustainable process index (SPI): Evaluating processes according to environmental compatibility, Journal of Hazardous Materials, 41 (2-3), 383-397.
Praks P., Kopustinskas V., Masera M., 2015, Probabilistic modelling of security of supply in gas networks and evaluation of new infrastructure, Reliability Engineering & System Safety, 144, 254-264.
Varbanov P., Friedler F., 2008, P-graph methodology for cost-effective reduction of carbon emissions involving fuel cell combined cycles, Applied Thermal Engineering, 28, 2020-2029.
Varbanov P.S., Friedler F., Klemeš J.J., 2017, Process network design and optimisation using p-graph: The success, the challenges and potential roadmap, Chemical Engineering Transactions, 61, 1549-1554.