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Project P7/36

Combinatorial Optimization: Metaheuristics and EXact methods (COMEX)

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Scientific Report 2013
(October 1, 2012 - September 30, 2013)

Contents

1 List of abbreviations

- **ACO-HCG**: Ant Colony Optimization / Heuristic Column Generation
- **AI**: Afriat's efficiency Index
- **DP**: Dynamic Programming
- **GARP**: Generalized Axiom of Revealed Preference
- **GRASP**: Greedy Randomized Adaptive Search Procedure
- **HARP**: Harmonic Axiom of Revealed Preference
- **HI**: Houtman and Maks Index
- **LOH**: Loss of Heterozygosity
- **LP**: Linear Program(ming)
- **MC-TOP-MTW**: Multi-Constraint Team Orienteering Problem with Multiple Time Windows
- **MEP**: Minimum Evolution Problem
- **MIP**: Mixed-Integer Program(ming)
- **MPI**: Money Pump Index
- **MRCPSP**: Multi-mode Resource-Constrained Project Scheduling Problem
- **MSTP**: Multiple Spanning Tree Protocol
- **PLOHP**: Parsimonious Loss of Heterozygosity Problem
- **PTP**: Prisoner Transportation Problem
- **SARP**: Strong Axiom of Revealed Preference
- **SBRP**: School Bus Routing Problem
- **SLS**: Stochastic Local Search
- **TP**: Transportation Problem
- **VI**: Varian Index
- **VRP**: Vehicle Routing Problem
- **WARP**: Weak Axiom of Revealed Preference

2 Composition of the network

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3 Overview of scientific results and networking activities

The main objectives of the Combinatorial Optimization: Metaheuristics and EXact methods (COMEX) project are:

- Bring together the available Belgian expertise on combinatorial optimization problems, exploit synergies between the partner research groups, and create a network with a sufficient mass to attract young and experienced top-level scientists in Belgium, and further financing for research in the field.
- Train young researchers in the field of combinatorial optimization. These profiles are in high demand, both in academic research centers worldwide and in private organizations.
- Develop new models, algorithmic techniques and implementations for complex, large-scale combinatorial optimization problems.
- Develop new international collaborations with other large teams working in the field of combinatorial optimization.

The first year of the project gave the opportunity to hire 10 new doctoral students and 4 postdoctoral researchers, fully funded by the project, among the 7 partners. The kick-off meeting and the 19th Belgian Workshop on Mathematical Optimization were two opportunities for all partners to get together, present their research activities and discuss future collaborations. High quality tutorials during the workshop, in addition to the day-to-day follow-up of the students in each team ensured that the second objective is met. The visibility of the network was ensured through participations to national and international conferences, and in particular through dedicated sessions at the ORBEL and EURO conferences.

Interactions between the partners were also initiated through several bilateral meetings between teams over the year.

For the third objective, the main research directions followed in the project are:

- Study and modelling of problems.
- Advancements in algorithmic techniques.
- Implementation of solution methods for large-scale, practically relevant problems.

As this is the beginning of the project, the focus was mainly on the modelling of problems. The next section describes in details achievements obtained in different application domains (Networks, Transportation & Logistics, Operations Management, Bio-informatics, Economics). Advancements in algorithmic techniques are reported in WP1.1 to WP1.4. This first year, for these workpackages, was mainly targeted as exchanging ideas between the teams about possible collaborations and setting up the directions for future research. Finally, the implementation of some solution methods is definitely a target for the end of the project, but some preliminary implementations for some specific problems are already available as reported further in this report.

The last objective, to develop international collaborations, started with some exchanges with the two international partners. These exchanges are also at an early stage but will be extended in the future. In particular, colleagues from the University of Maastricht were invited to

the Belgian Workshop on Mathematical Optimization to give a tutorial talk, and we expect our colleagues from Montreal to attend next year's workshop as well. The international visibility of the network was also ensured by a COMEX session organized at the EURO conference in July 2013.

4 Research achievements

WP 0.1 Management

This work package is mostly administrative. It aims at organizing the meetings between the partners and setting the framework for the teams of the project to organize the workshops, summer schools and conferences.

The major events organized during the first year of the project were:

- a kick-off meeting at ULB on October 11, 2012,
- the organization of a stream of sessions at the ORBEL 27 conference in Kortrijk, February 7-8, 2013,
- the organization of the 19th edition of the Belgian Mathematical Programming Workshop in La-Roche-en-Ardennes on March 6-8, 2013, including a full day dedicated to the COMEX project on March 6.

Another task performed in this work package was the coordination of the redaction of this report, and the collection of data for the administrative report.

WP 0.2 Dissemination

WP 0.2.1 Website and mailing list

A website for the project has been set up at http://comex.ulb.ac.be. It is still in construction.

Two mailing lists are also used:

comex-project@euro-online.org: This is an internal mailing list used for the exchange of informations between researchers involved in the project. Archives of the mailing list are publicly available at
http://www.euro-online.org/pipermail/comex-project/.

comex-announces@euro-online.org: This public mailing list is used to announce events (seminar, workshops, ...) related to the dissemination of the project research activities. Archives of the mailing list are publicly available at
http://www.euro-online.org/pipermail/comex-announces/.

WP 0.2.2 Publications

The list of publications emanating from the project is available in Section 6.

WP 0.2.3 Conferences

- **ORBEL 27, KU Leuven, Kortrijk, February 7-8, 2013**
  A stream of sessions was organized, spanning the whole duration of the conference. Recent work of researchers involved in the COMEX project were presented in 17 talks spanning 5 sessions.

- **EURO-INFORMS 2013, Rome, July 1-4, 2013**
  Session *«COMEX - Exact and heuristic algorithms for hard problems»*
  - Dantzig-Wolfe reformulation for the network pricing problem with connected toll arcs
    Alessia Violin (ULB/GOM), Bernard Fortz (ULB/GOM), Martine Labbé (ULB/GOM)
  - An exact formulation for three-dimensional bin-packing with transportation constraints
    Célia Paquay (ULg), Sabine Limbourg (ULg), Michaël Schyns (ULg)
  - Approximation algorithms for multi-dimensional vector assignment problems
    Trivikram Dokka (KUL), Yves Crama (ULg), Frits Spieksma (KUL)
  - An algebra of boolean functions and their relation with heuristics
    Patrick De Causmaecker (KUL)
- **Mista 2013, Gent, 27-30 Augustus 2013**
  Graham Kendall (chair), Barry McCollum (co-chair) Greet Vanden Berghe (co-chair, organiser)
  Organisation and participation by COMEX members.
- Mista challenge organised by members of COMEX group KUL/CODeS: Tony Wauters (Chair), Joris Kinable, Pieter Smet, Wim Vancroonenburg, Greet Vanden Berghe,Jannes Verstichel.
- Yves Crama (ULg), Invited plenary talk: ROADEF, Congress of the French Operations Research Society, Troyes, France, February 2013.
- Martine Labbé (ULB/GOM). Invited plenary talk on *Network design problems in phylogenetics* at the International Network Optimization Conference, Tenerife, Spain, May 2013.
- Thomas Stützle (ULB/IRIDIA). Invited plenary talk on *Automated Algorithm Configuration: Methods, Applications and Prospects* at the IEEE Congress on Evolutionary Computation, CEC 2013, in Cancun, Mexico, June 2013.
- Thomas Stützle (ULB/IRIDIA). Tutorial on *Metaheuristics for Combinatorial Optimization* at the Evolutionary Algorithms summer school in Quiberon, France, June 2013.
- Thomas Stützle and Manuel López-Ibáñez (ULB/IRIDIA). Tutorial on *Automatic (Offline) Configuration of Algorithms* at the Genetic and Evolutionary Computation Conference, GECCO 2013, Amsterdam, The Netherlands, July 2013.

WP 0.2.4 Seminars

- Optimization approaches applied to the strategic planning of transportation infrastructures
  Bruno F. Santos (University of Coimbra, Portugal)
  November 13, 2012, ULg

- Calibration opportunities for activity-based travel demand models predicting passenger transport
  Mario Cools (University of Liege)
  November 20, 2012, ULg

- Disaster Mitigation and Humanitarian Relief Logistics
  Alper Döyen (University of Liege)
  November 27, 2012, ULg

- Metaheuristics - the metaphor exposed
  Kenneth Sörensen (University of Antwerp)
  December 11, 2012, ULg

- A location-inventory model for large three-level supply chains
  Jean-Sébastien Tancrez (UCL)
  January 21, 2013, ULg

- Differentiating Defaulters in Credit Scoring using Data Mining and Game Theory.
  Richard Weber (U. de Chile)
  February 28, 2013, ULB/GOM

- 2D Rectangular Cutting and Packing Problems: all the same or all different?
  José F. Oliveira (University of Porto, Portugal)
  March 11, 2013, ULg

- Architectural issues of NOKIA's Maemo/MeeGo mobile platform
  Andrey Kochanov (CBTeC Oy, Helsinki, Finland)
  May 6, 2013, KUL

- Algorithm Selection as a Collaborative Filtering Problem
  Mustafa Misir (INRIA, Paris, France)
  May 14, 2013, KUL

- Column generation approachs for two combinatorial problems of a telecommunication company
  Murat Firat (France Telecom, Sophia Antipolis. Orange Labs)
  June 6, 2013, ULB/GOM

- Stochastic Optimization in Multi-Periods Transportation Problems
  Thierry Pironet (HEC-ULg)
  June 13, 2013, ULg

- Efficient algorithms for Personnel Scheduling Problems
  Peter Brucker (University of Osnabrueck, Germany)
  June 18, 2013, KUL

- Minimizing Greenhouse Emissions in Vehicle Routing
  Gilbert Laporte (CIRRELT and Canada Research Chair in Distribution Management, Montreal, Canada)
  June 24, 2013, ULg

- A new integer linear programming formulation for the Job Sequencing and Tool Switching Problem
  Catanzaro (Operations Research, Faculty of Economics and Business, University of Groningen, The Netherlands)
  August 23, 2013, KUL

- A bilevel programming approach for network pricing optimization problems
  Martine Labbé (ULB)
  September 20, 2013, ULg

It is also worth mentioning that at ULB/IRIDIA, regular optimization group meetings and optimization reading group meetings are done (12 in the reporting period). In the optimization meetings IRIDIA postdoctoral and PhD students present their ongoing work for informal discussions while in the optimization reading groups, recent interesting articles are presented and actively discussed. Sometimes also new ideas for papers arise from these reading group meeting, one example actually being the article by Mascia, López-Ibáñez, Dubois-Lacoste and Stützle published at the LION 2013 conference.

WP 0.3 Training of young researchers

The PAI project is currently financing 10 PhD students and 4 postdocs. It allowed these researchers, as well as other PhD students not on the personal budget of the IAP, to attend several international conferences. The day-to-day training of the PhD students and young researchers is done at each of the partners. In particular, regular meetings between the supervisor and the students help to give direct feedback. These local measures are then extended through network-wide meetings, where the students' works are discussed among a wider audience, and to participation of other partners to doctoral jurys and comittees..

Specific activities of the project targeted at the PhD students and joined participations to doctoral jurys and comittees are reported below.

WP 0.3.1 19th Belgian Workshop on Mathematical Optimization

The annual Belgian Mathematical Programming Workshop aims at gathering the whole Belgian community active in mathematical programming, optimization and related areas. Each two-day workshop consists in a series of presentations by PhD students and two longer tutorial sessions by invited speakers. It took place on March 7-8, 2013.

The tutorials were:

- «Stackelberg games in networks: pricing and routing» by Stan Van Hoesel (Maastricht University), international COMEX partner.

- «Column Generation and Branch-and-Price» by Marco Lübbecke (RWTH Aachen University)

The workshop was preceded on March 6 by a full day dedicated to the COMEX project, with presentations of research activities by all partners and a discussion on possible new collaborations.

WP 0.3.2 Doctoral jurys and committees

- Yves Crama (ULg) was on the jury of T. Dokka at KUL (advisor: F.C.R. Spieksma), September 2013
- Gerrit Janssens (UHasselt) is on the jury of Th. Pironet at ULg (advisor; Y. Crama).
- An Caris (UHasselt)is on the committee of M. Mostert at ULg (advisor: S. Limbourg)
- S. Limbourg (ULg) is on the committee of H. Pollaris at UHasselt
- Kenneth Sörensen (UA) is on the committee of V. François at ULg (advisors: Y. Arda and Y. Crama)
- Yves Crama (ULg) is on the committee of Carlos Casorran at ULB/GOM (advisor: M. Labbé)
- Thomas Stützle (ULB/IRIDIA) is on the committee of Martim Moniz at ULB/GOM (advisor: B. Fortz)

WP 0.3.3 Doctoral courses

- Nguyen Dang (CODeS, KUL) participated in the doctoral course 2013 «Multicriteria decision analysis and multi-objective optimization», organised by Y. De Smet, Th. Marchant, M. Pirlot. at ULB and UMONS.

WP 1.1 Exact methods

L.A. Wolsey (UCL) and co-authors G. Cornuejols S. Yildiz from Carneggie Mellon (USA) settle an open problem about cut-generating functions: they show that any valid inequality for a natural model arising in cutting plane theory is dominated by an S-intersection cut (i.e. a very structured type of cut for which a constructive procedure can be given).

L.A. Wolsey (UCL) and H. Yaman from Bilkent (Turkey) study two continuous knapsack sets. These sets arise as relaxations in many mixed-integer programming problems involving capacities, demands and/or fixed costs. Consequently strong valid inequalities for these sets can be used in solving more complicated problems in supply chain management. When the coefficients of the integer variables are integer and divisible, the authors show that the convex hull is the intersection of the bound constraints and 2m polyhedra arising from a continuous knapsack set with a single unbounded continuous variable. The latter polyhedra are in turn completely described by an exponential family of partition inequalities. Polynomial size extended formulations are also given. A consequence of these results is that the coefficients of the continuous variables all take the values 0 or 1 (after scaling) in any non-trivial facet-defining inequality. Also optimisation over these sets can be carried out by solving a polynomial size linear program.

A. Aly, E. Cuvelier, S. Mawet, O. Pereira and M. Van Vyve (UCL) explore the possibility for several participants in a system to jointly optimise without revealing some private data. This problem lies at the intersection of combinatorial optimisation and cryptography. Potential applications can be found in benchmarking, auctions, and supply chain management. Two classical problems in combinatorial optimisation are studied: shortest path and maximum flow.

For these two problems algorithms suitable for usage of Secure Multiparty Computation are described, an implementation discussed and their performance is empirically studied.

M. Van Vyve and L.A. Wolsey (UCL) consider the computational usage of extended formulations when the size of the formulation is too large to be used in a branching scheme, but its LP relaxation can be solved reasonably fast. The question studied is: knowing a primal-dual optimal solution of the LP relaxation of the (strong) extended formulation, can we efficiently compute an LP relaxation in the original variable space that admits the same optimal solution? Can we guarantee that the constraints generated are facets? A theory is developed and some experiments with a multi-stage production planning problem are presented.

Polyhedral analysis of combinatorial problems has been a hugely successful approach. The efficiency of such algorithms heavily depends on the strength of the LP formulation. Ideally a good formulation represents the convex hull of solutions and is of polynomial size. S. Pokutta from GeorgiaTech (USA) and M. Van Vyve (UCL) show that the knapsack polytope, arguably the simplest of the NP-Hard problems, does not admit an extended formulation of polynomial size. Note that this result does not rely on the conjecture that P is different from NP. Although the result by itself is not very surprising, it adds to our theoretical understanding as to what is and what is not possible when using Linear Programming for solving combinatorial problems.

M. Van Vyve (UCL) proposes a polyhedral study of a special case of a very classical but poorly understood problem: fixed-charge transportation. In this problem, there is a set of depot, each with its own capacity and a set of clients, each with its known demand. For each depot-client pair, there is a fixed and a variable transportation cost. The goal is to find the optimal transportation schedule (what fraction of the demand of each client to serve from which depot). The authors show that fixed-charge transportation is both a special case and a strong relaxation of the practically important big-bucket multi-item lot-sizing problem. A complete characterisation of the convex hull is then given in the special case where the underlying network is a path.

A prerequisite for solving a particular integer programming formulation using a cutting plane approach, is knowledge of its convex hull. Dokka (KUL), together with Spieksma (KUL) have investigated the convex hull of the traditional formulation of the (axial) three-index assignment problem, a well-known problem in combinatorial optimization. A number of classes of valid inequalities for this formulation are known, and an open question is whether all inequalities with right-hand side 2 are known. Although this question remains open, a contribution in this work is the identification of a new class of valid inequalities. There are opportunities for generalizing these inequalities to multi-index assignment problems.

V. Pirenne (ULB/GOM) and B. Fortz (ULB/GOM) recently started studying the automation of the Benders decomposition method. This method is very successful for resolving linear, mixed and integer mathematical programs. Nevertheless, it is difficult to implement and it requires a huge knowledge of optimization techniques and problem structure. Each problem resolution requires a specific ad-hoc implementation. So the idea is to provide an automatisation of the method with software extensions libraries, as independent as possible of the solver architecture.

WP 1.2 Metaheuristics

WP 1.2.1 Aims and scope

Three main goals have been set for this work package:

- Give expertise and possibly hands-on help to partner groups who at some stage of their research need to implement metaheuristic algorithms but do not have the particular expertise
- Discover the relationship between the performance of metaheuristic components and different problems
- Obtain scientific insight into the working of (components of) metaheuristic frameworks

Obviously, it is too early in the project for much work to have been done with respect to goals 2 and 3 in this list. These goals will be accomplished near the end of the five year term of the COMEX project, since they need to draw on the extensive experience developed during the execution of the project.

Concerning the first goal, we observe that the COMEX network is becoming more intertwined. In this way, expertise on the development of metaheuristics is dispensed by the partners more experienced in this topic. Several meetings of the COMEX project teams have been organised and the development of metaheuristics has been a heavily debated topic at each one of them.

WP 1.2.2 Metaheuristic development

Several metaheuristics have been or are being developed for specific problems within the COMEX network. Detailed descriptions of these methods are given in the work-packages on domain-specific optimization (2.X). Below is a non-exhaustive list.

- At ULg, various heuristic algorithms are proposed to generate decision policies for the stochastic optimization model over a long rolling horizon for a multi-period vehicle loading problem with stochastic information regarding the release dates of items to be transported.
- At ULg, M. Schyns is working on an ant colony system metaheuristic to solve a dynamic capacitated vehicle routing problem with time windows and split delivery.
- UH in collaboration with ULg are developing a metaheuristic to solve a VRP in which several loading constraints are integrated. The main goal is to study how axle weight constraints may be taken into account when constructing vehicle routes. In the future, a meta-heuristic algorithm will be proposed to solve the problem.
- At ULg (in collaboration with HEC Montréal) metaheuristic algorithms for vehicle routing with multiple trips are developed
- At UA, metaheuristics are developed for various routing problems, like vehicle routing problems with hotel selection and risk-constrained vehicle routing problems.

- At UH metaheuristics are developed for drayage operations with time-dependent travel times.
- At UA, metaheuristics are being developed for various other optimization problems: the optimization of water distribution networks, the automatic composition of music, etc.
- Various types of "hyper-heuristics" are being developed at KUL.

WP 1.2.3 Preliminary observations

As mentioned, it is too early in the project to draw any significant conclusions on goals 2 and 3 of this work package. Nevertheless, some preliminary observations can be made:

- Although different types of metaheuristics are being developed by the various research teams, there seems to be a convergence on component-based techniques of the local search type. This is in alignment with the current views expressed in the metaheuristics literature. "Pure" metaheuristics of the evolutionary or metaphor-based type have not been developed by any of the research groups.
- Several teams are analyzing combinations of (meta)heuristics with exact methods, using both types of algorithms for subproblems where they seem most suitable.
- The flexibility of metaheuristics is demonstrated by the size and the complexity of problems that can be solved using these techniques.

WP 1.3 Integration of exact methods and heuristics

This work package deals with research that is targeted to integrate techniques from methods in integer and, more general, mathematical programming and (meta)heuristics into hopefully better performing, hybrid algorithms. This is a challenging but also very promising direction in combinatorial optimization. It is challenging also because integer programming (IP) and the heuristic optimization communities have been working in isolation from each other. As the COMEX project combines research groups rooted in either of these domains, it is also an opportunity to explore such techniques. Despite the early stage in the project, some work in this direction has been done and initiated.

The number of possible ways of combining exact and heuristic methods is multiple and often problem specific. In the following, we discuss several works that have been developed or where currently progress is being made. These works concern the derivation of heuristics methods from exact formulations, the solution of stochastic optimization problems, the usage of variable fixing strategies to derive simpler sub-problems for exact solution, and simply the experimental comparison of exact and heuristic methods to identify their relative strengths.

In their working paper "Approximation Algorithms for Multi-Dimensional Vector Assignment Problems" Yves Crama, Trivikram Dokka and Friets Spieksma deal with a special class of axial multi-dimensional assignment problems called multi-dimensional vector assignment (MVA) problems. They analyze two classes of polynomial-time heuristics for MVA, namely, hub heuristics and sequential heuristics, which are both based on iterative (exact) solutions of bipartite assignment problems from a worst case approximation ratio. In particular, it was

shown that, when the cost function is monotone and subadditive, hub heuristics, as well as sequential heuristics, have finite approximation ratio for every fixed number of vectors. Moreover, better approximation ratios are established for certain variants of hub heuristics and sequential heuristics when the cost function is monotone and submodular, or when it is additive.

Stochastic optimization problems are a common area where solutions to exact sub-problems may be useful. In particular, Yasemin Arda, Yves Crama, David Kronus, Thierry Pironet, and Pascal Van Hentenryck considered a multi-period vehicle loading problem with stochastic information about the release dates of items that have to be transported. The approach makes use of scenario techniques that rely on the exact solution of the underlying deterministic version of the problem. The deterministic version of the problem can be formulated as a large-scale set covering problem and be solved reasonably efficiently by a commercial IP solver. Several heuristic algorithms are proposed to generate decision policies for the stochastic optimization model over a long rolling horizon taking. These heuristics rely, in various ways, on the exact solution of the deterministic problems associated with subsets of scenarios. The computational tests demonstrate the benefits of the multi-period stochastic model over simple myopic strategies. A simple and efficient heuristic is shown to deliver good policies and to be robust against errors in the estimation of the probability distribution of the release dates. The paper is in press for *EURO Journal on Transportation and Logistics* (available at DOI 10.1007/s13676-013-0035-z).

L. Berghman (Toulouse Business School), V. T'Kindt (U Tours), and F. Spieksma (KUL) study the impact of combining the use of cutting planes with the use of variable fixing. They consider a time-indexed formulation for the unrelated parallel machine scheduling problem. The time-indexed formulation for single machine scheduling problems is well studied in the literature. However all this polyhedral knowledge has not been applied to time-indexed formulations of scheduling problems with multiple machines, in particular unrelated parallel machine scheduling. First they argue that all polyhedral knowledge known from the single machine problem (in particular, valid inequalities) is applicable to this formulation. They present new facet-inducing valid inequalities and a preprocessing technique involving fixing variables based on reduced costs. Both techniques are combined in a basic cutting- plane algorithm and the performance of the resulting algorithm is tested by running it on randomly generated instances. The primary goal of this work is to show the computational performance of an algorithm that combines valid inequalities and variable fixing by testing this algorithm on randomly generated instances. Computational experiments show that new valid inequalities lead to stronger linear relaxations of the time-indexed formulation. These experiments also show that the proposed cutting-plane algorithm with variable fixing helps to solve the instances that are hard to solve for the mathematical solver, more efficiently.

Jannes Verstichel, Patrick De Causmaecker, Frits Spieksma, and Greet Vanden Berghe developed exact and heuristic approaches to the problem of placing ships in locks, which is an important problem in the area of lock scheduling. A direct solution of the problem using an IP formulation and commercial IP solvers turned out to be computationally heavy. Hence, a decomposition approach was developed, where a heuristic method is used to improve the lower bound on the number of ships that can be placed in a same chamber, resulting in significant computational improvements. A comparison of the developed exact and heuristic algorithms shows that the decomposition-based approaches are rather effective; however, if high quality solutions are required in very short computation times (e.g. less than a second), the heuristic algorithms are clearly the method of choice. Interestingly, the heuristic algorithms also

find very high quality solutions (on average only 3.24% above optimal on the largest instances considered) within this short time. The possibility of having predictable run-times and high solution quality was deemed to be important in the context of the considered problem, as in the lock scheduling problem, frequently a fast solution to the problem of where to place ships is required.

One basis for such integration is the understanding of the relative performance of such methods on different problems, sometimes making an integration not useful. One such example where an integration is not necessary may be at least NP-hard puzzles. For example, Nils Fagerburg, Franco Mascia, Thomas Stützle (all ULB) have explored to solution of the NP-complete Light Up puzzle, which so far mainly has been tackled by heuristic techniques, using an integer programming formulation. In fact, it was found that the integer programming formulation solved by a standard software (SCIP version 3.0.0) outperforms by far the heuristic algorithms proposed in the literature. In fact, instances that have been tackled in the literature by heuristic methods can be solved in fractions of a second in this formulation. This work is currently submitted for journal publication.

WP 1.4 Testing and configuration of parameters

This work-package deals with all the research efforts that are dedicated to specific usages and developments in the direction of automatic algorithm configuration and tuning. In many of the contributions that are described in this report experimental analysis and experimental design play a significant role in the developments done. Many of these applications of experimental analysis and design follow mainly common standards that are being more widely spread in algorithmically oriented research. Specific guidelines and the development of a comparison standard for heuristics and exact algorithms will be undertaken later in the project. In the report on work-package 1.4, we focus on the usage of and the development of advanced techniques for supporting the offline and online configuration of algorithms and algorithm selection approaches. Such methods are currently a hot topic in research on heuristic and also exact methods. In the following, we first report on applications of offline configuration methods where these have or probably will be crucial to obtain very high performance algorithms. We then discuss the research targeted towards the development and improvement of automatic configuration methods and end with a discussion of the network's work on algorithm selection.

WP 1.4.1 Applications of tuning and configuration methods

Tianjun Liao and Thomas Stützle have developed a new hybrid algorithm for real-parameter optimization. This algorithm loosely couples IPOP-CMA-ES, an advanced evolution strategy with covariance matrix adaptation integrated with an occasional restart strategy and increasing population size, and (ii) an iterated local search (ILS) algorithm that repeatedly applies a different local search from CMA-ES to perturbations of previous high-quality solutions. The two algorithms are combined in an cooperative–competitive manner where limited information is exchanged between the two and both algorithms compete for further deployment during the available run-time. Automatic algorithm configuration of this algorithm with the irace tool developed at the IRIDIA/ULB partner has been crucial to reach highest possible performance. In fact, the tuned algorithm has won the IEEE CEC 2013 benchmark competition on real-parameter optimization.

In a collaboration with Florence Massen and Yves Deville from Université Catholique de Louvain, Manuel López-Ibáñez and Thomas Stützle from IRIDIA/ULB have examined the impact of automatic algorithm configuration on the performance of a pheromone-based heuristic column generation (ACO-HCG) approach for vehicle routing problems (VRP) with black-bock feasibility. ACO-HCG is a hybrid algorithm that combines ant colony optimization and a MIP solver. In this case, offline automatic algorithm configuration was used to obtain performance-optimizing parameter settings but also to analyze the impact specific algorithm parameters have on high-performance configurations. This is done by modifying the parameter settings of the tuned configuration in order to understand the significance of each parameter setting. In this way, we avoid wasting effort analyzing parameter settings that do not lead to a high-performing algorithm. Concerning the impact of offline algorithm configuration, it is interesting to remark that the tuned parameter settings did improve strongly the performance of the algorithm on the multi-pile vehicle routing problems and the three-dimensional loading capacitated vehicle routing problems and, in particular for the multi-pile VRP, for many problem instances new best-known solutions could be identified, making the tuned algorithm a new state-of-the-art algorithm for the considered problem.

In a collaboration between the IRIDIA and the GOM team of Université libre de Bruxelles, Bernard Fortz, Martine Labbé, Alessia Violin, Leslie Perez, and Thomas Stützle are examining the impact automatic algorithm configuration has on the performance and the engineering of branch-and-price algorithms for a network pricing problem. In this work is considered the automatic configuration of the branch-and-price part but also in addition the parameters of the underlying solver, which in this case is SCIP, version 3.0.1.

WP 1.4.2 Development of tuning and configuration methods

Work on the improvement of automatic algorithm configuration has followed several lines of research.

Zhi Yuan and co-authors have considered the usage of a post-selection mechanism for identifying the best out of a candidate set of high performance algorithm configurations. The central idea of the post-selection mechanism is to generate in a first phase a set of high-quality candidate algorithm configurations and then to select in a second phase from this candidate set the (statistically) best configuration. Hence, this method can be used as a post-processing to several runs of an automatic configuration method, but it can also be used as a method to handle the inherent stochasticity in automatic configuration. The analysis of this mechanism indicated its high potential and suggested that it may be helpful to improve automatic algorithm configuration methods.

Automatic algorithm configuration methods are themselves heuristic algorithms that tackle a n optimization problem that could be described as a stochastic, non-linear mixed-variable black-box optimization problem. As any other heuristic methods, also the automatic algorithm configuration methods have their own set of parameters. Leslie Perez, Manuel López-Ibáñez and Thomas Stützle have analyzed the impact specific parameters have on the performance of the irace method, which implements a flexible tool for the automatic configuration of algorithms: irace itself has specific parameters that enable the customization of the search process according to the tuning scenario. They have analyzed five parameters of irace: the number of iterations, the number of instances seen before the first elimination test, the maximum number of elite configurations, the statistical test and the confidence level of the statistical test.

These parameters define some key aspects of the way irace searches and identifies good configurations. Originally, their values have been set based on rules of thumb and an intuitive understanding of the configuration process. This work aims at giving insights about the sensitivity of irace to these parameters in order to provide guidance for their settings and possible further improvements of irace.

Tuning stochastic local search algorithms on large instances is impractical due to the large amount of CPU-time testing algorithm configurations requires on such large instances. Franco Mascia et al. define an experimental protocol that allows to tune an algorithm on small instances and extrapolate from the obtained configurations a parameter setting that is suited for tackling large instances. As a proof of concept, they study an iterated local search algorithm for the quadratic assignment problem and try to extrapolate the perturbation size of the algorithm to large instances through a regression model. A key point in their approach is that they leave the stopping time of the algorithm on small instances to be set in the regression, which allows to obtain more easily high regression fits.

Franco Mascia, Manuel López-Ibáñez, Jérémie Dubois-Lacoste and Thomas Stützle have studied the possibility of assembling algorithms from simple components by automatic algorithm configuration techniques in a bottom-up manner. Previously, mainly genetic programming or grammatical evolution methods have been used for such a task. They both use an implicit definition of algorithms based on a context-free grammar that defines possible compositions of algorithm components and parameter settings. They have shown that the process of instantiating such a grammar can be described in terms of parameters that in turn can be set and optimized using standard automatic algorithm configuration techniques. In experiments on the generation of iterated greedy algorithms they could show that the parametric approach they proposed resulted in better performing algorithms than grammatical evolution.

The parameterization of grammar rules is also relevant for recent work by the IRIDIA/ULB team on the automatic generation of hybrid stochastic local search (SLS) algorithms. In this work, first a practical, unified structure that encompasses several such SLS methods (aka metaheuristics) is proposed. From this structure, known SLS methods such as Iterated Greedy, Iterated Local Search, Simulated Annealing, Tabu Search, GRASP, and few others can be instantiated. At the same time, combinations of these SLS methods can be generated, thus, resulting in hybrid SLS algorithms. This structure is also practical since we propose a method to instantiate actual algorithms for practical problems in a semi-automatic fashion. The method presented in this work implements a general local search structure as a grammar; an instantiation of such a grammar is a program that can be compiled into executable form. We propose to find the appropriate grammar instantiation for a particular problem by means of automatic configuration. The result is a semi-automatic system that, with little human effort, is able to generate powerful hybrid SLS algorithm. The work on this research subject has been presented in several stages at conferences such as ORBEL, MIC, or HM but it is subject also of ongoing research.

An alternative to automatic offline algorithm configuration is to adapt the parameter settings during the search process for solving a particular problem instance. Such online parameter adaptation techniques are typically limited towards adapting few known important algorithm parameters. The IRIDIA/ULB group has examined the impact such online parameter adaptation have on algorithm performance and, in particular, what is the sensitivity of algorithm performance on the parameters of the online adaptation technique. In particular, it was examined the performance of the Reactive Tabu Search method, one of the best known and most

widely used methods to adapt the tabu list length while solving a problem. In a nutshell, the result is that for the problems tested (maximum clique and quadratic assignment), the online parameter adaptation techniques typically do not yield improvements over properly offline tuned fixed parameter settings and are also not able to adapt to specific stages of the search process. Even worse, sometimes these methods can be shown to adapt the wrong parameter. Nevertheless, if fixed offline tuned parameters are not available, the adaptation mechanism in Reactive Tabu Search (i) may adapt parameters to instance-specific best offline settings and (ii) the performance of Reactive Tabu Search is little sensitive to the parameters of the adaptation mechanism in Reactive Tabu Search as long as they are chosen in a reasonable range.

Initial research by Nguyen Dang and Patrick De Causmaecker considers automatic configuration as a multi-objective problem, where algorithm configurations need to be identified that provide a balance between different measures how the performance of algorithms can be evaluated. One such example they consider is the number of instances solved and the average computation time to optimum. They have considered several ways of how to tackle this problem and computational work is on the way.

WP 1.4.3 Algorithm selection

The general task in algorithm selection is to choose an algorithm from a set of candidate algorithms that achieves the best performance for solving a particular set of problem instances or a single problem instance. In a similar vain, an analogous problem arises when during the run of an algorithm one of several heuristics or operators need to be chosen. (In this latter case, the problem is sometimes also referred to as operator selection.)

Messelis, De Causmaecker, and Vanden Berghe (KUL) have investigated the construction of an automatic algorithm selection tool for the multi-mode resource-constrained project scheduling problem (MRCPSP). This research relies on the notion of empirical hardness models. These models map problem instance features onto the performance of an algorithm. Using such models, the performance of a set of algorithms can be predicted and based on these predictions, one can automatically select the algorithm that is expected to perform best given the available computing resources. We apply this strategy to the classic problem of project scheduling with multiple execution modes. We show that we can indeed significantly improve on the performance of state-of-the-art algorithms when evaluated on a set of unseen instances.

Misir, Verbeek, De Causmaeker and Vanden Berghe (KUL) have considered hyperheuristic approaches. In a first study, they have designed a new hyper-heuristic using a learning-based heuristic selection mechanism together with an adaptive move acceptance criterion. The selection process was supported by an online heuristic subset selection strategy. In addition, a pairwise heuristic hybridization method was designed. The motivation behind building an intelligent selection hyper-heuristic using these adaptive hyper-heuristic sub-mechanisms is to facilitate generality. The designed hyper-heuristic was tested on a number of problem domains defined in HyFlex, a high-level framework. The framework provides a set of problems with a number of instances as well as a group of low-level heuristics. Thus, it can be considered a good environment to measure the generality of selection hyper-heuristics. The computational results demonstrated the generic performance of the proposed strategy in comparison with other tested hyper-heuristics composed of the sub-mechanisms from the literature. Moreover, the performance and behavior analysis conducted for the hyper-heuristic clearly showed its adaptive characteristics under different search conditions. The principles comprising the

here presented algorithm were at the heart of the algorithm that won the first international cross- domain heuristic search competition.

In another study, the same group of authors studies the generality of selection hyper-heuristics across various problem domains with a focus on different heuristic sets in addition to distinct experimental limits. In order to demonstrate the effect of these elements, nine heuristic sets with different improvement capabilities and sizes were generated for each of three target problem domains. These three problem domains are home care scheduling, nurse rostering and patient admission scheduling. Fourteen hyper-heuristics with varying intensification/diversification characteristics were analysed under various settings. Empirical results indicate that the performance of selection hyper-heuristics changes significantly under different experimental conditions.

WP 2.1 Networks

Here we describe the different research activities that were carried out by diverse research teams within COMEX that focus on Networks. It is clear that the domain of networks is a large one, and that there are many connections to the other workpackages.

WP 2.1.1 Telecommunication

Ethernet. The Multiple Spanning Tree Protocol (MSTP), used in Ethernet networks, maintains a set of spanning trees that are used for routing the demands in the network. Each spanning tree is allocated to a pre-defined set of demands. B. Fortz (ULB/GOM), L. Gouveia and M. Moniz (ULB/GOM) study the Traffic Engineering problem of optimally designing a network implementing MSTP, such that the maximal link utilization is minimized. Past research available in the literature on the problem had been focusing, exclusively, on heuristic methods. Fortz, Gouveia and Moniz propose two mixed-integer programming models: one that makes use of multi-commodity flows (MFF), and another of arborescences (AF), to design the multiple spanning trees. These models are implemented using CPLEX. Numerical experiments shows that even though MFF is stronger than AF, solving the problem with AF is more effective in practice.

Routing. In today's communication networks, distributed control functions such as routing inherit design driven by processing capacity and memory consumption. Henceforth, the routing protocol decision process (distributed and online) remains still decoupled from the routing optimization process (centralized and offline). Distributed optimization does not take into account the distributed nature of the online routing decision making process because distributed optimization is not decomposed along the same dimensions as the routing decision making process. The challenge becomes thus how to modify the routing decision process to include optimization objectives and how to make the optimization problem aware of the distributed nature of the online routing decision process under dynamic conditions. As a first evolution in that direction, B. Fortz (ULB/GOM) and D. Papadimitriou propose a new combined optimization model that integrates network design decisions and routing decisions, with time-dependant demands. As part of our their contribution, the proposed model keeps in sight the need for a distributed routing function, through the use of scalable routing tables. That work was submitted to ICC2014 (and is available at http://hdl.handle.net/2013/ULB-DIPOT:oai:dipot.ulb.ac.be:2013/152674).

It will next be extended in the perspective of a fully distributed, decomposed optimization setting.

Network topology discovery. B. Fortz (ULB/GOM), C. Requejo and O. Oliveira (ULB/GOM) study the problem of reconstructing a tree network by knowing only its set of terminal nodes and their pairwise distances, so that the reconstructed network has its total edge weight minimized. This problem has applications in several areas, namely the inference of phylogenetic trees and the inference of routing networks topology. Phylogenetic trees allow the understanding of the evolutionary history of species and can assist in the development of vaccines and the study of biodiversity. The knowledge of the routing network topology is the basis for network tomography algorithms and it is a key strategy to the development of more sophisticated and ambitious traffic control protocols and dynamic routing algorithms.

A related problem was also studied by R. Aringhieri, D. Catanzaro (ULB/GOM), M. di Summa and R. Pesenti. The Minimum Evolution Problem (MEP) is a network design problem characterized by having unknown edge weights and specific degree constraints on the internal vertices. They have presented an exact solution approach based on a sophisticated combination of both a parallel branch-price-and-cut scheme and a non-isomorphic enumeration of all possible trees that are solutions to the problem. This particular approach allows to break symmetries and improve upon the performance of the current exact solution approaches.

WP 2.1.2 Transportation

Fixed Charge Transportation In work by T. Christensen and M. Labbé, an exact solution method is reported for the transportation problem with piecewise linear costs. This problem is fundamental within supply chain management and is a straightforward extension of the fixed-charge transportation problem. We consider two Dantzig-Wolfe reformulations and investigate their relative strength with respect to the linear programming (LP) relaxation, both theoretical and practical, through tests on a number of instances. Based on one of the proposed formulations we derive an exact method by branching and adding generalized upper bound constraints from violated cover inequalities. The proposed solution method is tested on a set of randomly generated instances and compares favorably to solving the model using a standard formulation solved by a state-of-the-art commercial solver.

Constrained Transportation. A research team consisting of W. Vancroonenburg (KUL), D. Goossens (U Gent), F. della Croce (U Torino), and F. Spieksma (KUL) consider the following natural generalization of the transportation problem, which they call the Red-Blue Transportation Problem (Red-Blue TP). In Red-Blue TP the supply nodes are partitioned into two sets (red supply nodes and blue supply nodes) and so-called exclusionary constraints are imposed. This means that supply nodes of different color cannot both supply a same demand node, ie, a demand node can only be delivered by supply nodes of the same color. They encountered a special case of this problem in a hospital context, where patients need to be assigned to rooms. The problem's complexity is established, and two integer programming formulations are compared. Furthermore, a maximization variant of Red-Blue TP is presented, for which a constant-factor approximation algorithm is proposed. They conclude with a computational study on the performance of the integer programming formulations and the approximation algorithms, by varying the problem size, the partitioning of the supply nodes, and the density of the problem.

WP 2.1.3 Smart Grids

At the UAntwerpen, work has started on modeling the network upgrading problem in smart grids. In this problem, the aim is to find a minimum-cost and robust upgrading strategy of the electricity network to allow for distributed production of electricity. An initial model has been built and contact has been established with the Flemish electricity network management organizations (Eandis, Infrax). In 2014, work will continue focusing on algorithms to solve this problem.

Further, research continues on the optimization of water distribution networks. This is a challenging optimization problem, and the literature is flooded with metaheuristic methods that do not meet the criteria for objective scientific research. A first paper providing an overview of the state of the art was published before the start of the COMEX project. A second paper, in which a generator for artificial water distribution networks was developed, has been accepted for publication in the journal “Water Resources Management”. Current work focuses on the development of metaheuristic methods for this challenging problem.

WP 2.2 Transportation & Logistics

WP 2.2.1 Intermodal transport

A. Caris (UH), S. Limbourg (ULg), C. Macharis (VUB), T. Van Lier (VUB) and M. Cools (ULg) have identified *research opportunities* which will enable the further integration of inland waterway transport in the intermodal supply chain. Their paper entitled "Integration of inland waterway transport in the intermodal supply chain: a joint research agenda" was presented at PIANC SMART Rivers 2013 Conference.

M. Mostert (ULg) and S. Limbourg (ULg) have studied *intermodal network design*, motivated by the need to reduce the environmental impact of freight transportation. The objective is to develop a network design model which allows the optimal location of intermodal terminals to be determined, subject to both economic and environmental efficiency. Three possible combinations are considered: (i) road-only, (ii) rail-road and (iii) inland waterway-road. The developed model can be used to test how modal split is influenced by the undertaken policies. Tests are carried out on the case study of Belgium. A first approach was presented at the conference ORBEL 2013.

At Hasselt University, a full truckload pickup and delivery problem is studied which arises in the context of *pre- and end-haulage (or drayage) activities* around intermodal container terminals. Loaded and empty containers need to be transported with either the origin or the destination of empty container transports being unknown in advance. Three meta-heuristic algorithms are proposed and compared with each other by K. Braekers (UH), A. Caris (UH) and G.K. Janssens (UH). Best results are obtained by a two-phase hybrid deterministic annealing and tabu search algorithm. A paper on this work is accepted for publication in Transportation Research Part E: Logistics and Transportation Review. An exact algorithm for a similar problem is proposed by G.K. Janssens (UH) and K. Braekers (UH). The work is accepted for publication in The International Journal of Computer Aided Engineering and Technology.

WP 2.2.2 Rich VRPs

Distributors are faced with loading constraints in their route planning. These loading constraints include multi-dimensional packing constraints, unloading sequence constraints, stability constraints and axle weight limits. Not taking these loading constraints into account makes a route planning often not feasible in practice and gives rise to last-minute (non-optimal) changes. The development of *vehicle routing models that incorporate loading constraints* is studied by H. Pollaris (UH), K. Braekers (UH), A. Caris (UH), G.K. Janssens (UH) and S. Limbourg (ULg). The number of contributions to this field of research has increased enormously in the last couple of years. A paper reviewing the recent literature has been submitted to OR Spectrum. Besides, the authors are currently studying a VRP in which several loading constraints are integrated. The main goal is to study how axle weight constraints may be taken into account when constructing vehicle routes. Preliminary results were presented at the HMS 2013 conference. In the future, a meta-heuristic algorithm will be proposed to solve the problem.

Dial-a-ride problems are concerned with the design of efficient vehicle routes for transporting individual persons (often elderly and disabled people) from specific origin to specific destination locations. K. Braekers (UH), A. Caris (UH) and G.K. Janssens (UH) study an extension of the standard dial-a-ride problem by considering heterogeneous users, heterogeneous vehicles and multiple depots. An exact branch-and-cut algorithm and a meta-heuristic algorithm are proposed to solve the problem. Extensive numerical experiments are presented on the homogeneous and heterogeneous variants of the dial-a-ride problem. Both solution approaches outperform current state-of-the-art algorithms. The work has been presented at the EURO 2013 conference and is submitted for publication to Transportation Research Part B: Methodological. A model to determine the resource requirements of a dial-a-ride system is proposed by A. Neven (UH), K. Braekers (UH), K. Declerq (UH), T. Bellemans (UH), D. Janssens (UH), G. Wets (UH). A case study on Flanders is performed. Transportation requests to be processed by each individual service provider are obtained by a microscopic simulation of the demand while accounting for spatial and temporal effects. Next, a separate vehicle routing plan is created for each service provider, using the meta-heuristic algorithm mentioned above. Finally, Y. Molenbruch (UH), K. Braekers (UH) and A. Caris (UH) are currently investigating the effect of service quality characteristics (time windows, maximum ride times) on the cost of dial-a-ride systems. First results will be submitted for presentation at the VeRoLog 2014 conference.

Y. Arda (ULg), Y. Crama (ULg), and H. Küçükaydın (ULg) consider an *elementary shortest path problem with resource constraints*, where a capacitated single vehicle serves customers within their time windows. Distance and time based variable costs are incurred when serving the customers. On the other hand, each served customer brings in a revenue. The aim is to find out the optimal service start time of the vehicle from the depot along with the trips to be performed in order to minimize the total transportation costs minus the collected revenues. The authors propose an exact dynamic programming (DP) algorithm which can deal with an infinite number of Pareto-optimal states by representing total traveling and waiting time as a piecewise linear function and develop appropriate dominance rules. Finally, a column generation algorithm is devised for solving the relaxed set covering formulation of the related vehicle routing problem where new columns are determined by the proposed DP algorithm.

J. Kinable (KUL), G. Vanden Berghe (KUL), and F. Spieksma (KUL) have worked on the *School Bus Routing Problem (SBRP)*, a generalization of the VRP. The problem involves the routing, planning and scheduling of public school bus transportation, and can be decomposed

into several subproblems. An exact branch-and-price framework for the SBRP is presented, with a strong emphasis on efficiency issues inherently related to column generation. Experiments are conducted on a set of 128 SBRP instances. Many of these instances are solved optimally. For the remaining instances, strong lower bounds have been derived. Furthermore, better integer solutions were found for a number of instances reported in the literature. Both lower bounds computed on the optimum solution, as well as stabilization added to the column generation procedure significantly improved computation times.

M. Schyns (ULg) is considering a *dynamic capacitated vehicle routing problem with time windows, (partial) split deliveries and heterogeneous service times*. An Ant Colony System meta-heuristic is proposed to solve the problem. The research question was initiated during a meeting with a main European cargo airport which would like to develop a system to optimize the journey of their refueling trucks. The problem corresponds to a VRP since the goal is to determine the trucks visiting sequence of aircrafts that need refueling. The objective is to maximize responsiveness and minimize the traveled distances. Responsiveness is defined here as the rapidity of completing operations such that each aircraft is free to depart as soon as possible. Some elements of this research were presented at EURO 2013.

Y. Arda (ULg), Y. Crama (ULg), V. François (ULg), and G. Laporte (HEC Montréal) are currently developing heuristic solution procedures for *vehicle routing problems with multiple trips (VRPM)*, variants of the VRP where each vehicle is allowed to perform one or more trips. In this work, the authors compare the use of specific multi-trip local search operators with more classical solution methods for the VRPM which consist in using VRP metaheuristics in combination with bin packing techniques. The adaptive large neighborhood search framework is used to tackle the problem and a special focus is put on understanding the effects of each algorithm component as well as their interactions during the search process. For now, the authors concentrate on the most classical version of the problem.

Finally, at the University of Antwerp, risk-constrained routing problems and routing problems with "hotel selection" are studied. *Risk-constrained routing problems* form a relatively new class of optimization problems, the aim of which is to minimize transportation cost while at the same time minimizing the risk of the transport. The models developed in this area are useful in transportation of, e.g., cash and valuables, and dangerous chemical substances. Several variants of this problem have been modeled, respectively with and without time windows. both have resulted in a paper that has been submitted for publication. A new vehicle routing problem the aim of which is to find several alternative solutions at the same time, has also been developed, and is almost ready for submission. *Routing problems with "hotel selection"*, in which a set of intermediate points (hotels) are given and in which the maximum length of each trip is constrained, have recently been introduced. The aim of this research is, on the one hand, to develop faster algorithms (two papers have been submitted for publication), and, on the other hand, to extend them in order to allow more realistic problems to be modeled.

WP 2.2.3 Travel time variations and time-dependent VRPs

K. Braekers (UH), A. Caris (UH) and G.K. Janssens (UH) are investigating the *effect of time-dependent travel times on drayage operations* in the service area of intermodal terminals. A deterministic annealing meta-heuristic is used to solve the problem. First results for the case in which all links have the same congestion effect were presented at the ORBEL 2013 conference. In the future, more realistic speed profiles will be examined.

A *shortest path problem with soft time windows* is studied by K. Braekers (UH) and G.K. Janssens (UH). Earliness and tardiness costs are considered next to the usual criterion of total path length. While the distance between the nodes may be fixed or time-dependent, criteria like total earliness or total tardiness are, by definition, time-dependent, i.e. they depend on the time one leaves a node. To solve this multi-criteria time-dependent shortest path problem, a dynamic programming approach is used. Preliminary results were presented at the ESM 2013 conference.

WP 2.2.4 Loading problems

Y. Arda (ULg), Y. Crama (ULg), D. Kronus (ULg), Th. Pironet (ULg) and P. Van Hentenryck have investigated a *multi-period vehicle loading problem with stochastic information* regarding the release dates of items to be transported. Several heuristic algorithms are proposed to generate decision policies for the stochastic optimization model over a long rolling horizon. These heuristics rely, in various ways, on the exact solution of the deterministic problems associated with subsets of scenarios. The resulting policies have been extensively tested on instances which display the main characteristics of the industrial case-study that motivated the research. The tests demonstrate the benefits of the multi-period stochastic model over simple myopic strategies. A simple and efficient heuristic is shown to deliver good policies and to be robust against errors in the estimation of the probability distribution of the release dates. The paper is due to appear in EURO Journal on Transportation and Logistics.

In addition, *loading problems in the context of air cargo transportation* are studied at ULg. V. Lurkin (ULg) and M. Schyns (ULg) address the problem of optimizing the loading of a set of containers and pallets into cargo aircraft serving multiple airports. Due to the pickup and delivery operations occurring at intermediate airports, this problem is simultaneously a weight and balance problem and a sequencing problem. The objective is to minimize fuel and handling operations costs. On the basis of a professional partner's real-world data, TNT Airways, numerical experiments using a standard branch-and-cut library are performed on a mixed integer linear program. This approach yields better solutions than traditional manual planning, which results in substantial cost savings. This research was presented at ORBEL 2013, ROADEF 2013, EURO 2013 and AGIFORS 2013. C. Paquay (Ulg), M. Schyns (Ulg) and S. Limbourg (ULg) have looked into the problem of optimizing the loading of boxes into containers. The goal is to minimize the unused volume. This type of problem belongs to the family of Multiple Bin Size Bin Packing Problems. The approach includes an extensive set of constraints encountered in real-world applications in the three-dimensional case: the stability, the fragility of the items, the weight distribution and the possibility to rotate the boxes. It also includes the specific situation in which containers are truncated parallelepipeds. While most papers on cutting and packing problems describe ad-hoc procedures, this paper proposes a mixed integer linear program. The validity of this model is tested on small instances. This research was presented at ORBEL 2013, ROADEF 2013 and EURO 2013 and has been submitted for publication.

Related to the work mentioned above, Vancroonenburg, Wim, Verstichel, Jannes, Tavernier, Karel, Vanden Berghe, Greet in Automatic air cargo selection and weight balancing: a mixed integer programming approach (Transportation Research E, Logistics and Transportation Review) introduce a mixed integer linear programming model as a decision support tool for air cargo load planning. The main objective for the model is to find the most profitable selection from a set of cargo to be loaded on an aircraft. The secondary objective is to minimize the

deviation between the aircraft's centre of gravity, and a known target value so as to reduce fuel consumption and improve stability. The model is subject to a large number of constraints that ensure structural integrity and stability of the aircraft, as well as the safety of the cargo and crew. A set of additional constraints guarantees safe and efficient loading and unloading. Experimental results on real-life data show that the model outperforms human expert planners on both objectives, while remaining computationally fast enough for interactive use. This advocates the use of such a decision support model for all air cargo load planning.

WP 2.2.5 Other

Horizontal collaboration in logistics is studied at the University of Antwerp. This field of study gives rise to new optimization models in which the aim is to lower the costs of a coalition of logistics partners, while at the same time giving proper incentives for each partner to benefit the coalition (generally through an adequate gain sharing mechanism). A model and algorithm for point to point transportation in the context of horizontal logistics collaborations, has been developed and the corresponding paper is currently under review. In this model, a cost allocation mechanism (the Shapley value) is integrated into the optimization problem to ensure that each partner receives an adequate share of the coalition profit. A second model is built in a selective vehicle routing context. Partners in this problem can set a cost of non-delivery for each customer and the algorithm will simultaneously choose the best set of customers to serve, while compensating each partner for its non-served customers.

Another research topic, in which the aim is to optimize the activities of vans that redistribute bikes across the different stations of a *bike sharing network* (Velo in Antwerpen, Villo in Brussels, ...), has been started recently at the UA. Initial models have been built and meta-heuristic algorithms are currently being developed.

M. Van Vyve (UCL), H. Yaman (Bilket, Turkey) and L.A. Wolsey (UCL) several consider variants of the two-level lot-sizing problem with one item at the upper level facing dependent demand, and multiple items or clients at the lower level, facing independent demands. They first show that under a natural cost assumption, it is sufficient to optimize over a stock-dominant relaxation. They further study the polyhedral structure of a strong relaxation of this problem involving only initial inventory variables and setup variables. They consider several variants: uncapacitated at both levels with or without start-up costs, uncapacitated at the upper level and constant capacity at the lower level, constant capacity at both levels. They finally demonstrate how the strong formulations described improve our ability to solve instances with up to several dozens of periods and a few hundred products.

Finally, transportation problems have often an underlying network structure, and as such, problems reported in WP 2.1.2 belong naturally to this workpackage as well.

WP 2.3 Operations Management

In this work package we study a number of applications in operations management. The applications serve as a valuator for the methodological development in the methodology packages and are selected from the range of applications in which the consortium has experience. In this first phase of the project, applications have been developed building on techniques widely used and studied in the community and the consortium. Many of the contributions discussed below were presented at the MISTA 2013 and ORBEL 2013 conferences which were both organized

by members of the IAP consortium.

WP 2.3.1 Health care

Personnel management in hospitals has received considerable attention in the scientific literature over the latest decades. Problems of staffing as well as of detailed rostering turn out to require complicated models with large and diverse constraint sets. At the strategic level, the mix of disciplines needed to support the care of a specific pathology set determines the composition of wards. This composition determines a critical size. The staffing problem is concerned with the assignment of personnel to these wards in order to create workable units. In their daily operation, ward operators or head nurses decide when nurses will be called in. They have to meet the demand generated by momentarily patient population and have to respect conditions on the work patterns origination in legal conditions, labor agreements, rules for healthy work organization and personal preferences. In 2011 we reviewed the broad problem domain, building on our work in 2004 discussing the literature on nurse rostering. Apart from personnel management, problems such as bed planning, patient admission and operation quarter planning, as well as home care scheduling (a combination of vehicle routing and personels planning) pose challenging problems.

Below we list and briefly discuss recent work (2013) on this and related subjects.

Smet, P., Bilgin, B., De Causmaecker, P., Vanden Berghe, G. (2013). Modelling and evaluation issues in nurse rostering. Annals of Operations Research. Smet, P., De Causmaecker, P., Bilgin, B., Vanden Berghe, G. (2013). Nurse Rostering: a Complex Example of Personnel Scheduling with Perspectives. In: Uyar S., Ozcan E., Urquhart N. (Eds.), Automated Scheduling and Planning Springer, 129-153.

Practical models of nurse rostering and the appreciation of what a good roster is do not completely coincide with the models and evaluation procedures in current benchmarks. This paper comments on these discrepancies and proposes new models and evaluation techniques. Descriptions of nurse rostering problems vary largely across the literature, which makes it almost impossible to track down scientific advances of models and corresponding approaches. The chapter introduces a mathematical formulation of a generic nurse rostering model. It provides common elements present in most nurse rostering research as well as important hospital constraints that are usually omitted from academic models. The new mathematical model satisfies all the basic requirements for future nurse rostering research and practical developments. Finally, the importance of public datasets is discussed, together with the characteristics of the various benchmark instances and research results obtained working on these instances.

Vancroonenburg, W., De Causmaecker, P., Vanden Berghe, G. (2013). A study of decision support models for online patient-to-room assignment planning. Annals of Operations Research.

In the framework of patient admission, the assignment problem is an important component. Patient admission significantly influences the costs and revenues in a hospital. It has an important impact on the organization and occupation of all units. In this paper, various decision support models for the room assignment are studied and compared.

A heuristic approach to an integrated personnel rostering and task assignment problem Smet, Pieter, Vanden Berghe, Greet Proceedings of the 6th Multidisciplinary International Conference on Scheduling: Theory and Applications The importance of this paper for OR in a hospital is the integration of two different problem domains: rostering and task assignment. The

interaction between the two is studied.

Messelis, T., De Causmaecker, P., Vanden Berghe, G. (2013). Algorithm performance prediction for nurse rostering. Proceedings of the 6th Multidisciplinary International Scheduling Conference: Theory and Applications (MISTA 2013).

This paper studies the application of techniques for algorithm behavior prediction to the case of nurse rostering. It demonstrates that these techniques can be applied to real world problems, in particular to the case of nurse rostering. Although algorithm performance prediction has been studied for some time now, examples of applications are still rare. This paper can be considered a first attempt and exhibits details of a real world application.

Automatic Constraint Weight Extraction for Nurse Rostering: A Case Study, Mihaylov, Mihail, Smet, Pieter, Vanden Berghe, Greet, 27th Annual Conference of the Belgian Operations Research Society (ORBEL) Kortrijk, Belgium (2013)

An important and hard problem in many applications of OR, and especially in health care, is about inferring the preferences and the aims of the planners. The authors investigate how machine learning techniques can be used to establish the goal function. By optimizing this function, the implicit expectations of the users should be maximally met.

It's time for a change to better utilize resources in healthcare Nordlander, Tomas Eric, Vanden Berghe, Greet, Schittekat, Patrick

To manage the rapid increase of hospital patients, there is an immediate need to improve efficiency of resource utilisation in healthcare. Adopting and applying traditional Operational Research techniques such as optimization is probably the most potent instrument to do this. However, to create a significant impact we need to dissolve the traditional problem partitions — formed by the limitation in processing power, outdated methods, and manual practice. Over the years, a substantial increase in processing power with significant improved methods has taken place. Still, the old partitions remain. We argue that it is high time to move to a more efficient partition that supports a better resource utilisation.

Cooperative search for fair nurse rosters Martin, Simon , Ouelhadj, Djamila, Smet, Pieter, Vanden Berghe, Greet, Ozcan, Ende Expert Systems with Applications

The development of decision support systems acceptable for nurse rostering practitioners still presents a daunting challenge. Building on an existing nurse rostering problem, a set of fairness-based objective functions recently introduced in the literature has been extended. To this end, a generic agent-based cooperative search framework utilising new mechanisms is described, aiming to combine the strengths of multiple metaheuristics. These different metaheuristics represent individual planners' implicit procedures for improving rosters. The framework enables to explore different ways of assessing nurse rosters in terms of fairness objectives. Computational experiments have been conducted across a set of benchmark instances. The overall results indicate that the proposed cooperative search for fair nurse rosters outperforms each metaheuristic run individually.

A time pre-defined variable depth search for nurse rostering Burke, Edmund K. , Curtois, Tim, Qu, Rong, Vanden Berghe, Greet INFORMS Journal on Computing

A variety of neighbourhood operators have been used in local search and metaheuristic approaches to solving nurse rostering problems. We test and analyse the efficiency of these neighbourhoods on benchmark problems taken from real world scenarios. A variable depth search is then developed based on the results of this investigation. The algorithm heuristically chains together moves and swaps which define the more effective search neighbourhoods. A number of heuristics for creating these chains were developed and we present experiments

conducted to identify the best ones. As end users vary in how long they are willing to wait for solutions, a particular goal of this research was to create an algorithm that accepts a user specified computational time limit and uses it effectively. When compared against previously published approaches the results show that the algorithm is very competitive.

WP 2.3.2 Production scheduling

Adaptive, reactive and responsive scheduling applications in production are characterized by a demand for fast, sufficiently good decision making under dynamically changing conditions. Of particular interest are situations with incomplete information and uncertainty. In (Wauters et al. 2011) we studied such a problem in the food industry where the behavior and the capacities of the production units were only predictable under very restrictive conditions. These conditions could not be met by the demand that would vary significantly in amount as well as in characteristics. The aim of the project was to improve a number of preset key performance indicators. We investigated the modeling aspects and the solution power of meta-heuristics for this kind of applications in combination with elements of machine learning. In this project we will build on this experience to investigate the possibilities of hybrid approaches in meeting all the aforementioned requirements.

Nesting has been a long standing problem in operational research. In collaboration with an SME specialized in production of leather goods, the following were studied and results were obtained:

Solving nesting problems Wauters, Tony, Vanden Berghe, Greet Wauters, Tony, demo and presentation at iMinds The Conference(2013)

Cutting and packing problems are some of the hardest optimization problems to address. And the issue only becomes worse if shapes are irregular. Together with the Belgian company INSYS (which develops integrated solutions for the textile and leather processing industry), our researchers are developing a nesting problem solver for leather cutting purposes. State-of-the-art methods from the literature are studied and implemented in a software tool. The goal is to have a fast (less than 2 minutes) and efficient (minimum waste) problem solver. This demo shows a proof-of-concept nesting problem solver where real irregular patterns are nested on a real irregular hide.

A heuristic approach to the prisoner transportation problem Christiaens, Jan , Wauters, Tony, Vanden Berghe, Greet MISTA 2013

The present paper introduces the Prisoner Transportation Problem (PTP) where prisoners have to be transported at a minimal cost. The PTP is a special case of the vehicle routing problem with pickup and delivery and time windows (PDPTW) (Dumas et al, 1991) The problem has been mentioned by J.G. Partyka (2000). As far as we know, no elaborated case has been published in the literature as of yet. The problem originates from a real-world prisoner transportation case in the Netherlands, where the transportation service has about 300 employees and its head quarter receives 750 transportation requests per day on average. The Prisoner Transportation Problem presents many interesting challenges related to vehicle types, personnel qualications, service time constraints, exclusionary constraints, etc. A problem formulation and a heuristic approach based on specialized data structures will be discussed presently.

A hybrid constructive algorithm for the integrated task and shift scheduling problem Smet, Pieter , Vanden Berghe, Greet, Proceedings of the 10th Metaheuristics International Conference Metaheuristics International Conference (MIC 2013)

In general, personnel rostering deals with assigning either tasks or shifts to a set of (multi-)skilled personnel. The integrated problem of task and shift scheduling has rarely been discussed, while in practice, it is an often occurring problem for which an inefficient solution can lead to large operational expenses. We introduce the single day variant of the integrated task and shift scheduling problem. An exact decomposition approach already greatly improved the required calculation time to find an optimal solution compared to solving a mathematical model of the integrated problem. In this study we present a constructive matheuristic which iteratively solves heuristically delineated subproblems to optimality. Experimental results on a generated benchmark dataset show that the constructive matheuristic finds near-optimal solutions in very short calculation time.

A decomposition approach for the integrated task and shift scheduling problem Smet, Pieter, Vanden Berghe, Greet, Proceedings of the 26th European conference on operational research

We present a decomposition approach for the single day task and shift scheduling problem. This problem deals with the challenge of assigning tasks to a set of multi-skilled employees, while also determining their shift assignments. We present an algorithm which decomposes the problem into a master problem of assigning tasks and a slave problem of assigning shifts. For larger instances, a general purpose exact solver requires too much time to optimally solve a mathematical model of the integrated problem, whereas the decomposition approach finds the optimal solution very quickly.

Using Advanced Algorithms to Optimize Concrete Delivery Wauters, Tony, Kinable, Joris, Vanden Berghe, Greet Wauters, Tony, iMinds The Conference Brussels, Belgium

Concrete suppliers are faced with an impressive number of operational challenges — including the acquisition of raw materials, scheduling production facilities, and (obviously) the actual delivery of concrete. This research leverages advanced algorithms to find efficient routes for a fleet of (heterogeneous) vehicles that commute between concrete production centers and construction sites, while adhering to strict scheduling and routing constraints. Or in other words: how can concrete suppliers serve more customers in less time? Based on new, data sets with real-world constraints, this demo shows a visualization of the generated solutions. In addition, an instant optimization of the waste is performed.

Using Advanced Algorithms to Generate Efficient Packing Solutions Wauters, Tony , Vanden Berghe, Greet

Finding efficient solutions for 3D packing problems is hard, especially when items (e.g. boxes or crates) are of different sizes. Mixed-case palletizing falls into this category of hard-to-solve problems. A heuristic approach has been developed to solve 3D packing problems in a short amount of time, it has shown to be very competitive. This demo shows the underlying algorithms in action: boxes of different sizes are packed onto one or multiple pallets in such a way that the generated solutions are stable, efficient, and respect real-world constraints. In addition, the solution foresees a separation into layers — to accommodate robotic loadings with minimal movements.

The overlapping case in an integrated staffing and rostering formulation Komarudin, Komar, Guerry, Marie-Anne, Vanden Berghe, Greet, De Feyter, Tim Proceedings of the 27 ORBEL Annual Conference of the Belgian Operations Research Society

Hardness analysis and a new approach for the shift minimisation personnel task scheduling problem Smet, Pieter , Wauters, Tony, Vanden Berghe, Greet the 27th Annual Conference of the Belgian Operations Research Society (ORBEL)

Mixed case 3D pallet loading with optimized robotic loadings Wauters, Tony, Christiaens, Jan, Vanden Berghe, Greet ESICUP meeting

The present paper considers the mixed case 3D pallet loading problem with optimized robotic loadings. The problem has been derived from a real-world pallet loading case. A number of rectangular shaped boxes of different sizes have to be loaded onto one or multiple pallets, subject to various hard and soft constraints. In addition to this complex three dimensional loading problem, the boxes have to be partitioned into layers. Each layer contains a set of boxes which can be loaded simultaneously by a robotic arm. A set of n rectangular shaped boxes have to be loaded on one or multiple rectangular pallets. All pallets have a fixed length, width and height. Each box belongs to a particular box type with defined length, width, height, weight, weight class, order line and family. The boxes have a 'this side up' restriction, and can only be rotated for 0 or 90 degrees around the z-axis. The main objective is to place all given boxes onto a minimal number of pallets, while still respecting the following hard and soft constraints. Hard constraints: - Pallet dimensions: each box must be placed on a pallet such that it does not exceed the pallet boundaries. - Overlap: each box must be placed on a pallet such that it does not overlap with other boxes. - Support: each box must be supported by other boxes for a certain percentage of its surface. No floating boxes are allowed. - Weight class: a box can only be placed on boxes of the same or a lower weight class (heavy boxes have lower weight classes), or on the pallet surface. Soft constraints: - Number of loading steps: minimize the number of steps needed for loading all boxes using a robotic arm. The robotic arm can carry multiple boxes together, but has several properties that limit which boxes can be carried together. - Center of gravity: for each pallet minimize the absolute difference between the center of gravity and the middle of the pallet. - Order line grouping: put boxes belonging to the same order line close together. - Family grouping: put boxes belonging to the same family close together. Some box families cannot be adjacent. All hard constraints have to be respected at any time. The soft constraints can be added as extra terms to the objective function. The hard constraints make it very hard to obtain a feasible solution for this problem, while the soft constraints are possibly conflicting with the main objective (minimize the number of required pallets). An example of such a conflict is that the positions of the boxes have a large effect on the number of loading steps. We present a heuristic approach to this complex pallet loading problem. This algorithm combines a new best fit placement strategy for positioning the boxes, and a state-of-the-art graph colouring heuristic for partitioning the boxes into layers. Good results are observed compared to current packing solutions on real-world problem instances.

A hybrid heuristic for a real world task assignment problem Garraffa, Michele, Smet, Pieter, Vanden Berghe, Greet, Proceedings of the 26th European conference on operational research

We present a heuristic algorithm for a real world problem in which tasks need to be assigned to a set of multi-skilled employees. The problem is modelled so that the Hungarian algorithm can be used to find the optimal solution in polynomial time. However, due to the large scale of the problem instances and limitations on calculation time, the run time of the Hungarian algorithm is too high to be acceptable. Therefore, we present a hybrid heuristic algorithm which iteratively solves small subproblems to optimality, thereby reducing computation time while still finding high quality solutions.

Route Planning Enhancement through Collective Intelligence Maervoet, Joris, Baker, Kevin, Vanden Berghe, Greet, LICT Scientific Symposium on Adaptivity in ICT Heverlee 11 September 2013

An effective shaking procedure for 2D and 3D strip packing problems Wauters, Tony, Ver-

stichel, Jannes, Vanden Berghe, Greet Computers & Operations Research

Two- and three-dimensional strip packing: a shaking procedure Wauters, Tony, Verstichel, Jannes, Vanden Berghe, Gree Proceedings of ORBEL27

In the present work we propose a shaking procedure for the two- and three-dimensional strip packing problems (2SP and 3SP). A set of rectangular items of given dimensions have to be packed into a strip with fixed base and open height such that the covered height is minimized. The items can be rotated by 90 degrees. Both 2SP and 3SP are NP-hard. The proposed procedure builds upon the common bottom-left-fill methods (BLF), and employs multiple sorting criteria to improve the solutions. Large improvements are observed on well known benchmarks sets.

A computational study of a cutting stock problem with sequence dependent cut losses Garraffa, Michele, Salassa, Fabio, Vancroonenburg, Wim, Vanden Berghe, Gree Multidisciplinary International Scheduling conference: Theory & Applications (MISTA 2013)

The paper presents a new cutting stock problem formulation that considers sequence dependent cut losses between items. It is shown that the problem formulation is strongly related to the distance constrained vehicle routing problem, and that the formulation reduces to the bin packing problem under specific conditions. A computational study will be presented at the conference that investigates the relevance of considering such sequence dependent cut losses. To this end, classic bin packing and vehicle routing heuristics, as well as a tailored pattern based heuristic based on an exact set covering formulation, are compared on a set of instances with varying characteristics

A Tabu Search Approach to the Truck Scheduling Problem with Multiple Docks and Time Windows Van Belle, Jan , Valckenaers, Paul, Vanden Berghe, Greet Computers & Industrial Engineering

While organizing the cross-docking operations, cross-dock managers are confronted with many decision problems. One of these problems is the truck scheduling problem. This paper presents a truck scheduling problem that is concerned with both inbound and outbound trucks at multiple dock doors. The objective is to minimize the total travel time and the total tardiness. The truck scheduling problem under study is described in detail and a mathematical model of the problem is provided which can be solved to optimality with a mixed integer programming solver, at the expense of a high computation time. Next, a tabu search approach is presented. Experimental results on new benchmark instances indicate that the proposed tabu search is able to find good quality results in a short time period, thus offering potential for integration in cross-docking decision support systems. Algorithm to maximize the degree of attainability and the degree of desirability of manpower planning Komarudin, , Guerry, Marie-Anne, Vanden Berghe, Greet, De Feyter, Tim Applied Stochastic Models and Data Analysis International Conference

This work studies a Markov manpower planning problem concerned with fulfilling the long term personnel need. Two criteria are considered for evaluating a personnel structure, i.e. the degree of attainability and the degree of desirability. The degree of attainability is an extension of the concept attainability described by Bartholomew et al. (1991) to overcome the crisp division of the set of the attainable and the set of the unattainable personnel structures. The degree of attainability represents the similarity of a personnel structure and the set of personnel structures that are attainable (Guerry, 1999). The degree of desirability is the degree in which the personnel structure corresponds with the long term objectives defined by the top management. The degree of desirability reflects the degree of similarity of a personnel structure and the de-

sired personnel structure. In previous work, both criteria have been defined based on fuzzy set theory. Current state of the art has combined these two criteria and presented a model under several assumptions (De Feyter & Guerry, 2009). One of the assumptions is that the personnel structure has a fixed value for the total size, i.e. the total number of personnel. At present no optimization method has been presented for finding a personnel structure with a high value for the degree of attainability as well as for the degree of desirability. We extend the previous model and propose two new models that provide more flexibility. The new models are flexible in terms of providing generalizations by, for example, allowing fixed total size constraint relaxation. Moreover, the new models can accommodate additional constraints, such as a required ratio between the number of personnel in one subgroup to another, etc. The two models are formulated using different membership functions. The first model uses a reciprocal function to formulate the degree of attainability and the degree of desirability whereas the second model employs a triangular function to define them. The first model can be formulated as a linear program. However, the second model can only be formulated as a mixed integer nonlinear program. Two different algorithms are proposed to address the second model, i.e. piecewise linear approximation(PLA) and particle swarm optimization PSO). Extensive experiments have been performed to instances derived from existing nurse rostering data sets, in order to assess the algorithms. It is shown that each of the proposed algorithms can be used to effectively solve its respective model.

Extended roster quality staffing problem - A medium term roster quality to support staffing decisions Komarudin, , De Feyter, Tim, Guerry, Marie-Anne, Vanden Berghe, Greet MISTA 2013

This paper is concerned with integrating the roster quality and the staffing decisions. In particular, the roster quality is aggregated over time to match the staffing planning period. It is in contrast with previous research that relied on the quality of a roster representing a much shorter horizon than the staffing period. This model extends on previous work by providing more accurate staffing decisions based on roster quality for the whole staffing period and taking into account all rostering constraints. The roster quality is obtained by a scenario-based aggregation. A simulated annealing has been applied to the model. The method has been tested on several problem instances, and the results show that it can produce a better personnel structure in terms of the roster quality than the initial personnel structure.

Messelis, T., De Causmaecker, P. (2013). An automatic algorithm selection approach for the multi-mode resource-constrained project scheduling problem. European Journal of Operational Research. This paper studies the application of automatic algorithm selection to project scheduling. As an algorithm selection approach is is also relevant for WP 1.4.3 Algorithm Selection as is mentioned there.

Finally, the work of Yves Crama, Trivikram Dokka and Frits Spieksma, on «Approximation Algorithms for Multi-Dimensional Vector Assignment Problems», as mentioned in WP1.3 Integration of exact and metaheuristic approaches finds its motivation in semi-conductor manufacturing.

WP 2.3.3 Other problems

A number of problems related to the passage of ships through locks were studied in depth. They were studied partly in the PhD work of Dr. Jannes Verstichel in close cooperation with the harbor of Antwerp where they led to concrete application:

Verstichel, J., De Causmaecker, P., Spieksma, F., Vanden Berghe, G. (2013). The generalized lock scheduling problem: An exact approach. Transportation Research E, Logistics and Transportation Review.

The lock scheduling problem is formulated, a mathematical program is given and solver performance is studied.

Verstichel, J., De Causmaecker, P., Spieksma, F., Vanden Berghe, G. (2013). Exact and heuristic methods for placing ships in locks. European Journal of Operational Research. Verstichel, J., De Causmaecker, P., Vanden Berghe, G. (2013). Placing ships in locks: a decision support approach using exact and heuristic methods. 10th ESICUP Meeting. Lille, France, 24-26 April 2013.

Placing ships in locks is studied as a subproblem of of the lock scheduling problem. Comparison and combination of exact and heuristic methods leads to efficient solutions that can be used in practice.

Verstichel, J., De Causmaecker, P., Vanden Berghe, G. (2013). An improved best fit heuristic for the orthogonal strip packing problem. International Transactions in Operational Research, 20(5), 711-730.

As a side of the the study of ship placement in locks, an approach for the orthogonal strip packing problem is investigated. New best results are presented.

An automated decision support tool for prisoner transportation in The Netherlands Christiaens, Jan, Wauters, Tony, Vanden Berghe, Greet, BNAIC, Delft, The Netherlands 7-8 November 2013

DV & O is responsible for prisoner transportation in The Netherlands. The organization needs to solve a vehicle routing problem with time windows [2], where prisoners have to be picked up and delivered while respecting capacity and safety constraints. A daily demand of about 700 prisoner transportations yields a very complex combinatorial problem, solved by three full time planners. A new heuristic approach, developed in cooperation with Conundra, will be demonstrated. The heuristic enables computing a routing solution for the prisoner transportation problem in less than 100 seconds with a potential to a significant cost reduction.

Geoxam: Decision Support Tool for Geographically Distributed Exam Scheduling Mihaylov, Mihail, Wauters, Tony, Vanden Berghe, Greet, BNAIC Delft,

A 3-phase approach to geographically distributed exam timetabling Mihaylov, Mihail , Wauters, Tony , Vanden Berghe, Greet MISTA 2013

These 2 papers deal with geographically distributed exam timetabling. Such problems are important in real-world applications, for example, for certification agencies. The authors propose a three-phase solution method, including a first phase where appropriate locations are identified, a second phase where the exams are scheduled, and finally a third phase to hiring exam supervisors. The problem is interesting and I understand the motivation for the decomposition approach. However, I miss a more detailed description of solution aspects and in addition some computational results.

The roster quality staffing problem - A methodology for improving the roster quality by modifying the personnel structure Komarudin, Guerry, Marie-Anne, De Feyter, Tim, Vanden Berghe, Greet European Journal of Operational Research

Quantitative decision support on personnel planning is often restricted to either rostering or staffing. There exist some approaches in which aspects at the staffing level and the rostering level are treated in a sequential way. Obviously, such practice risks producing suboptimal solutions at both decision levels. These arguments justify an integrated approach towards improving

the overall quality of personnel planning. This contribution constitutes (1) the introduction of the roster quality staffing problem and (2) a three-step methodology that enables assessing the appropriateness of a personnel structure for achieving high quality rosters, while relying on an existing rostering algorithm. Based on the rostering assessment result, specific modifications to the personnel structure can be suggested at the staffing level. The approach is demonstrated by means of two different hospital cases, which have it that they are subject to complex rostering constraints. Experimental results show that the three-step methodology indeed points out alternative personnel structures that better comply with the rostering requirements. The roster analysis approach and the corresponding staffing recommendations integrate personnel planning needs at operational and tactical levels.

The Multiconstraint Team Orienteering Problem with Multiple Time Windows Souffriau, Wouter, Vansteenwegen, Pieter, Vanden Berghe, Greet, Van Oudheusden, Dirk Transportation Science This paper introduces the multiconstraint team orienteering problem with multiple time windows (MC-TOPMTW). In the MC-TOP-MTW, a set of vertices is given, each with a service time, one or more time windows, and a score. The goal is to maximize the sum of the collected scores, by a fixed number of tours. The tours are limited in length and restricted by the time windows and additional constraints. Next to a mathematical formulation of the MC-TOP-MTW, the main contribution of this paper is a fast and effective algorithm for tackling this problem, by hybridizing iterated local search with a greedy randomized adaptive search procedure. On a large test set, an average run has a score gap of only 5.19

WP 2.4 Bio-informatics

The *Parsimonious Loss of Heterozygosity Problem* is studied at ULB/GOM. A Loss of Heterozygosity (LOH) event occurs when, by the laws of Mendelian inheritance, an individual should be heterozygote at a given site but, due to a deletion polymorphism, is not. Deletions play an important role in human disease and their detection could provide fundamental insights for the development of new diagnostics and treatments. D. Catanzaro, B. Fortz and L. Porretta investigate the Parsimonious Loss of Heterozygosity Problem (PLOHP), i.e., the problem of partitioning suspected polymorphisms from a set of individuals into a minimum number of deletion areas.

The PLOHP can be formulated as a specific version of the clique partition problem in a particular class of graphs called undirected catch-point interval graphs. The general problem is NP-hard.

The main issue for the resolution of the problem is the time needed to list of all possible cliques. In order to tackle this problem, we investigate the possibility to use column generation techniques, together with the use of graph decomposition methods and divide and conquer techniques in order to improve the solution time. We developed several preprocessing methods able to eliminate redundant information in the provided datasets and decomposition properties that make it possible to parallelize the solution procedure.

Genomic approaches to identify the factors underlying genetic diseases often generate large lists of candidate genes. In the last decade, several prioritization methods have been developed to help geneticists to identify in silico the most promising candidate genes from these lists in order to increase the yield of downstream experiments. F. Bonachela-Capdevila, D. Börnigen, L.C. Tranchevent, J. Breckpot, P. Brady, B. Thienpont, C. Laprise, J. Deprest, K. Devriendt, J.R. Vermeesch, B. De Moor, Y. Moreau and P. De Causmaecker (KUL) have developed a

strategy that integrates four prioritization tools (selected for their good performance) using dedicated statistics. This method is able to screen the complete genome in order to identify the few most promising genes that are predicted to be important for the disease under consideration. They apply this method to two birth defects, nonsyndromic congenital heart defect and congenital diaphragmatic hernia, and then to a more complex disease, asthma. For each disorder, they combine the predictions from the four prioritization tools to identify novel candidate genes. A closer look at the top predictions reveals both already known and novel candidate genes for the three disorders. In particular, BMPR1A, the top-ranking gene for congenital heart defects has recently been associated with syndromic heart defects. Furthermore, their results provide further support for the retinoic acid hypothesis (congenital diaphragmatic hernia) and propose two new candidate genes for asthma: RELA and FAS. The computational analysis reveals that the top predictions are either associated with syndromic cases of the diseases under study or are functionally linked to previously identified genes and therefore represent potentially new candidate genes. Altogether, these results demonstrate that computational disease gene prioritization methods can be used to quickly retrieve a small set of relevant candidate genes for further investigation.

Francisco Bonachela Capdvila used clustering techniques developed for gene prioritization in a text enrichment context (contribution to Human Language Technology for Language Learning, Stellenbosch, South-Africa, 11-12 November 2013, Automatic document enrichment for language learners, by Hans Paulussen, Francisco Bonachela Capdevila, Pedro Debevere, Maribel Montero Perez, Martin Vanbrabant, Wesley De Neve, Stefan De Wannemacker) as well as in a Personal dictionary for text selection Francisco Bonachela Capdevila, Maribel Montero Perez, Stefan De Wannemacker (poster at CLIN24, the Computational Linguistics in The Netherlands, about text similarity based on an algorithm that checks weighted co-occurrences between a particular text and a user based dictionary).

D. Catanzaro (ULB/GOM), S. E. Shackney and R. Schwartz investigated the problem of reconstructing a plausible progression of ductal carcinoma from single-cell sample data of an affected individual. Specifically, by using a number of assumptions derived from the observation of cellular atypia occurring in ductal carcinoma, they design a possible predictive model based on integer programming and the parsimony criterion. Preliminary experiments carried out on a population of 13 patients show that the corresponding predicted progressions are non-random and classifiable in subfamilies having specific evolutionary characteristics.

D. Catanzaro (ULB/GOM), S. Chaplick and B. V. Halldórsson and M. M. Halldórsson and J. Stacho investigated a particular new class of interval graphs called max-point interval graphs. This particular class of graphs naturally as a way to model e.g., relationships among DNA fragments in genome-wide association studies or basic transmission problems in telecommunications. They introduced and characterized this class of graphs; moreover, they investigated its relationships with other classes of graphs. Specifically, they show that the MPT graphs are a strict superset of interval graphs and incomparable to permutation, chordal, and planar graphs. Finally, they showed that the weighted independent set problem can be solved in polynomial time on MPT graphs and that the coloring problem is NP-complete.

Finaly, note that the problems related to network topology discovery described in WP2.1 have also applications in the reconstruction of phylogenetic trees.

WP 2.5 Economics

WP 2.5.1 Pricing problems

Several COMEX researchers are investigating variants of *pricing problems* involving two levels of decision making (or *bi-level optimization problems*).

At ULB/GOM, Fortz, Labbé and Violin (2013) developed a Branch-and-Price algorithm for the Network Pricing Problem with Connected Toll Arcs. They consider a network with two classes of arcs: a subset of arcs is owned by a company imposing tolls on their usage, and the remaining arcs are toll-free. Furthermore, toll arcs are connected such that they constitute a single path, as it occurs for instance in a highway network. The company is willing to maximise the revenue from tolls, whilst users seek their minimum cost path between their origin and destination.

In the paper "Dantzig-Wolfe Reformulation for the Network Pricing Problem with Connected Toll Arcs" (http://dx.doi.org/10.1016/j.endm.2013.05.083), Fortz et al. (2013) proposed a Dantzig-Wolfe reformulation of this problem. They showed that the linear relaxation is stronger than the formulation proposed in the literature and easily solvable. More advanced techniques have been included in the column generation algorithm, as initialisation alternatives, stabilisation of dual variables values and early stopping criteria. Furthermore, a full Branch-and-Price scheme has been proposed to solve the integer problem, with an ad-hoc branching algorithm using pseudo-costs to guide the choices. Finally some rounding heuristics have been investigated to improve the primal bound during the branching. The framework is currently being extended to branch-and-cut-and-price, including some efficient valid inequalities from the literature.

Additional work on related topics is in progress. C. Casorràn-Amilburu (ULB/GOM), B. Fortz (ULB/GOM), M. Labbé (ULB/GOM) and F. Ordóñez have been working on novel tight formulations which significantly improve existing formulations for single type of Follower Stackelberg Games and for single type of Attacker Stackelberg Security Games. They studied the polyhedral aspects of the relevant formulations and have been trying to establish links between formulations present in the literature.

For the Bayesian case, their main thrust is towards elaborating formulations which perform better than those already existing, in the sense that the LP relaxation of these new formulations are stronger. Computational experiments are being carried out to compare these new formulations with those in the literature.

WP 2.5.2 Decision-making models

Revealed preference is a classical concept in micro-economics. It relates the act of purchasing a bundle of goods to expressing a preference of the acquired bundle over other bundles. More precisely, by purchasing a specific bundle, the consumer reveals his or her preference for this bundle over other bundles available at the same price. Deciding whether a (group of) individual(s) acts "rationally" within this framework is an important question in economic analysis. It raises, in turn, various algorithmic and complexity issues.

This theme has been investigated by a joint team involving IAP researchers Y. Crama (ULg), B. Smeulders (KUL), F.C.R. Spieksma (KUL), F. Talla Nobibon (KUL), as well as several other researchers at KULAK and ULB.

In the working paper "(Revealed preference tests of collectively rational consumption behavior: formulations and algorithms", Talla Nobibon et al. (2013) consider revealed preference tests of the collective model of household consumption. They show that the decision problems 2-GARP and 2-SARP corresponding to testing collective rationality are NP-complete. This makes the application of these tests problematic for (increasingly available) large scale data sets. The authors present two approaches to overcome this negative result. First, they introduce exact algorithms based on mixed-integer programming (MIP) formulations of the collective rationality tests, which can be usefully applied to medium-size data sets. Next, they propose simulated annealing heuristics, which allow for efficient testing of the collective model in the case of large data sets. They illustrate these methods by a number of computational experiments based on Dutch labor supply data.

Their experiments indicate that the exact algorithms based on the new MIP formulations are effective for solving medium-size instances of both 2-GARP and 2-SARP. These results are a huge improvement compared to those obtained with previous models from literature. Secondly, the SA heuristic is able to solve even larger instances of the problems within a reasonable time, and it almost always provides the correct answer for all instances.

Another fundamental question in the field of revealed preference is related to the computation of so-called goodness-of-fit measures. We now elaborate on this question and on the progress achieved by B. Smeulders (KUL), L. Cherchye (KUL), B. De Rock (ULB) and F. Spieksma (KUL) in its investigation.

Given a dataset, it is well-known how to test for the Generalized Axiom of Revealed Preference (GARP), the Strong Axiom of Revealed Preference (SARP), the Weak Axiom of Revealed Preference (WARP), and the Harmonic Axiom of Revealed Preference (HARP). However, a frequently cited weakness of the basic revealed preference tests is that they are 'sharp' tests: they only tell us whether or not observed behaviour is consistent with the revealed preference axiom that is being tested. When consumption data do not pass the test, there is no indication concerning the severity or the number of violations. To deal with this, a number of measures have been proposed in the literature to express how close a data set is to satisfying rationality. Such measures are called "goodness of fit" measures; they tell us how well a revealed preference axiom fits the data at hand. Probably the most popular goodness of fit measure in applied work is Afriat's efficiency index (AI). Other frequently used measures are the ones of Houtman and Maks (HI), and Varian (VI).

It has been empirically recognized in literature that computing these goodness-of-fit measures is computationally intensive. However, no formal explanation of this phenomenon had been reported in literature.

Smeulders et al. (2013) have been able to establish the computational complexity of each problem that is a combination of one of the three goodness of fit measures (AI, VI and HI) and one of the four revealed preference axioms (GARP, SARP, WARP and HARP) mentioned above. More specifically, they have demonstrated that, for all four axioms, both Varian's and Houtman and Maks' index are inapproximable. Next, they have shown that these conclusions do not apply to Afriat's index, and they have presented exact polynomial algorithms for computing this index (for every revealed preference axiom that we considered).

There is a continuing interest in goodness of fit measures. This is illustrated by the recent introduction of several new indices in the literature; specifically the money pump index by Echenique et al. which calculates the monetary cost of irrational behaviour and the minimal swaps and minimal loss index by Apesteguia and Ballester. Indeed, irrational behavior makes

consumers vulnerable as it allows arbitrageurs to "pump money" from them. In particular, arbitrageurs can extract money from irrational consumers by following an opposite purchasing strategy. In a recent and insightful contribution, Echenique et al. operationalized this idea by proposing the money pump index (MPI). These authors present an intuitive MPI that is defined on the basis of revealed preference axioms characterizing rational consumer behavior.

Cherchye, De Rock, Smeulders and Spieksma (2013) have established that computing the mean and median MPIs is an NP-hard problem. This result provides a formal statement of the fact that it is computationally challenging to compute these measures in practice, in particular, for data sets with large numbers of observations.

Because of the computational difficulties associated with the mean and median MPIs, Cherchye et al. (2013) propose the maximum and minimum MPIs as easy-to-apply alternatives. The maximum MPI gives the percentage of money lost in the most severe violation of rationality, while the minimum MPI does the same for the least severe violation. Clearly, these measures preserve the intuition underlying the mean and median MPIs. In particular, they figure as natural bounds on the amounts of money that an arbitrageur can extract from irrational consumers. Importantly, the newly proposed maximum and minimum MPIs have clear practical usefulness. Cherchye et al. (2013) show that the maximum and minimum MPIs can be computed efficiently, i.e., in polynomial time, which makes them easily applicable to large data sets. They also indicate how such computation can proceed in practice.

This research was presented at the Symposium on Algorithmic Game Theory (Aachen), and EURO.

5 Network organisation and operation

5.1 Project and Management structure

The project is a collaboration between seven Belgian research groups from six different universities, and two international partners from the Netherlands and Canada. The project coordinator it responsible for the day-to-day coordination of the project. He is also so the main interface between the network and the funding agency (Belgian Federal Science Policy Office). He monitors the project planning and progress, consolidates the annual reports, and is responsible for the communication between the partners and for the dissemination of information provided by the partners.

The importance given by the project to organization, management, and dissemination is reflected by the workpackages WP 0.1 to WP 0.3, led by the project coordinator. We refer to Section˜4 of this report for details on the achievements in these workpackages.

For each workpackage, the workpackage coordinator is responsible for coordinating the research, and reporting to the project coordinator of any sensible matter related to the activities of the workpackage itself.

The steering committee of the project is formed by the local co-ordinators of all project partners, and be chaired by the project coordinator. The steering committee decides about the high level management issues, including training of researchers, scientific, financial, planning, and control matters. It supervises the project as a whole and is responsible to resolve conflicts and disputes in case they should arise.

The steering committee met two times during the first year of the projetc: during the kick-off meeting at ULB (October 11, 2012) and during the COMEX day at the 19th Belgian Workshop on Mathematical Optimization in La-Roche-en-Ardenne (March 6, 2013).

5.2 Networking activities

- Kick-off meeting, ULB, October 11, 2012.
- 19th Belgian Workshop on Mathematical Optimization, La-Roche-en-Ardenne, March 6-8, 2013. A full day (March 6) was dedicated to the COMEX project, with presentations of research activities by all partners and a discussion on possible new collaborations.
- Bilateral meeting between ULg and UHasselt on July 9, 2013, at the University of Hasselt, to investigate possible research collaborations.
  Participants:
  - ULg: Yves Crama , Michaël Schyns, Sabine Limbourg, Thierry Pironet, Virginie Lurkin, Martine Mostert
  - UH: Gerrit Janssens, An Caris, Katrien Ramaekers, Tabitha Maes, Lotte Verdock, Hanne Pollaris
  - ULB/GOM: Bernard Fortz (network coordinator)
- Various meetings between Leslie Perez (ULB/IRIDIA) and Alessia Violin (ULB/GOM) and occasionally in a larger group including Martine Labbé (ULB/GOM), Bernard Fortz (ULB/GOM), and Thomas Stützle (ULB/IRIDIA) to discuss common research on the

automatic configuration of a Branch-and-Price algorithm for a pricing problem in road networks. The work is ongoing.

- Meeting between Véronique François and Yasmin Arda from ULg and the ULB/IRIDIA team to discuss about joint research on the automatic generation of large-scale neighborhood searches for rich vehicle routing problems with multiple trips. Some concrete collaboration may arise in the future.

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