Theses of doctoral (PhD) work

Optimization of energy and utility supply systems

András Éles

Supervisor:
István Heckl, PhD

University of Pannonia
Faculty of Information Technology
Department of Computer Science and
Systems Technology

Doctoral School of Information Science and Technology

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1 Introdution

Today's supply chains, industrial and logistical systems are very complex. If decision making relies solely upon best practices and intuition, resources and time can easily be wasted and profit may be lost. Computational tools for optimization are required to find the best possible design and/or operation of a process. These tools are not only useful for economic purposes. Sustainability is one of the most important challenges for humanity today. Inspecting processes in a sustainability point of view can pose new goals and constraints. These can be incorporated into the optimization procedures, which can enhance the consideration of such aspects in decision making.

During my research I was part of several projects of economical or sustainability purposes. My goal was to design optimization methods, for particular purposes but as general as possible. These methods are intended to be useful for decision making, but were also designed keeping in mind to provide a basis for developing even better methods in the future. There are two main directions in which significant results were obtained. The first direction is energy consumption optimization at local scale, for which an optimization model was developed. Furthermore, I also managed to extend the theory of the applied optimization framework, the P-Graph framework, with a new technique relying on the concept of operations with flexible inputs. The second direction is the cost-efficient management of mobile workforce, for which an algorithmic framework based on mathematical programming was proposed.

2 Methods and approaches adopted

The obtained results required a complex knowledge of the following.

- Synthesis of process networks via the P-Graph framework, corresponding optimization algorithms, in particular the Accelerated Branch and Bound method, and modeling techniques with P-Graphs, in particular the multi-period modeling scheme.

- Efficient design of mathematical programming, in particular Mixed-Integer Linear Programming models, their development, implementation and solution, and the design of heuristics based on such models.

- A wide range of literature examples taking into account similar goals, case studies, or modeling techniques and tricks as needed in this work.

3 Major results and summary of accomplishments

My new scientific results can be summarized in the following three theses. Each of these are detailed in the dedicated chapter of the PhD dissertation.

Thesis 1. A P-Graph model was developed and its effectiveness demonstrated, for the purpose of energy supply optimization involving several biomass types and solar power generation as alternatives to purchasing natural gas and electricity, on the scale of a manufacturing plant. The model can be easily adapted to similar energy supply optimization problems.

Related publications: [S2], [S3].

T1.1. New operating unit models were proposed for the pelletizer and biogas plant equipment units, which allow flexible, independent inputs of several biomass types at the same time. In the PNS implementation of the models, capacity is calculated based on mass, which is different than heating value. This results in a more accurate model, which was demonstrated in the case study of the manufacturing plant.

T1.2. A multi-period extension of the model was performed, which represents seasonal solar power supply and energy demands more precisely, by the distinction of two periods: winter and mid-year. Results from solving this model indicate that biomass and solar power utilization can be economical, but a long investment horizon was needed in this particular case study.

Thesis 2. A new modeling technique for the P-Graph framework was presented, which allows operations with flexible inputs and arbitrary linear constraints on input composition to be modeled purely as a PNS problem and solved directly by existing algorithms like ABB for P-Graph models.

Related publications: [S4], [S6].

T2.1. Nine scenarios were considered, representing different modeling goals for input composition and constraints. P-Graph models were provided, and possible solution structures were investigated. The final scenario allows independent inputs with arbitrary linear constraints on the input amounts. The importance of flexible inputs and the applicability of the proposed method were demonstrated on two case studies involving pelletizer and biogas plant models in a manufacturing plant, and fermenter models in a rural biomass supply chain.

Thesis 3. A new method was developed and tested for solving mobile workforce management problems. This approach can handle several problem characteristics at once. The method is based on an MILP model which can be solved either in a standalone way or as part of an algorithmic framework which is capable of providing heuristic solutions for larger problem instances. The capabilities and limitations of both methods were investigated through a set of tests.

Related publications: [S1], [S5].

T3.1. An MILP model was developed which solves the mobile workforce management problem specification. The novelty is that a slot-based modeling technique was used, and a range of problem characteristics are covered including packing and unpacking times, time windows, resource and task relationship constraints.

T3.2. An algorithmic framework was developed which uses a modified version of the MILP model to heuristically add tasks to the existing schedule until a final solution is obtained. This method does not guarantee the optimal solution unlike the standalone MILP approach, and has other limitations, but succeeds in providing feasible solutions near the optimal in an acceptable amount of time, even for large problem instances.

4 Application of the scientific results

The P-Graph model for the energy consumption optimization case study can be used in general for optimization of energy supply in similar scenarios. Different energy sources can be taken into consideration using the methods presented for solar power and biomass-based biogas production, particularly where there are several possible input materials shared among a few technologies. The multi-period modeling scheme can be applied in scenarios where total demand and/or total supply fluctuate significantly, as heating requirements and accessible solar power do in the model.

The general method of modeling flexible inputs with arbitrary linear constraints in the P-Graph framework can be used in model design for particular problem instances, as it was shown for the energy supply optimization case study. Besides supporting decision making in particular cases, the work is also intended to encourage development of modeling techniques for the P-Graph framework. The presented method is capable of modeling a wide range of operations in the future, in which there are several different inputs that can be used up in arbitrary ratios. If the connection of inputs to outputs, and the restrictions on inputs can be described with linear constraints, then a general modeling method is offered. This method, unlike previous efforts, is purely a P-Graph-based solution, for which existing solution methods like the Accelerated Branch and Bound algorithm, and existing software like the P-Graph Studio is directly applicable, without the need to manually tamper with the procedure or use external tools.

The Mixed-Integer Linear Programming model proposed is a novel, general model for mobile workforce management, solving a problem formulation with a wide range of problem features. The model is applicable directly on scenarios for which the description is covered by the problem formulation. The algorithmic framework provides another option than using the MILP model alone. It can be used to find heuristic solutions in acceptable time, for much larger problem instances. The model was designed with the intention of algorithmically manipulating its solution procedure, and therefore to encourage the research of other possible solution algorithms.

5 List of publications

Related publications

[S1] **A. Éles**, H. Cabezas, and I. Heckl, "Heuristic algorithm utilizing mixed-integer linear programming to schedule mobile workforce," *Chemical Engineering Transactions*, vol. 70, pp. 895–900, 2018.

[S2] **A. Éles**, L. Halász, I. Heckl, and H. Cabezas, "Energy consumption optimization of a manufacturing plant by the application of the p-graph framework," *Chemical Engineering Transactions*, vol. 70, pp. 1783–1788, 2018.

[S3] **A. Éles**, L. Halász, I. Heckl, and H. Cabezas, "Evaluation of the energy supply options of a manufacturing plant by the application of the p-graph framework," *Energies*, vol. 12, no. 8, 2019, **IF: 2.707**.

[S4] **A. Éles**, I. Heckl, and H. Cabezas, "Modeling technique in the p-graph framework for operating units with flexible input ratios," *Central European Journal of Operations Research*, vol. 29, no. 2, pp. 463–489, 2020, **IF: 2.345**.

[S5] **A. Éles**, I. Heckl, and H. Cabezas, "New general mixed-integer linear programming model for mobile workforce management," *Optimization and Engineering*, vol. 23, pp. 479–525, 2022, **IF: 2.760**.

[S6] **A. Éles**, I. Heckl, and H. Cabezas, "Modeling renewable energy systems in rural areas with flexible operating units," *Chemical Engineering Transactions*, vol. 88, pp. 643–648, 2021.

Other publications

[E1] **A. Éles** and I. Heckl, "Application of the maximal bipartite matching algorithm to schedule medical appointments with quotas," in *Proceedings of the Pannonian Conference on Advances in Information Technology (PCIT'2019)*, I. Vassányi, Ed., ISBN 978-963-127-8, University of Pannonia, Veszprém, Hungary, 2019, pp. 1–7.

[E2] **A. Éles** and I. Heckl, "Solving an extended line balancing optimization problem using dynamic programming," in *Proceedings of the Pannonian Conference on Advances in Information Technology (PCIT'2020)*, I. Vassányi, Ed., ISBN 978-963-396-144-5, University of Pannonia, Veszprém, Hungary, 2020, pp. 31–37.

[E3] **A. Éles** and I. Heckl, "Dynamic programming approaches for line balancing problems," in *Short papers of VOCAL 2022 (9th VOCAL Optimization Conference: Advanced Algorithms)*, ISBN 978-615-01-5987-4, Hungarian Operations Research Society, Budapest, Hungary, 2022, pp. 30–35.