Final Project Report

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In the 3.5 years of this research project most of the project goals have been achieved. Through cooperation with the Slovenian partner, several interesting problems have been defined and various solution approaches have been investigated. The diversity of the problems attacked is well-illustrated by the 4 major areas of the project which define the numbered sections of this report. Two of the major areas are further divided to facilitate navigation between the various problems and results.

To classify somehow the problems from a theoretical point of view, it is enough to mention that many offline as well as online problems were studied.

Accordingly, the complexity of several problems has been investigated, and in the online world, lower bounds for the best competitive ratio were derived.

As for the methods, they range from polyhedral combinatorics to approximation algorithms, heuristics, and competitive algorithms for the online problems.

A number of application domains provided motivation and input for the work carried out. Wood industry is the primary example, but the transportation problems in factories, and between production facilities were equally important. The pricing of electricity was one of the main areas of the project, and it has become a rather current issue nowadays. Resource sharing between companies is yet another area touched by the project.

The diversity of the problems, methods, and applications illustrates that optimization is supply chains has many faces, and during the project a bigger team made some progress in some concrete areas of this very large domain.

The work has been done to a large extent during the COVID-19 pandemic, nevertheless, we had yearly project meetings, and several other visits in Slovenia and in Hungary.

1. Logistic network design and planning

Robust network design.

A novel resource allocation mechanism has been developed for the project scheduling problem with self-interested agents. In the studied model the jobs of a project are related with precedence relations and they require materials supplied at different time points. The utilities of the project agents are based on the tardiness of their jobs, but the due dates are private knowledge. A classical scheduling algorithm has been modified for implementing the Serial Dictatorship Mechanism that does not use monetary transfer as an incentive. The developed mechanism computes the material allocation and the schedule in polynomial time, furthermore, it is truthful and Pareto-optimal (Egri & Kis, 2020).

A network design problem of the waste wood recycling supply chain has been modelled, where the waste is collected in accumulation points and has to be transported to processing centers for decontamination and further preparation. The goal is to determine the number and location of the processing facilities to minimize the total cost even in case of a possible disturbance. A bilevel formulation and some exact and heuristic methods are described in (Egri et al, 2020).

The robust facility location model has been extended to handle non-linear processing costs, in order to consider economies of scale. A case study of the Austrian waste wood recycling network containing almost 2000 collection points and potential facility locations has been conducted, minimizing the facility building, waste wood processing and transportation costs. The extended model and the study have been published in (Egri et al, 2021).

Logistic network planning.

In recent years, global events have significantly disrupted supply chain of many industries. In the plywood industry, the lateness or cancellation of wood log deliveries caused the plant to miss orders on the demand side. In (Ősz et al, 2022d), a new approach was published with the objective to mitigate the effects of these disruptions by rearranging order deadlines and rescheduling. The proposed MILP model can be used to short- and mid-term instances, however, long-term planning needed a heuristic approach. In (Ősz et al, 2022c) a genetic algorithm was proposed and tested for these larger instances.

A planning model in supply chains may make a distinction between different product families. Models where the idea is to create batches in the manufacturing process is well-known. A packing variant of such model was investigated. Variants with two, three, and four batches were studied and improved lower bounds were derived for the standard and parametric variants in some of the cases. (Balogh et al. 2021b).

The routing and scheduling of autonomously guided vehicles (AGVs) is still a challenging optimization problem. The crux of the problem is that AGVs move autonomously, and traffic situations like deadlock, or livelock must be avoided while serving transportation requests. A centralized as well as a decentralized approach has been devised for solving the problem in which transportation requests arrive online, and an objective function related to the tardiness of serving the requests, or the delay in serving the requests is minimized (Drótos et el, 2021, Tamási and Kis, 2021).

In the framework of the ICAPS 2021 conference, a competition was organized by Huawei Ltd for solving a complex pickup-and-delivery problem. In this problem, there is a fleet of vehicles of identical capacity to serve requests arriving online over the day. The vehicles have a finite capacity and items of various sizes have to be collected and delivered as the transportation requests arrive. The goal is to serve all the requests while minimizing a combination of tardiness penalties and average distance traveled by the vehicles. There are other complicating factors, such as at each pickup and delivery points there are a limited number of loading and unloading ports, which limit the number of vehicles that can be served simultaneously. The team consisting of Péter György, Markó Horváth and Tamás Kis won the bronze medal on the competition, and delivered a talk on the method during the ICAPS 2021 conference.

The classical dial-a-ride problem has been further investigated and new classes of valid inequalities have been obtained based on the familiar compatibility relations of nodes along feasible vehicle routes. As it turned out, the new cuts, as well as some old ones, are strongly related to the edge polytope of bipartite graphs. The new cuts have been tested on benchmark instances (Sunil & Kis, 2022).

The logistics activities of larger construction companies were studied, that operate on several sites and work on simultaneous projects. Some decision support and optimization possibilities are discussed in (Békési et al. 2022)

2. Electricity tariff optimization

In electricity tariff optimization problem, a retailer must determine a time-of-use electricity tariff, whereas the consumers, who aim at maximizing their utility and minimizing their cost of electricity, decide on their consumption as a response to that tariff. The challenging optimization problem is that of the leader, i.e., determining the optimal tariff, which corresponds to a bilevel programming problem.

New, efficient solution methods were developed for the above optimization problem, based on reformulating the bilevel program into a single-level quadratically
constrained quadratic program (QCQP), and applying a successive linear programming (SLP) approach to solving it (Kovács, 2019a). In computational experiments, the proposed approach outperformed typical earlier methods based on the KKT reformulation.

New methods were elaborated for reconstructing the consumers' decision model from historic tariff and consumption data, using an inverse optimization approach (Kovács 2019b, Kovács 2019c, Kovács 2021). Paper (Kovács 2019b) received the outstanding paper award of the IEEE GPECOM 2019 conference.

In order to manage the inherent uncertainty in the consumers' decision model, novel robust bilevel programming solution approaches were developed. A basic level of robustness is achieved by adopting the so-called pessimistic bilevel approach, where in case of multiple optimal responses for a consumer, the retailer must prepare for the response that is the least favorable for it. In (Kis et al, 2021), an exact algorithm is proposed for solving the pessimistic variant. Recently, a novel column-and-constraint generation algorithm was developed for the generic robust bilevel approach where the consumers' utility parameters can originate from a polyhedral uncertainty set. The new algorithm was published at an international scientific conference that will take place after the reporting period, and submission to a high-impact operations research journal is currently being considered.

3. Scheduling at production facilities to minimize energy usage and reduce transportation and production costs

Simultaneous optimization of replenishment and production costs.

In the joint replenishment problem item ordering costs can be saved by combining the ordering of distinct items. However, combining orders has a negative impact in fulfilling requests for which the items are ordered. Thus, a good trade-off has to be made. One can combine the joint replenishment problem with machine scheduling if the items ordered must be processed by a machine before fulfilling the requests. Hence, a scheduling related criteria is combined with the ordering costs. This problem seems to be natural, but to our best knowledge, it has not been studied before. A number of complexity results along with online algorithms for scheduling objective functions such as total weighted completion time, total flow time, and maximum flow time are proposed in (Györgyi et al, 2021), (Györgyi et al, 2022).

Energy related scheduling problems.

A number of new results have been obtained for various resource leveling problems, which have direct applications in minimizing peak energy consumption, one of the main topics of the proposal. On the one hand, a common approximation framework for 2 seemingly different problem classes has been devised: resource leveling in a parallel machine environment, and minimizing the early (or the

late) work in a parallel machine environment with a common due-date of the jobs. It has been shown that the two problems are equivalent. In addition, a new technique has been devised for obtaining a PTAS for such problems, see (Györgyi and Kis, 2020). On the other hand, a mathematical programming based approach has been developed for the resource loading problem, where the objective is to minimize the weighted sum of extra resource consumption (above a certain limit), and the tardiness of the tasks (Song et al, 2020). The algorithm is based on a thorough polyhedral characterization of feasible intensity assignment to the tasks of a project network, which is turned into an efficient algorithm as well.

In the early phase of the project, a preliminary research was carried out with the aim to minimize energy usage in a processing plant by rescheduling. In the investigated problem class, energy consumption is mostly influenced by the selection of assignable units to tasks. The S-graph framework has been extended to tackle these problem requirements, and the results were published (Ősz & Hegyháti, 2019). In the second phase of the project, in collaboration with the Slovenian partner, case-study data were collected for a sawmill, and the approach applied to minimize its energy needs. The results were recently submitted for publication (Ősz et al, 2022a).

Scheduling in waste wood facilities.

Research in the optimization of reverse wood value chains focuses mostly on network-level problems. In collaboration with the Slovenian partner, the operation of a waste wood processing facility was investigated. Several problem classes were identified based on an extensive literature review, on-site interviews and stakeholder feedback. Various solution approaches based on mathematical programming and evolutionary algorithms were developed and tested for these problem classes. In (Dávid et al, 2021a), energy minimization and minimization of lateness costs were considered for a waste-wood processing facility with multiple sources and quality of incoming wood deliveries. The proposed MILP model was later adjusted to address semi-continuous behavior within the facility in (Dávid et al, 2021b). In (Ősz et al, 2022b), the efficiency of continuous vs. discrete time models were compared.

Miscellaneous results.

New complexity and approximability results were obtained for machine scheduling problems with non-renewable resources and the total weighted completion time objective (Györgyi and Kis, 2022).

In the single machine coupled task scheduling problem each job consists of two subtasks, separated by some fixed delay in a feasible schedule. For a special case where there are only two possible delays between the pairs of subtasks, an approximation algorithm - called First Fit Decreasing (FFD) – was devised, and it was shown that the approximation ratio is in the interval (1.57894; 1.57916). (Békési et al. 2021a).

The classical online bin packing problem and one of its variants were investigated. The advantage of branching and the applicability of full adaptivity in the design of lower bounds for the classic online problem was demonstrated. The lower bound on the asymptotic competitive ratio of any online algorithm for bin packing was improved to above 1.54278. (Balogh et al 2020a). Cardinality constrained bin packing is a well-known variant of the classical problem. An online problem was solved in the sense that a lower bound of 2 was proved on the overall asymptotic competitive ratio. This closed the longstanding open problem of finding the value of the best possible overall asymptotic competitive ratio, since an algorithm with absolute competitive ratio 2 for any fixed value of k is known (Balogh et al 2020b).

Disjunctive programming is a key optimization method that finds applications in planning and scheduling problems in supply chains. A new, general technique has been devised to obtain ideal, non-extended mathematical programming formulations for disjunctive constraints, which require that the solution is in the union of some polyhedra that admits a certain network representation. A list of examples from the literature demonstrate the applicability of the method (Kis & Horváth, 2021).

4. Resource sharing between enterprises

A simulation- and cloud-ready software solution was developed, called Open Manufacturing Federation (OMF in the followings), which can be used to support the offering and requesting of free capacities by the federated production facilities.

Leveraging the so-called crowdsourcing principle in production networks, in the first year of this research the functional and technical specification for a mutualism-driven resource allocation platform were realized (Szaller et al 2020).

Effects of lead time prediction accuracy have been investigated in the OMF trust-based resource sharing environment and the performance of facilities have been compared with agent-based simulation (Szaller and Kádár 2021a). Agent-based simulation is used to compare the two mechanisms with respect to utilization rate, service level and communication load. The findings can be applied in the design of crowdsourced manufacturing platforms (Szaller and Kádár 2021b).

The original concept of mutualistic crowdsourced supply-chain of the OMF was further investigated in the light of a cost-oriented methodology (Szaller et al., 2022), The integration of a factory's manufacturing execution system, underlying the decisional process, and realized for a cloud-based, big-data oriented IIoT platform is summarized in (Marosi et al., 2022), with the aim to enable real industrial use-cases for standardized data integration and analysis.

References

Ádám Szaller, Gianfranco Pedone, Péter Egri, Ádám Szalóki, Gábor Nick (2020), A mutualistic framework for sustainable capacity sharing in manufacturing. 53rd CIRP Conference on Manufacturing Systems. https://doi.org/10.1016/j.procir.2020.04.024

Ádam Szaller, Botond Kádár (2021a), Effect of lead time prediction accuracy in trust-based resource sharing. INCOM 2021, 17th IFAC Symposium on Information Control Problems in Manufacturing. https://doi.org/10.1016/j.ifacol.2021.08.132

Ádam Szaller, Botond Kádár (2021b), Platform and direct exchange-based mechanisms for resource sharing in distributed manufacturing: a comparison. CIRP Annals - Manufacturing Technology. https://doi.org/10.1016/j.cirp.2021.04.048

Ádám Szaller, Christian Fries, Botond Kádár (2022), Financial aspects of a trust-based resource sharing platform. CIRP Journal of Manufacturing Science and Technology (submitted)

Attila Csaba Marosi, Márk Emődi, Attila Farkas, Róbert Lovas, Richárd Beregi, Gianfranco Pedone, Balázs Németh, Péter Gáspár (2022), Towards Reference Architectures: a Cloud-agnostic Data Analytics Platform Empowering Autonomous Systems. IEEE Access. https://doi.org/10.1109/ACCESS.2022.3180365

János Balogh, József Békési, György Dósa, Leah Epstein, Asaf Levin (2020a), A New Lower Bound for Classic Online Bin Packing, In: E. Bampis and N. Megow (Eds.): WAOA 2019, LNCS 11926, pp. 18–28, Springer, Cham https://doi.org/10.1007/978-3-030-39479-0_2

János Balogh, József Békési, György Dósa, Leah Epstein, Asaf Levin (2020b), Online bin packing with cardinality constraints resolved, Journal of Computer and System Sciences, 112, 34-49, 2020 https://doi.org/10.1016/j.jcss.2020.03.002

János Balogh, József Békési, György Dósa, Leah Epstein, Asaf Levin (2021b) Lower bounds for batched bin packing. Journal of Combinatorial Optimization 43, 613–629 (2022). https://doi.org/10.1007/s10878-021-00797-z

József Békési, György Dósa, Gábor Galambos (2021a), A First Fit Type Algorithm for the Coupled Task Scheduling Problem with Unit Execution Time and Two Exact Delays, European Journal of Operational Research, 297:3, 844-852, 2022. https://doi.org/10.1016/j.ejor.2021.06.002

József Békési, Miklós Krész, Ákos Szirányi (2022), Transportation optimization of heavy machinery in construction logistics using a pickup and delivery model, submitted to Logistics, 2022.

Péter Egri, & Tamás Kis (2020), Allocating raw materials to competing projects. Computers & Industrial Engineering, 143, 106386. https://doi.org/10.1016/j.cie.2020.106386

Péter Egri, Balázs Dávid, Tamás Kis, & Miklós Krész (2020). Robust reverse logistics network design. In *Logistics operations and management for recycling and reuse*. Springer, Berlin, Heidelberg. pp. 37-53, 2020, https://doi.org/10.1007/978-3-642-33857-1_3

Péter Egri, Balázs Dávid, Tamás Kis, & Miklós Krész (2021). Robust facility location in reverse logistics. *Annals of Operations Research*, in press, 2021. https://doi.org/10.1007/s10479-021-04405-5

Balázs Dávid , Olivér Ősz , Máté Hegyháti (2021a), Robust Scheduling of Waste Wood Processing Plants with Uncertain Delivery Sources and Quality, Sustainability, 2021, vol. 13, 5007, DOI: 10.3390/su13095007

Balázs Dávid , Olivér Ősz , Máté Hegyháti (2021b), Scheduling of Waste Wood Processing Facilities with Overlapping Jobs, Proceedings of the 16th International Symposium on Operational Research in Slovenia, 2021.

Márton Drótos, Péter Györgyi, Markó Horváth, Tamás Kis, (2021), Suboptimal and conflict-free control of a fleet of AGVs to serve online requests, Computers & Industrial Engineering, vol 152, 106999, 2021. https://doi.org/10.1016/j.cie.2020.106999

Péter Györgyi, Tamás Kis (2020), A common approximation framework for early work, late work, and resource leveling problems, European Journal of Operational Research, *286*(1), 129-137, (2020). https://doi.org/10.1016/j.ejor.2020.03.032

Péter Györgyi, Tamás Kis (2022), New complexity and approximability results for minimizing the total weighted completion time on a single machine subject to non-renewable resource constraints, Discrete Applied Mathematics, *311*, 97-109, (2022). https://doi.org/10.1016/j.dam.2022.01.009

Péter Györgyi, Tamás Kis, Tímea Tamási, József Békési, (2021), Joint replenishment meets scheduling, submitted to Journal of Scheduling, accepted subject to minor revisions.

Péter Györgyi, Tamás Kis, Tímea Tamási (2022), An online joint replenishment problem combined with single machine scheduling, manuscript, ready to be submitted.

Tamás Kis, Markó Horváth (2022), Ideal, non-extended formulations for disjunctive constraints admitting a network representation, Mathematical Programming, *194*(1), 831-869, 2022. https://doi.org/10.1007/s10107-021-01652-z

Markó Horváth, Tamás Kis, Györgyi Péter, Solution approach of the Quickest Route team for solving the „ICAPS 2021: The Dynamic Pickup And Delivery Problem" challenge by Huawei, ICAPS 2021, Guangzhou, China on Aug 2-13.

Tamás Kis, András Kovács, Csaba Mészáros (2021), On optimistic and pessimistic bilevel optimization models for demand response management. Energies, 14(8):2095, 2021. https://doi.org/10.3390/en14082095

András Kovács (2019a): Bilevel programming approach to demand response management with day-ahead tariff. Journal of Modern Power System and Clean Energy, 7(6): 1632-1643, 2019. https://doi.org/10.1007/s40565-019-0569-7

Andras Kovács (2019b): Parameter elicitation for consumer models in demand response management. Proc. of the IEEE Global Power, Energy and Communication Conference (GPECOM 2019), pp. 456-460, 2019.

András Kovács (2019c): Fogyasztói modellek identifikációja energiahálózatok keresletoldali szabályozásához. XXXIII. Magyar Operációkutatás Konferencia, Szeged, pp. 77, 2019.

András Kovács (2021): Inverse optimization approach to the identification of electricity consumer models. Central European Journal of Operations Research, 29(2):521-537, 2021. https://doi.org/10.1007/s10100-020-00699-1

Sunil Morapitiye, Tamás Kis: Strong cuts from compatibility relations for the Dial-a-Ride Problem, Discrete Applied Mathematics, vol 309: 240-257, 2022. https://doi.org/10.1016/j.dam.2021.12.010

Olivér Ősz, Balázs Dávid, Máté Hegyháti (2022b), Comparison of Discrete- and Continuous-Time Models for Scheduling Waste Wood Processing Facilities, Central European Journal of Operations Research, submitted, 2022.

Olivér Ősz, Balázs Dávid, József Garab, Máté Hegyháti (2022c). Long-term plant-level scheduling with uncertainty in the plywood industry. 10th Hardwood Conference Proceedings, 2022. ISBN 978-963-334-446-0, https://doi.org/10.35511/978-963-334-446-0, ISSN 2631-004X, pp. 263-270, 2022.

Olivér Ősz, József Garab, Máté Hegyháti, Balázs Dávid (2022d), Mitigating Supply Chain Disruptions in Plywood Production by Rescheduling. Central European Journal of Operations Research, submitted, 2022.

Olivér Ősz, Máté Hegyháti (2019), Energy usage minimization with the S-graph framework, Information Society - Proceedings of MATCOS 2019, pp. 59-62, 2019

Olivér Ősz, Máté Hegyháti, Balázs Dávid (2022a), Minimization of total energy usage with the S-graph framework: a sawmill case-study, Sustainability, submitted, 2022

Guopeng Song, Tamas Kis, Roel Leus (2021), Polyhedral results and branch-and-cut for the resource loading problem, INFORMS Journal on Computing, *33*(1), 105-119, (2021). https://doi.org/10.1287/ijoc.2020.0957

Tímea Tamási, Tamás Kis, (2021), Decentralized and prioritized algorithm for AGV fleet management, INCOM 2021, 17th IFAC Symposium on Information Control Problems in Manufacturing,