# Synthesis of reliable processes based on P-graph framework

Theses of doctoral (PhD) work

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# 1. Objectives

A fundamental problem of process systems engineering is to synthesize the network of the processing system. Several properties and indicators have to be considered during the design of processing systems for selecting the best system among the vast set of possibilities. Most of these indicators can be defined by a mathematical formulation that can be directly integrated into the objective function of an optimization problem. The operating cost and the sustainability index are two examples of indicators that can have proper formulation. There are other indicators, however, such as reliability, which can only be determined by a systematic enumeration of possible cases. Thus, a general reliability formulation cannot directly be integrated into the objective function.

The aim of the current work is to introduce the theoretical basis of a general method to determine the reliability of complex process network, and to integrate it into process network synthesis. The aim of the work consists of three objectives. The first objective is to define the general reliability formula to determine the reliability of any process network. This is achieved via a P-graph-based enumeration method. This also elaborates on the computational complexity of the method, and the possible acceleration techniques. The second objective is to analyze the possible redundancy options in a process network to improve its reliability. The third objective is to perform process network synthesis with integrated reliability consideration. Here, two synthesis algorithms are introduced; both are capable of generating the Pareto-front of possible process design options based on reliability and cost.

# 2. Methods and approaches adopted

The work is primarily based on the algorithms of the P-graph framework [1]. The formula for determining the reliability of a process involves the exhaustive enumeration of the states of the process, examining each state for operability. This operability test is based on algorithm MSG of the P-graph framework [2], and can be extended to consider complex mathematical models. The presented algorithm is capable of the deterministic and precise determination of the reliability of the process. Such algorithm was only found in the literature for systems with specific structures, while the method presented in this work is general, and can be applied to any process. The work presents multiple ideas to reduce the computation time of the algorithm for large processes, one of them is based on Binary Decision Diagrams [3]. Two methods are introduced for process network synthesis with the consideration of reliability, both utilizes algorithm SSG of the P-graph framework [4].

# 3. New scientific results

The novelty of the work is summarized in the following theses:

1) **A general formulation was proposed for determining the reliability of processing systems, assuming that the reliabilities of the operating units are independent and time invariant. [S1, S2, E1, E2, E7]**

   a) The reliability formula is based on the enumeration of operational networks on the basis of the P-graph algorithms.
   b) If the enumeration algorithm generates the combinatorially feasible networks, then the formula gives the structural reliability. If the feasible networks are generated, the formula expresses the reliability of the processing system.
   c) Acceleration tools were proposed to reduce the computational complexity of the algorithm.
   d) The method was demonstrated through multiple case studies.

2) **It has been shown that in a synthesis procedure considering only local structural redundancy instead of global structural redundancy, the globally optimal solution may not be achieved. [S3, S4, E3, E4]**

3) **Two algorithms have been developed to perform process network synthesis with a lower bound on reliability, these are described in a) and b). [S1, S3, S5, S6, E1, E3, E5, E6, E7]**

   a) A method, based on the algorithms of the P-graph framework, that evaluates all generated combinatorially feasible networks with respect to economic efficiency and reliability.
   b) A method, that generates the networks of potential solutions by combining feasible subprocesses, then evaluates the economic efficiency and the reliability of the generated networks.
   c) The methods given in a) and b) are both able to determine the set of Pareto solutions.

# 4. Applications of the scientific results

The presented method for determining the reliability of a process is general, it can be applied to processes with any structure, provided that the reliabilities of the operating units are independent and time invariant. The goal of the work is to integrate reliability consideration into process network synthesis; the thesis proposed two algorithms for this purpose. Based on either of these algorithms, it is possible to generate those networks that satisfy the reliability requirement, even when the objective of the optimization itself does not include the reliability.

# 5. List of publications

The following papers and presentation correspond with the presented work:

## International journal papers

[S1] Á. Orosz, F. Friedler, P. S. Varbanov, and J. J. Klemes, "Systems reliability, footprints and sustainability", *Chemical Engineering Transactions*, vol. 63, pp. 121–126, 2018, doi: 10.3303/CET1863021. [Q3]

[S2] Z. Kovacs, A. Orosz, and F. Friedler, "Synthesis algorithms for the reliability analysis of processing systems", *Central European Journal of Operations Research*, vol. 27, no. 2, pp. 573–595, 2019, doi: 10.1007/s10100-018-0577-0. [Q2]

[S3] A. Orosz, Z. Kovacs, and F. Friedler, "Processing Systems Synthesis with Embedded Reliability Consideration", *Computer Aided Chemical Engineering*, vol. 43, pp. 869–874, 2018, doi: 10.1016/B978-0-444-64235-6.50152-2. [Q3]

[S4] Á. Orosz and F. Friedler, "Synthesis technology for failure analysis and corrective actions in process systems engineering", *Computer Aided Chemical Engineering*, vol. 46, pp. 1405–1410, 2019, doi: 10.1016/B978-0-12-818634-3.50235-6. [Q3]

[S5] A. Orosz, Z. Kovacs, and F. Friedler, "Synthesis of processing systems taking into account reliability", *Chemical Engineering Transactions*, vol. 70, pp. 1111–1116, 2018, doi: 10.3303/CET1870186. [Q3]

[S6] Á. Orosz, Z. Kovács, and F. Friedler, "Synthesis of heat integrated processing systems taking into account reliability", *Energy*, vol. 181, pp. 214–225, 2019, doi: 10.1016/j.energy.2019.05.173. [D1]

### International conference presentations

[E1] A. Orosz, Z. Kovacs, and F. Friedler, "Reliability Analysis of Production Systems", *VOCAL Optimization Conference: Advanced Algorithms* (VOCAL 2016), Esztergom, Hungary, December 12-15, 2016

[E2] Á. Orosz, F. Friedler, P. S. Varbanov, and J. J. Klemes, "Systems Reliability, Footprints and Sustainability", *International Conference of Low Carbon Asia* (ICLCA 2017), Bangkok, Thailand, November 1-3, 2017

[E3] A. Orosz, Z. Kovacs, and F. Friedler, "Processing Systems Synthesis with Embedded Reliability Consideration", *European Symposium on Computer-Aided Process Engineering* (ESCAPE-28), Graz, Austria, June 10-13, 2018

[E4] A. Orosz, Z. Kovacs, and F. Friedler, "Synthesis of Processing Systems Taking into Account Reliability", *Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction* (PRES 2018), Prague, Czech Republic, August 25-29, 2018

[E5] A. Orosz, Z. Kovacs, and F. Friedler, "P-graph algorithms for the synthesis of reliable processing systems", *VOCAL Optimization Conference: Advanced Algorithms* (VOCAL 2018), Esztergom, Hungary, December 10-12, 2018

[E6] A. Orosz and F. Friedler, "Synthesis technology for failure analysis and corrective actions in process systems engineering", *European Symposium on Computer-Aided Process Engineering* (ESCAPE-29), Eindhoven, The Netherlands, June 16-19, 2019

[E7] A. Orosz and F. Friedler, "Reliability of Processing Systems: Structural Approach", *European Safety and Reliability Conference* (ESREL 2022), Dublin, Ireland, August 28 – September 1, 2022

## 6. References

[1] F. Friedler, K. Tarjan, Y. W. Huang, and L. T. Fan, "Combinatorial algorithms for process synthesis," *Comput Chem Eng*, vol. 16, pp. S313–S320, May 1992, doi: 10.1016/S0098-1354(09)80037-9.

[2] F. Friedler, K. Tarjan, Y. W. Huang, and L. T. Fan, "Graph-theoretic approach to process synthesis: Polynomial algorithm for maximal structure generation," *Comput Chem Eng*, vol. 17, no. 9, pp. 929–942, Sep. 1993, doi: 10.1016/0098-1354(93)80074-W.

[3] R. Drechsler and B. Becker, *Binary Decision Diagrams*. Boston, MA: Springer US, 1998. doi: 10.1007/978-1-4757-2892-7.

[4] F. Friedler, J. B. Varga, and L. T. Fan, “Decision-mapping: A tool for consistent and complete decisions in process synthesis,” *Chem Eng Sci*, vol. 50, no. 11, pp. 1755–1768, Jun. 1995, doi: 10.1016/0009-2509(95)00034-3.