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Advanced solution methodologies for loading and transportation problems

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14. ABSTRACT
In this document we report the research activities that have been performed during the three years of the grant. The aim of this research was to include innovative techniques in the study of loading, packing, and transportation problems arising in real-world situations where additional constraints make it dicult to adopt the classical modelling tools from the literature. Spec cally, our research addressed the following four main topics:
--one-dimensional cutting and packing problems;
--two-dimensional cutting and packing problems;
--uncertain optimization problems;
--multi-stage optimization.
Some of these topics were studied in cooperation with researchers of our department currently engaged in Grant FA8655-20-1-7019.

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Advanced solution methodologies for loading and transportation problems

Principal Investigator: Professor **Michele Monaci**

Period of performance: May 1, 2020 - April 30, 2023

Contents

1 Summary

In this document we report the research activities that have been performed during the three years of the grant. The aim of this research was to include innovative techniques in the study of loading, packing, and transportation problems arising in real-world situations where additional constraints make it difficult to adopt the classical modelling tools from the literature. Specifically, our research addressed the following four main topics:

- one-dimensional cutting and packing problems;
- two-dimensional cutting and packing problems;
- uncertain optimization problems;
- multi-stage optimization.

Some of these topics were studied in cooperation with researchers of our department currently engaged in Grant FA8655-20-1-7019.

2 Introduction

Loading and transportation problems have a direct impact in many application contexts, such as logistics, telecommunications, and high performance computing. In addition, basic knapsack problems appear as subproblems in many more complex systems, arising, e.g., in big data analytics or in data clustering. For these reasons, the study of this class of problems is of paramount importance from a practical viewpoint and a wide scientific literature has been proposed in recent years for addressing these problems, in many variants. During the project, the research teams designed and implemented exact and heuristic solution approaches for these problems, using standard modelling tools of the optimization community combined with advanced techniques like, e.g., metaheuristics, machine learning approaches, and Stackelberg games.

3 Methods, Assumptions and Procedures

All the models and algorithms discussed in the next section have been implemented (mostly in C language) and experimentally evaluated, on benchmarks from the literature and on new benchmarks derived from real-world applications, using state of the art computers. We refer to the published papers for details on the specific experiments.

4 Results and discussion

The specific areas of the research, related to the topics introduced above, can be grouped into 4 main topics.

4.1 One-dimensional cutting and packing problems

One of the basic problems in combinatorial optimization is the well-known (linear) *knapsack problem*, which can be formulated as follows: given n items, each having an associated profit p_j and weight w_j ($j = 1, \dots, n$), and one container (knapsack) with capacity c, select a maximum profit subset of items such that the total weight of the selected items does not exceed the capacity. This problem is one of the most studied problems in the combinatorial optimization area, and is strictly related to the *bin packing problem*, in which each item is characterized by a positive weight, and an unlimited number of identical bins with limited capacity are given. Here, the objective is to allocate all items to a minimum number of bins, while satisfying the capacity constraint of each container.

Both problems have relevant applications in real contexts and arise as subproblems for more complex problems. For this reason, the literature includes many variants of these two problems. In the *quadratic knapsack problem*, besides the profit of the selected items, the objective function includes some terms associated with the simultaneous selection of pairs of items. This makes the resulting function quadratic, and hence the resulting optimization problem extremely challenging to solve, both from a theoretical and from a practical viewpoint.

In (linear and quadratic) *multiple knapsack problems*, instead of a single knapsack, m knapsacks are available, each with its own capacity. The objective is to select m, non intersecting, subsets of items (one per knapsack) so that the total profit is a maximum and the capacity of no knapsack is exceeded.

In the *time-bomb knapsack problem*, each item has a given probability of exploding, thus destroying the entire content of the knapsack. The objective is to maximize the expected profit of the selected items, resulting again in a highly nonlinear objective function.

Finally, the *generalized assignment problem* can be viewed as a variant of the bin packing problem in which assigning an item to a container produces a profit and uses some capacity. In the nonlinear version of this problem, items can be partially assigned to containers, and both the objective function and the capacity functions are nonlinear functions of the assignment of items to containers.

The results of our research on these topics have been published in

- V. Cacchiani, M. Iori, A. Locatelli, S. Martello. Knapsack problems - An Overview of Recent Advances. Part I: Single knapsack problems. *Computers & Operations Research* 143 (2022), 105692.
- V. Cacchiani, M. Iori, A. Locatelli, S. Martello. Knapsack problems - An Overview of Recent Advances. Part II: Multiple, multidimensional, and quadratic knapsack problems. *Computers & Operations Research* 143 (2022), 105693.
- L. Galli, S. Martello, C. Rey, P. Toth. Polynomial-size formulations and relaxations for the quadratic multiple knapsack problem. *European Journal of Operational Research* 291 (2021), 871–882.
- L. Galli, S. Martello, C. Rey, P. Toth. Lagrangian matheuristics for the quadratic multiple knapsack problem. *Discrete Applied Mathematics* 335 (2023), 36–51.
- M. Monaci, C. Pike-Burke, A. Santini. Exact algorithms for the 0–1 Time-bomb Knapsack Problem. *Computers & Operations Research* 145 (2022), 105848.

- C. D'Ambrosio, S. Martello, M. Monaci. Lower and upper bounds for the non-linear generalized assignment problem. *Computers & Operations Research* 120 (2020), 104933.

4.2 Two-dimensional cutting and packing problems

A relevant variant of the knapsack and bin packing problems mentioned above arises when items are two-dimensional objects to be allocated to (one or more) two-dimensional containers. The resulting class of problems, denoted as cutting and packing, finds applications in loading, logistics, cutting, manufacturing, telecommunications and high performance computing systems.

The results of our research on these topics have been published in

- M. Iori, V.L. de Lima, S. Martello, F.K. Miyazawa, M. Monaci. Exact solution techniques for two-dimensional cutting and packing. *European Journal of Operational Research* 289 (2021), 399–415.

- M. Iori, V.L. de Lima, S. Martello, M. Monaci. 2DPackLib: A Two-dimensional Cutting and Packing Library. *Optimization Letters* 16 (2022), 471–480.

4.3 Uncertain optimization problems:

A standard assumption when solving an optimization problem is that all input data are known in advance. Unfortunately, this is not always the case when real problems are considered, since classical models only provide an approximation of real systems and uncertainty can change the effective value of some parameters. Different paradigms have been introduced in the literature for dealing with uncertainty. Stochastic optimization is based on the definition of a large set of possible realizations of the data (*scenarios*) and of the associated probabilities.
For a given stochastic optimization problem, the maximum regret of a solution is defined as the difference between the value attained by the solution in its best and worst scenario. Accordingly, the min-max regret policy is to select a solution for which the maximum regret is a minimum, which corresponds to find a solution which is "the most robust' with respect to changes in the objective function.
In K-adaptability approaches, the user is requested to compute K alternative solutions before the uncertainty materializes; afterwards, the best of them can be chosen for the realized scenario. The objective is again to optimize the expected solution value over all scenarios. The input parameter K allows to determine the ideal trade-off between flexibility and quality of the solution when facing different scenarios of the problem.

The results of our research on these topics have been published in

- W. Wu, M. Iori, S. Martello, M. Yagiura. An Iterated Dual Substitution Approach for Binary Integer Programming Problems under the Min-Max Regret Criterion. *INFORMS Journal on Computing* 34 (2022), 2523–2539.

- E. Malaguti, M. Monaci, J. Pruente. K-Adaptability in stochastic optimization. *Mathematical Programming* 196 (2022), 567–595.

4.4 Multi-stage optimization:

Classical optimization problems usually model a single-stage decision flow where every decision must be taken here and now. In many contexts, however, some decisions can be postponed depending on some previous decisions and, possibly, on the actual realization of some exogenous parameters that cannot be observed immediately.
In chance-constrained stochastic optimization the decision maker has to take decisions that are feasible with high probability and, depending on the realization of uncertainty, a limited set of recourse actions is allowed.
The adjustable robust optimization paradigm is a three-level problem in which the decision maker takes some strategic decisions here-and-now, whereas other operational decisions are taken only when the exact value of some uncertain parameters is fixed. The objective is to optimize either the worst-case solution value or the expected value over possible scenarios.
Finally, a similar context arises in fortification games, which can be seen as three-level problems with two players who take decisions at different times. In the first level, a player selects some assets to be protected from potential malicious attacks. In the second level, the other player attacks some unprotected assets, either destroying them or reducing their efficiency. Finally, the last level asks the first player to take some recourse actions over the surviving or partially damaged assets. Typically, while the first player wants to maximize her profit, the objective of the second player is to minimize this figure.

The results of our research on these topics have been published in

- A. Lodi, E. Malaguti, M. Monaci, G. Nannicini, P. Paronuzzi. A solution algorithm for chance-constrained problems with integer second-stage recourse decisions. *Mathematical Programming* (to appear).
- H. Lefebvre, E. Malaguti, M. Monaci. Adjustable robust optimization with discrete uncertainty. (submitted)
- M. Leitner, I. Ljubic, M. Monaci, M. Sinnl, K. Taninmis. An Exact Method for Fortification Games. *European Journal of Operational Research* 307 (3), 1026–1039, 2023.

5 Conclusions

The grant was used by the research team for research activities on a large variety of optimization problems that have great relevance in many practical contexts. The quality of the research is witnessed by the large number of publications, appeared on high-quality scientific international journals, that explicit acknowledgement AFOSR Grant FA8655-20-1-7012 as well as by the presentations that were done at international conferences. In addition, the grant allowed for financial support to young researchers (typically, post-doc students) who collaborated to the research activities.

6 References

Papers already published (or accepted) in peer-reviewed journals

- V. Cacchiani, M. Iori, A. Locatelli, S. Martello. Knapsack problems - An Overview of Recent Advances. Part I: Single knapsack problems. *Computers & Operations Research* 143 (2022), 105692.
- V. Cacchiani, M. Iori, A. Locatelli, S. Martello. Knapsack problems - An Overview of Recent Advances. Part II: Multiple, multidimensional, and quadratic knapsack problems. *Computers & Operations Research* 143 (2022), 105693.
- L. Galli, S. Martello, C. Rey, P. Toth. Polynomial-size formulations and relaxations for the quadratic multiple knapsack problem. *European Journal of Operational Research* 291 (2021), 871–882.
- L. Galli, S. Martello, C. Rey, P. Toth. Lagrangian matheuristics for the quadratic multiple knapsack problem. *Discrete Applied Mathematics* 335 (2023), 36–51.
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- M. Iori, V.L. de Lima, S. Martello, F.K. Miyazawa, M. Monaci. Exact solution techniques for two-dimensional cutting and packing. *European Journal of Operational Research* 289 (2021), 399–415.
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- W. Wu, M. Iori, S. Martello, M. Yagiura. An Iterated Dual Substitution Approach for Binary Integer Programming Problems under the Min-Max Regret Criterion. *INFORMS Journal on Computing* 34 (2022), 2523–2539.
- E. Malaguti, M. Monaci, J. Pruente. K-Adaptability in stochastic optimization. *Mathematical Programming* 196 (2022), 567–595.
- A. Lodi, E. Malaguti, M. Monaci, G. Nannicini, P. Paronuzzi. A solution algorithm for chance-constrained problems with integer second-stage recourse decisions. *Mathematical Programming* (to appear).
- M. Leitner, I. Ljubic, M. Monaci, M. Sinnl, K. Taninmis. An Exact Method for Fortification Games. *European Journal of Operational Research* 307 (3), 1026–1039, 2023.

Conference presentations

Due to the pandemic situation and to the war situation in Europe, we were able to present our research results only at few international conferences/workshops:

- E. Malaguti, M. Monaci, J. Prünte. K-Adaptability for Stochastic Optimization. Presented at the ODS 2020 International Conference on Optimization and decision Science, held online (November 2020).
- L. Galli, S. Martello, C. Rey, P. Toth. Polynomial-size formulations and relaxations for the quadratic multiple knapsack problem. Presented at the ODS 2020 International Conference on Optimization and decision Science, held online (November 2020).
- L. Galli, S. Martello, C. Rey, P. Toth. Lagrangian heuristics for the Quadratic Multiple Knapsack Problem. Presented at ECCO XXXIV, the 34th Conference of the European Chapter on Combinatorial Optimization, held online (June 2021).
- L. Galli, S. Martello, C. Rey, P. Toth. Lagrangian Heuristics for the Quadratic Multiple Knapsack Problem. Presented at the 34th Conference of the European Chapter in Combinatorial Optimization, held (online) in Madrid, Spain (June 2021);
- L. Galli, S. Martello, C. Rey, P. Toth. Matheuristic Algorithms for the Quadratic Multiple Knapsack Problem. Presented at the 31st European Conference on Operational Research, held in Athens, Greece (July 2021);
- A. Santini, M. Monaci, and C. Pike-Burke. The 0–1 Time-bomb Knapsack Problem. Presented at the 31st European Conference on Operational Research, held in Athens, Greece (July 2021);
- A. Santini, M. Monaci, and C. Pike-Burke. The 0–1 Time-bomb Knapsack Problem. Presented at the Internal Seminars series at the Department of Information Systems, Decision Sciences and Statistics, ESSEC Paris, France (December 2021).
- M. Sinnl, M. Leitner, I. Ljubic, M. Monaci, K. Taninmis. A decomposition method for solving fortification games. Presented at the 32nd European Conference on Operational Research, held in Espoo, Finland (July 2022);
- H. Lefebvre, E. Malaguti, M. Monaci. Adjustable robust optimization with discrete uncertainty. Presented at the 32nd European Conference on Operational Research, held in Espoo, Finland (July 2022);

Attachments

The twelve papers published (or to appear) in peer-reviewed journals are attached.