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Project P7/36

Combinatorial Optimization: Metaheuristics and EXact methods (COMEX)

Coordinator: Bernard Fortz

Scientific Report 2015
(October 1, 2014 - September 30, 2015)

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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 project is currently hiring 19 researchers, among the 7 partners. The annual meeting and the 21st 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 conference.

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

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.

The next section describes in detail 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. For these workpackages, some possible collaborations between the teams have been identified and will be pursued in the future. 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 development of international collaborations was intensified. Bernard Gendron from CIRRELT (Montreal) attended the annual meeting of the project in Brussels. Two sessions were organized at the CORS-INFORMS International conference in Montreal in June 2015 were researchers from 4 COMEX teams presented their work. A dedicated one day COMEX workshop was also organized in Montreal in November 2014.

3.1 Networking and training activities

3.1.1 Meetings and workshops

- COMEX Workshop on Network Design, CIRRELT, Université de Montréal
- Annual meeting, ULB, December 4, 2014.
- 21st COMEX Belgian Workshop on Mathematical Optimization, La-Roche-en-Ardenne, April 23-24, 2015. The workshop is a COMEX activity. A meeting of the COMEX steering committee took place during the workshop.
- Several meetings took place between members of the groups at Hasselt University and KU Leuven (campus KULAK) to explore joint research opportunities on the tuning, analysis and optimization of heuristic algorithms (e.g., at 24/6 and 5/10). Participants in these meetings were Jeroen Corstjens, An Caris, Benoit Depaire, Kris Braekers (UH), Patrick De Causmaecker and Nguyen Thi Thanh Dang (KUL). Currently, PhD students Jeroen Corstjens and Nguyen Thi Thanh Dang are jointly studying and comparing different methodologies to tune, analyze and optimize heuristics.
- On January 27, 2015, An Caris, Katrien Ramaekers, Kris Braekers and Piet Pauwels (UH) visited Maastricht University to meet with André Berger, Tjark Vredeveld, Evelyne Vanpoucke, Lieven Quintens and Louis Boon to share research ideas. Additionally, it was agreed to initiate four PhDs under a double degree arrangement between Hasselt University and Maastricht University. Currently, administrative details are taken care off to formalize these arrangements. Three of the four PhD candidates have already started.

3.1.2 PhD Committees involving members of different COMEX teams

- Sabine Limbourg (ULg) is on the committee of Hanne Pollaris at UHasselt
- Yves Crama (ULg) is on the committee of Carlos Casorran at ULB/GOM
- Yves Crama (ULg) is on the committee of Bart Smeulders at KUL
- Yasemine Arda (ULg) is on the committee of Stef Moons at UHasselt
- An Caris (UHasselt) is on the committee of Martine Mostert at ULg
- An Caris (UHasselt) is on the committee of Christof Defryn at UAntwerp
- Greet Vanden Berghe (KUL) is on the committee of Yves Molenbruch at UHasselt
- Greet Vanden Berghe (KUL) is on the committee of Fabio Sciamannini at ULB/GOM
- Frits Spieksma (KUL) was a member of the PhD-committee of Abdelrahaman Aly at UCL (thesis defended in August 2015)
- Kenneth Sörensen (UAntwerp) is on the committee of Jeroen Corstjens at UHasselt
- Kenneth Sörensen (UAntwerp) is on the committee of Véronique François at ULg

- Thomas Stützle (ULB/IRIDIA) is co-supervisor of the thesis of Nguyen Thi Thanh Dang (KUL)
- Thomas Stützle (ULB/IRIDIA) is on the committee of Martim Moniz at ULB/GOM
- Thomas Stützle (ULB/IRIDIA) was on the jury of Alessia Violin at ULB/GOM (thesis defended in December 2014)

3.1.3 Other training activities

- UMaastricht and UHasselt have a joint PhD degree.
- A yearly doctoral course on metaheuristics is given by Kenneth Sörensen (UAntwerp) and is attended by many PhD students belonging to COMEX teams.

3.2 Dissemination

3.2.1 Website and mailing list

The website of the project is `http://comex.ulb.ac.be`. 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/.

3.2.2 Publications

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

3.2.3 Conferences and Workshops

- **ORBEL 29, Antwerp, February 5-6, 2015**

  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 33 talks spanning 9 sessions.

- **21st COMEX Belgian Mathematical Programming Workshop**

  The COMEX network took over the organization of the workshop. The workshop consisted in 11 presentations by PhD students and postdoctoral researchers, and two tutorial talks:

  - Jeff LINDEROTH (University of Wisconsin)
    "Mixed-Integer Nonlinear Optimization: Applications, Algorithms, and Computation"
  - Holger HOOS (University of British Columbia)
    "From Programs to Program Spaces: Leveraging Machine Learning and Optimisation for Automated Algorithm Design"

- **MAPSP2015** - http://www.mapsp2015.com

  The **12th Workshop on Models and Algorithms for Planning and Scheduling Problems (MAPSP2015** was organized in La Roche, Belgium, June 7-12, 2015.

  The workshop was supported by COMEX and co-organized by two partners of the project (ULg and KUL). The members of the organizing committee were Y. Crama (ULg), D. Goossens, R. Leus (KUL), M. Schyns (ULg), F.C.R. Spieksma (KUL).

  Proceedings: A. Marchetti-Spaccamela, Y. Crama, D. Goossens, R. Leus, M. Schyns, and F. Spieksma, editors. *Proceedings of the 12th Workshop on Models and Algorithms for Planning and Scheduling Problems*. KU Leuven, 2015.

- **Plenary talks by COMEX members at international conferences:**

  - Frits Spieksma. *An overview of multi-index assignment problems*. Plenary talk given at the Workshop on Tractable special cases of hard combinatorial optimization problems, Graz, Austria, Dec. 2014.
  - Frits Spieksma. *Balanced Optimization with Vector Costs*. BIRS Workshop on Approximation Algorithms and Parameterized Complexity, Banff, November 2015.
  - Yves Crama. *Revealed preference tests of collectively rational consumption behavior*. Conference on Graphs & Decisions, Luxembourg, October 2014.
  - Yves Crama. *Boolean Functions for Classification: Logical Analysis of Data*. DA2PL' 2014 (Decision Aid To Preference Learning Workshop), Ecole Centrale Paris, November 2014.
  - Thomas Stützle. *Towards Automatically Configured Multi-objective Optimizers*. Plenary invited talk given at the Evolutionary Multi-objective Optimization Conference (EMO 2015), Guimarães, Portugal, 2015.
  - Thomas Stützle. *Automated Algorithm Configuration: Recent Advances and Prospects*. Plenary invited talk given at the VIII ALIO/EURO Workshop on Applied Combinatorial Optimization, Montevideo, Uruguay, 2014.

- **Invited tutorials:**

  - Thomas Stützle. Invited tutorial on *Automatic (Offline) Configuration of Algorithms* at the EURO 2015 Conference, Glasgow, UK, Juli 2015.
  - Thomas Stützle and Manuel López-Ibáñez. Tutorial on *Automatic (Offline) Configuration of Algorithms* at the Genetic and Evolutionary Computation Conference, GECCO 2015, Madrid, Spain, Juli 2015.
  - Thomas Stützle and Manuel López-Ibáñez. Invited tutorial on *Automatic Algorithm Configuration: From Parameter Tuning to Automatic Design* at the Learning and Intelligent Optimization conference, LION 9, Lille, France, January 2015.

3.2.4 Awards

Virginie Lurkin (ULg) was awarded the Anna Valicek medal by AGIFORS (the Airline Group of the International Federation of Operational Research Societies) for her joint work with Michaël Schyns on airline container loading problems with pick-ups and deliveries

3.2.5 Seminars

1. ULB/GOM

    - June 22, 2015
      On Solving Hard Quadratic 3-Dimensional Assignment Problems from Wireless Comminications
      Hans Mittelmann (Arizona State University, USA)
    - May 5, 2015
      Modeling and Solving the One-to-One Multi-Commodity Pickup and Delivery Traveling Salesman Problem
      Mario Ruthmair (AIT, Austria)
    - April 21, 2015
      A multi-stage stochastic supply network design problem with financial decisions and risk management: modeling aspects and an exact algorithm
      Francisco Saldanha da Gama (University of Lisbon, Portugal)
    - February 12, 2015
      Railway Timetabling for Passengers
      Peter Sels (Logically Yours/Infrabel/KU Leuven)
    - December 18, 2014
      GCG: A Generic Branch-Price-and-Cut Solver
      Marco Lübbecke (Aachen University, Germany)
    - December 3, 2014
      Virtual Network Embedding: Models, Complexity, and Computations
      Arie Koster (Aachen University, Germany)
    - November 26, 2014
      Extensions and limitations of a simple approach to revenue management
      Patrice Marcotte (Université de Montréal, Canada)
    - November 13, 2014
      Exact solution of quadratic programs through quadratic convex reformulation
      Souror Elloumi (ENSIIE and CEDRIC, France)

2. ULg

    - June 2015, Tuesday 16
      Une approche basée sur la programmation mathématique à deux niveaux pour résoudre des problèmes de tarification
      Luce Brotcorne (Inria Lille – Nord Europe)

- March 2015, Friday 20
  Computational strategies for a multi-period network design and routing problem
  Bernard Fortz (ULB)
- March 2015, Tuesday 03
  The Intelligent RAO Simulator
  Serguei Iassinovski (Project Manager at Multitel)
- January 2015, Thursday 22
  Sequential diagnosis of k-out-of-n systems with imperfect tests
  Kris Coolen(HEC-ULg)
- November 2014, Friday 28
  Modeling convex subsets of points
  Prof. Maurice Queyranne (Université Catholique de Louvain)
- October 2014, Thursday 16
  A bi-objective homecare scheduling problem: analyzing the trade-off between costs and patient convenience
  Kris Braekers (Hasselt University)

3. KULeuven

- January 2015, Friday 9, CODeS Gent
  Selected topics from Health Care Logistics
  Prof. Stefan Nickel (Karslruhe Institute of Technology)
- January 2015, Tuesday 13, CODeS Gent
  Case-based Reasoning in Radiotherapy Treatment Planning for Brain Tumour
  Prof. Sanja Petrovic from the University of Nottingham
- February 12, 2015, CODeS Gent
  Challenges for pathplanning in highly dynamic environments
  Ignace Saenen (UGent-iMinds)
- February 23, 2015, CODeS Gent
  Column generation based heuristics for an integrated task and personnel
  Pieter Smet (KULeuven, CODeS)
- April 11, 2015, CODeS KU Leuven
  Applications of automatic configuration/tuning, generating hybrid local search algorithms from a grammar.
  Manuel López-Ibáñez IRIDIA laboratory in the Université Libre de Bruxelles (ULB)
- April 16, 2015, CODeS Kortrijk
  Synergy of knowledge and optimization
  Clarisse Dhaenens, Laetitia Jourdan and Marie-Eléonore Marmion (INRIA - Lille)
- August 18, 2015, CODeS Gent
  Systematic comparison of multi-agent systems and centralized algorithms in large scale and dynamic logistics
  Rinde van Lon (Distrinet, KU Leuven)

- August 18, 2015, CODeS Gent
  An analysis of the Verolog solver
  Nguyen Thi Thanh Dang (CODeS, KU Leuven)
- October 10, 2015, CODeS Gent
  Talk 1: An Exact Semidefinite Programming Approach for the Max-Mean Dispersion Problem
  Talk 2: An Exact Exponential Branch-and-Reduce Algorithm for the Single Machine Total Tardiness Problem
  Michele Garraffa (Politecnico di Torino)
- October 27, 2015, CODeS KU Leuven
  An Exact Semidefinite Programming Approach for the Max-Mean Dispersion Problem
  An Exact Exponential Branch-and-Reduce Algorithm for the Single Machine Total Tardiness Problem
  Michele Garraffa, Politecnico di Torino
- November 20, 2015, CODeS Gent
  MIP-Based Variable Neighborhood Search Algorithm For Solving Nurse Scheduling Problems
  Erfan Rahimian (University of Strathclyde)
- November 30, 2015, CODeS KU Leuven
  MIP-Based Variable Neighborhood Search Algorithm For Solving Nurse Scheduling Problems
  Erfan Rahimian, University of Strathclyde, UK.

4. ULB/IRIDIA

   - June 22, 2015
     On Solving Hard Quadratic 3-Dimensional Assignment Problems from Wireless Communications.
     Hans Mittelmann (U Arizona, USA).
   - May 21, 2015
     The Price of Complexity in Financial Markets.
     Tarik Roukny (ULB).
   - April 22, 2015
     Experimenters believe in experience! Selected examples on how a material chemistry/biochemistry unit faces the "experience-based" experimental design.
     Riccardo Marega (U Namur).

   It is also worth mentioning that at ULB/IRIDIA, regular optimization group meetings and optimization reading group meetings are done. 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.

5. UCL

- November 25, 2014
  Coordinate descent methods for I0-regularized convex optimization problems.
  Ion NECOARA, University Polytehnica of Bucharest
- December 9, 2014
  Adaptivity in opportunistic communication networks
  Neil OLVER, CWI
- December 16, 2014
  On Chubanov's algorithm for solving the linear feasibility problem
  Cornelius ROOS, University of Delft
- February 10, 2015
  A Multiplicative Weights Update Algorithm for Polynomial MINLP
  Luca MENCARELLI, Ecole Polytechnique
- February 24, 2015
  A Strong Formulation for Minsum Scheduling Problems on Unrelated Parallel Machines
  Halil Şen, Sabancı University
- March 3, 2015
  How Good Are Sparse Cutting-Planes?
  Marco Molinaro, TU Delft
- March 5, 2015
  Projection-free Learning and Optimization
  Dan Garber, Technion
- March 10, 2015, exceptionally in DOYE 21
  Mathematical Programming Methods for Stochastic Optimization Methods with a Class of Risk Measures
  Alexander Vinel, University of Iowa
- March 24, 2015
  Robust Multiobjective Optimization
  Ralf WERNER, University of Augsburg
- March 26, 2015
  Public Multi-Product Health Procurement: The Dynamic Inventory Budget Allocation Problem
  Iva RASHKOVA, London Business School
- April 21, 2015
  Structured Stochastic Integer Programs: Understanding the Effects of Uncertainty
  Stein W. WALLACE, Norwegian School of Economics
- April 28, 2015
  Global Polynomial Diffeomorphisms, Coercive Polynomials and Newton Polytopes
  Tomas BAJBAR, Karlsruhe Institute of Technology
- May 5, 2015
  A Simple Model for Commodity Markets
  Ivar EKELAND, Université Paris Dauphine

- May 26, 2015
  On the Polyhedrality of the T-branch Closure
  Diego MORAN, Virginia Tech
- June 2, 2015 Non-tâtonnement Price Adjustment Based on Convex analysis
  Vladimir SHIKHMAN, Université catholique de Louvain
- September 22, 2015
  On the use of Non-stationary policies for infinite-horizon Markov Decision Processes
  An improved version of the Random-Facet pivoting rule for the simplex algorithm
  Bruno SCHERRER, Université de Lorraine, and Thomas DUEHOLM HANSEN, Aarhus University
- September 25, 2015
  A revealed preference theory of monotone choice and strategic complementarity
  John QUAH, Oxford University
- October 6, 2015
  Complementary Pivot Algorithms for Market Equilibria
  Jugal GARG, Max-Planck-Institute for Computer Science
- October 13, 2015
  Primal-Dual Symmetric Interior-Point Methods for Convex Optimization
  Levent TUNÇEL, UWaterloo
- October 27, 2015
  Randomized Iterative Methods for Linear Systems
  Peter RICHTARIK, School of Mathematics, University of Edinburgh
- October 27, 2015
  Bin Packing and Related Problems: General Arc-flow Formulation with Graph Compression
  Filipe Brandão, Universidade do Porto

4 Research achievements

WP 0 Management / Dissemination / Training of young researchers

See Section 3.

WP 1.1 Exact methods

In [63], Laurence Wolsey and Maurice Queyranne (UCL) fully characterize the convex hull of solutions of poset convex subsets. Poset convex subsets arise in applications that involve precedence constraints, such as in project scheduling, production planning, and assembly line balancing. They give a strongly polynomial time algorithm which, given a poset and element weights (of arbitrary sign), finds a convex subset with maximum total weight. They use it to construct a compact, ideal extended formulation for the convex hull CP of the characteristic vectors of all convex subsets in poset P. They also define a class of alternating inequalities that they show are sufficient to describe the convex hull of solutions in the original variable space. This will help in obtaining tighter bounds in any problem having this kind of structure as a relaxation.

Laurence Wolsey (UCL) and Maurice Queyranne (UBC, Canada) [64] consider the problem of switching machines on and off. This is an important aspect of unit commitment problems and production planning problems, among others. They study tight mixed integer programming formulations for two aspects of such problems: bounded length on- and off-intervals, and interval-dependent start-ups. For the problem with both these aspects we develop a tight (convex hull) formulation involving additional variables. This will help in obtaining tighter bounds in any problem having this kind of structure as a relaxation.

Aissi et al. [1] (UCL) consider multiobjective and parametric versions of the global minimum cut problem in undirected graphs and bounded-rank hypergraphs with multiple edge cost functions. For a fixed number of edge cost functions, they show that the total number of supported non-dominated (SND) cuts is bounded by a polynomial in the numbers of nodes and edges, i.e., is strongly polynomial. They strongly sharpen this bound in the case of two objectives. These results significantly improve on earlier graph cut results. They also imply that the parametric curve and all SND cuts, and, for the bicriteria problems, all Pareto optimal cuts, can be computed in strongly polynomial time when the number of objectives is fixed.

Anthony et al. (ULg) [3] study the problem of determining the smallest-size quadratization of boolean functions. This is of some practical interest because minimization of quadratic functions has been thoroughly studied for the last few decades, and much progress has been made in solving such problems exactly or heuristically. They initiate a systematic study of these quadratization approaches. They provide tight lower and upper bounds on the number of auxiliary variables needed in the worst-case for general objective functions, for bounded-degree functions, and for a restricted class of quadratizations. Their upper bounds are constructive, thus yielding new quadratization procedures. Finally, they completely characterize all "minimal" quadratizations of negative monomials.

Angulo and Van Vyve (UCL) [2] consider a class of fixed-charge transportation problems over graphs. They show that this problem is strongly NP-hard, but solvable in pseudo-polynomial time over trees using dynamic programming. They also show that the LP formulation associated to the dynamic program can be obtained from extended formulations of

single-node flow polytopes. Given these results, They present a unary expansion-based formulation for general graphs that is computationally advantageous when compared to a standard formulation, even if its LP relaxation is not stronger.

In Balandraud, Queyranne and Tardella (UCL) [5] solve two related extremal problems in the theory of permutations. The problems they consider are to determine the maximum cardinality of a minimal inversion-complete set of permutations, and that of a minimal pair-complete set of permutations. The latter problem arises in the determination of the Carathéodory numbers for certain abstract convexity structures on the (n-1)-dimensional real and integer vector spaces. Using Mantel's Theorem on the maximum number of edges in a triangle-free graph, we determine these two maximum cardinalities and we present a complete description of the optimal sets of permutations for each problem. Perhaps surprisingly (since there are twice as many pairs to cover as inversions), these two maximum cardinalities coincide whenever $n \geq 4$.

Van Daele et al. [25] (UCL) describe heurisitcs to determine the non-negative rank of (slack) matrices. This is a very important problem in combinatorial optimization since this number is equal to the minimum size extended formulation of the problem problem corresponding to this slack matrix. The heuristic is shown to be superior to earlier proposed algorithms and is then used to we disprove a conjecture on the nonnegative rank of a Kronecker product, propose a new upper bound on the extension complexity of generic n-gons and conjecture the exact value of (i) the extension complexity of regular n-gons and (ii) the nonnegative rank of a submatrix of the slack matrix of the correlation polytope.

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

Concerning the first objective, the different COMEX teams have been collaborating on the development of pure metaheuristics or hybrid exact/heuristic methods. Metaheuristics are developed in groups that previously focused more on exact methods (and vice versa). A comparison of both methods on the same problem can yield interesting results.

WP 1.2.2 Metaheuristics development

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. Many groups use the variable neighborhood search framework, which essentially combines different local search operators in a single heuristic algorithm. The advantages of this framework have been shown both in the general literature as in specific work within the COMEX project.

Heuristics based on the variable neighborhood search framework tend to be more robust and flexible and are able to solve a wide variety of optimization problems efficiently.

More recently, constructive metaheuristics have increased in popularity within the COMEX project framework, with a focus on the (adaptive) large neighborhood search heuristic. This metaheuristic is based on the idea to use several different constructive heuristics in a single heuristic. Essentially, adaptive large neighborhood search can therefore be seen as the constructive counterpart of variable neighborhood search. Again, the advantages of this framework are an increased robustness and flexibility (i.e., these heuristics are able to solve a range of different optimization problems efficiently and (auto-)adapt to different instances and even to different variants of the same optimization problem).

The COMEX partners align themselves with recent 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. Indeed, there is a growing resentment in the field against the indiscriminate use and development of ever more "novel methods" based on some kind of metaphor.

Several teams are analyzing combinations of (meta)heuristics with exact methods, using both types of algorithms for subproblems where they seem most suitable. The component-based view on metaheuristics seems to have pervaded throughout the COMEX community. Also, there is considerable research on the development of "hyper"-heuristics.

There is considerable research on tuning of metaheuristic algorithms, either automatic (by, e.g., the irace software) or manually, through a controlled statistical experiment. In this way, the development of metaheuristics is slowly losing its status as an "art". "Metaheuristic engineering" could be coined as a new way to describe the more systematic development of heuristic optimization algorithms the community is currently trying to achieve.

There is also an increasing focus within the COMEX project to develop multi-objective metaheuristics. Contrary to their single-objective counterparts, these tend to be of the evolutionary type, in that they work on a set of solutions (a "population") simultaneously. This can be explained by the fact that multi-objective heuristics output a set of non-dominated solutions, the so-called Pareto frontier.

As a conclusion, it can be said that the metaheuristics developed within the COMEX project are at the forefront of the field, both in terms of their quality as their scientific underpinning.

Further research will certainly focus on the development of other powerful heuristic methods for different optimization problems, and on the study of metaheuristics in general, to find out why and how these methods work as well as they do. In 2016, COMEX-sponsored workshop of EU/ME, the EURO working group on metaheuristics chaired by Kenneth Sörensen, will focus on these issues (www.eume2016.be).

WP 1.3 Integration of exact methods and heuristics

This work package deals with research that 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.

There are a number of ways of how to combine exact and heuristic methods; in most cases, the specific combinations are also problem specific. In the following, we highlight several research contributions that used some form of combination or collaboration of heuristic and exact techniques. In most of these cases, the context of the research and, in particular, the formulation of the problems is given in the descriptions of work-packages 2.1 to 2.5 as the specific combinations have been mostly developed in a problem-specific context. We do not explicitly mention here rather basic combinations such as the usage of heuristic algorithms to provide upper bounds to minimization problems that are solved by an exact method as such combinations are in the meantime a rather standard approach.

A. Rodriguez Chia, M. Gaudioso, E. Gorgone (ULB/GOM) and M. Labbé (ULB/GOM) [24] studied heuristics based on Lagrangian relaxation for dealing with feature selection in a standard L1 norm Support Vector Machine (SVM) framework for binary classification. The adopted feature selection model results in a mixed binary linear programming problem and it is suitable for a Lagrangian relaxation approach. The resulting Lagrangian dual is solved by means of a consolidated non-smooth optimization ascent algorithm. At every ascent step, it is provided a lower bound on the optimal solution as well as a feasible solution at low computational cost.

Y. Arda (ULg) and S. Michelini (ULg) have been working on the exact solution for an elementary shortest path problem with resource constraints (ESPPRC), where a capacitated single vehicle serves customers within specified time windows and can start its service at any desired time. The exact solution method, a bidirectional dynamic programming algorithm has been included in the design of a matheuristic, i.e., an integration of (meta)heuristics and MIP solving techniques. This work was presented at VeRoLog 2015 (4th Conference of the EURO Working Group on Vehicle Routing and Logistics Optimization, Vienna, June 2015) and at ORBEL29 (29th meeting of the Belgian Operational Research Society, Antwerp, February 2015).

Reducing environmental impact, related regulations and potential for operational benefits are the main reasons why companies share their returnable transport items (RTIs) among the different partners of a closed-loop supply chain. Iassinovskaia, Limbourg (ULg) and Riane [27] consider a producer, located at a depot, who has to distribute his products packed in RTIs to a set of clients. The problem formulation results in a pickup and delivery inventory-routing problem with time windows (PDIRPTW) over a planning horizon. They developed a mixed-integer linear program that could handle successfully small-scale instances but to handle more realistic large-scale problems, a cluster first-route second matheuristic is proposed [27].

In [60], Pollaris (Hasselt), Braekers (Hasselt), Caris (Hasselt), Janssens (Hasselt) and Limbourg (ULg) propose an Iterated Local Search method (ILS) for the CVRP with sequence-based pallet loading and axle weight restrictions. They developed matheuristics for two variants of the problem, which consists in solving the routing problem heuristically while the loading feasibility check is computed exactly.

In an article presented at [56] and submitted to Computers and Operations Research [55], Paquay (Ulg), Limbourg (Ulg), Oliveira and Schyns (Ulg) deal with finding a good feasible solution in a reasonable amount of computation time for the three dimensional Multiple Bin Size Bin Packing Problem (MBSBPP). The MBSBPP variant considered is one with additional constraints encountered in real-world air transportation situations such as the stability of the cargo or the particular shape of containers in air transportation. This extended MBSBPP has been formulated as a mixed integer linear programming problem (MIP), but currently only

poor results are achieved for even fairly small problem sizes. The goal of this work is to develop heuristics that may be able to provide better quality solutions, to then be used - if sufficiently good - as final solutions for the problem or as initial feasible solutions that may speed-up the mathematical programming model resolution. Three methodologies based on the decomposition of the original problem into easier subproblems are considered: the Relax-and-Fix, the Insert-and-Fix and the Fractional Relax-and-Fix matheuristics. They were tested on real data sets to determine the best parameters for each technique and then compared to the results of the Branch-and-Bound. Finally, extended experiments are carried out on the two best approaches to find their limitations. A best fit decreasing algorithm for the three-dimensional bin-packing problem with transportation constraints, currently under development, has been presented at [57].

Various other approaches to tackle complex vehicle routing type problems make at some point in the solution approach use of elements taken from heuristic and exact methods [22, 67, 13, 12]. As mentioned above, more details about these approaches can be found in the description of the problem-oriented workpackages in WP 2.2.

In the research on harbour and waterway logistics at the KUL partner, various methods that make a heuristic usage of exact formulations and decomposition approaches have been implemented. Verstichel and Vanden Berghe [83] use a combinatorial Benders' decomposition approach that enables the incorporation of traffic dependent lock capacity into exact solution methods for the serial lock scheduling problem. The method's performance is evaluated on a large set of small to medium sized instances, analysing the influence of traffic dependent lock capacities on both the ship waiting time and the total computation time. Despite promising results on small and medium sized instances, experiments show that the presented master problem is unable to tackle large real world instances. They therefore introduce a heuristic master problem of the presented combinatorial Benders' decomposition and discuss some preliminary results.

In his PhD thesis, Pieter Smet has addressed nurse rostering problems from a practical perspective [68]. He developed a number of solution approaches for these problemss that are based on decomposition algorithms, which combine exact techniques and heuristic search. Computational experiments illustrate the effectiveness and versatility of the proposed approaches on a large variety of benchmark instances.

Hoos and Stützle (ULB/IRIDIA) [26] investigate the empirical performance of the long-standing state-of-the-art exact TSP solver Concorde on various classes of Euclidean TSP instances and show that, surprisingly, substantially more time tends to be spent on finding optimal solutions than on completing the respective proofs of optimality, where the time to complete a proof of optimality is defined as the difference between the overall running time of Concorde on the given TSP instance and the time required for first finding an optimal solution. This finding holds for the widely studied random uniform Euclidean (RUE) instances as well as for several other widely studied sets of Euclidean TSP instances. On RUE instances, the median fraction of Concorde's total running time spent on completing proofs of optimality ranges from 0.23 for $n = 500$ to 0.03 for $n = 3500$; on TSPLIB, National and VLSI instances, we pegged it at 0.14, 0.26 and 0.39, respectively, with a tendency of even smaller values for larger instances.

WP 1.4 Testing and configuration of parameters

Work-package 1.4 deals with research efforts dedicated to specific usages and developments for automatic algorithm configuration and tuning. The contributions described in this report are typically based on in-depth experimental analyses and experimental designs; often, these follow common standards that are being more widely spread in algorithmically oriented research. Differently, in the report on specific developments relevant for 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.

WP 1.4.1 Automatic configuration software

The ULB/IRIDIA partner is developing the irace package for the offline automatic configuration of algorithms. In fact, modern optimization algorithms typically require the setting of a large number of parameters to optimize their performance. The immediate goal of automatic algorithm configuration is to find, automatically, the best parameter settings of an optimizer. Ultimately, automatic algorithm configuration has the potential to lead to new design paradigms of optimization software. The irace package is a software package that implements a number of automatic configuration procedures. In particular, it offers *iterated racing* procedures, which have been used successfully to automatically configure various state-of-the-art algorithms. During the current reporting period, further improvements have been introduced into the irace package that improve its performance and also usability aspects. Algorithmic improvements include the introduction of an elitist version of irace and modified sampling models. Usability improvements include the speed-up of some procedures of irace, improved parallelization, recovery mechanisms, and improved reporting features that indicate the importance and the impact of parameters.

The irace package has been used in a number of additional research efforts mainly concerning the systematic evaluation of optimizers, the development of configurable heuristic solver frameworks, and the final tuning of heuristic and exact algorithms.

WP 1.4.2 Applications of tuning and configuration methods

Liao et al. [35] experimentally examine the impact of tuning on the relative performance of continuous optimizers. In fact, the development of algorithms for tackling continuous optimization problems has been one of the most active research topics in soft computing in the last decades. It led to many high performing algorithms from areas such as evolutionary computation or swarm intelligence. These developments have been side-lined by an increasing effort of benchmarking algorithms using various benchmarking sets proposed by different researchers. In this article, the authors explore the interaction between benchmark sets, algorithm tuning, and algorithm performance. To do so, they compare the performance of seven proven high-performing continuous optimizers on two different benchmark sets: the functions of the special session on real-parameter optimization from the IEEE 2005 Congress on Evolutionary Computation and the functions used for a recent special issue of the Soft Computing journal on large-scale optimization. While one conclusion of our experiments is that automatic algorithm tuning improves the performance of the tested continuous optimizers, the main conclusion is

that the choice of the benchmark set has a much larger impact on the ranking of the compared optimizers. This latter conclusion is true whether one uses default or tuned parameter settings.

Bezerra et al. have also continued their studies on the automatic design of multi-objective evolutionary algorithms (MOEAs) to tackle multi-objective combinatorial optimization problems and the experimental comparison of algorithms. Their general approach to the design of MOEAs has been described in a journal article and is now accepted for publication in IEEE Transactions on Evolutionary Computation. Follow-up work on this has included the comparison of MOEAs that are based on problem decomposition and component-wise design on multi-objective continuous benchmark functions. In [9], they conduct a systematic analysis that compares algorithms produced using the MOEA/D decomposition-based framework and the AutoMOEA component-wise design framework. In particular, we identify a version of MOEA/D that outperforms the best known MOEA/D algorithm for several scenarios and confirms the effectiveness of decomposition on problems with three objectives. However, when we consider problems with five objectives, we show that MOEA/D is unable to outperform SMS-EMOA, being often outperformed by it. Conversely, automatically designed AutoMOEAs display competitive performance on three-objective problems, and the best and most robust performance among all algorithms considered for problems with five objectives. In a further study, they also consider the impact specific low-level operators have on the performance of MOEAs [10]. Strongly extended versions of a comparison of properly tuned MOEAs is the subject of ongoing work, which will lead to a journal submission in early 2016.

Aydin and Stützle have applied a generalized artificial bee colony (GABC) algorithm to the learning-based real-parameter optimization competition at the 2015 Congress on Evolutionary Computation [4]. The main idea underlying the GABC algorithm is to provide a flexible, freely configurable framework for artificial bee colony (ABC) algorithms. From this framework, one can not only instantiate known ABC algorithms but also configure new, previously unseen ABC algorithms that may perform even better than known ABC algorithms. One key advantage of a configurable algorithm framework is that it is adaptable to many different specific problems without requiring necessarily an algorithm re-design. This is relevant if in the application problem repeatedly instances of the problem need to be solved regularly. This situation arises in many practical settings e.g. in power control or other application areas: Routinely a sequence of specific instances of a more general continuous optimization problem arise and these instances have to be solved repeatedly (possibly for an infinite horizon) in the future: in this case the instances of the problem in the sequence will share similarities as they arise from a same source.

H. Pollaris, K. Braekers, A. Caris, G.K. Janssens (UH) and S. Limbourg (ULg) are studying a vehicle routing problem with sequence-based pallet loading and axle weight restrictions. In the past months, an Iterated Local Search heuristic has been developed to solve larger instances of the problem. The irace package, developed at ULB/IRIDIA, was applied to tune the parameters of the algorithm. Preliminary results of the heuristic have been presented at the VeRoLog 2015 conference.

Y. Arda (ULg), Y. Crama (ULg), V. François (ULg) and G. Laporte (Cirrelt, Montreal) [22] have developed heuristic solution procedures for multi-trip vehicle routing problems (MTVRP) where each vehicle is allowed to perform one or more trips without exceeding a maximum duration. The authors compare the use of multi-trip local search operators with more common solution methods for the MTVRP which consist in using VRP heuristics in combination with bin packing techniques. These two approaches are implemented within two different metaheuristic frameworks: the adaptive large neighborhood search (ALNS) and the tabu search (TS). A

special focus is put on understanding the interactions between heuristic components through experimentation. Since both ALNS algorithms have various implementation options and each more than 30 parameters to tune, collaboration with the research center IRIDIA (ULB) was initiated. The irace package was used to perform the automatic tuning of ALNS algorithms. This work was presented at VeRoLog 2014 (2nd Conference of the EURO Working Group on Vehicle Routing and Logistics Optimization, Oslo, June 2014) and at IFORS 2014 (20th Conference of the International Federation of Operational Research Societies, Barcelone/Espagne).

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 have examined the impact automatic algorithm configuration has on the performance of branch-and-price algorithms for a network pricing problem. The results have been described in the PhD thesis of Alessia Violoin, which has been defended in December 2014.

A. Frangioni, E. Gorgone (ULB/GOM) and B. Gendron (CIRRELT) [23] studied the tuning and the testing of a (generalized) subgradient method combined with different rules for the step-size and the search direction, for the standard network design problem. The algorithm includes the Primal-Dual variant designed by Yu. Nesterov and the incremental versions designed by D. Bertsekas.

WP 1.4.3 Gray-box parameter tuning

Gray box parameter tuning and algorithm selection are have been studied in depth and looked at from an algorithm design point of view. One aim of gray box parameter tuning is to come to a framework optimally supporting designers of algorithms for combinatorial optimisation problems in the course of the design process. An extensive case study has been performed on the behavior of a large number of neighborhoods in a metaheuristic for a vehicle routing problem [14]. Each neighborhood is accompanied by a weight value which represents the probability of choosing it at each iteration. These weights are fixed before the algorithm runs, and are considered as parameters of the algorithm. However, the large number of neighborhoods can make the tuning expensive and difficult. In this work, we propose a method to characterize each neighbourhood's behaviours, representing them as a feature vector, and using cluster analysis to form similar groups of neighborhoods. We show that using neighborhood clusters instead of individual neighborhoods helps to reduce the parameter configuration space without misleading the search of the tuning procedure. Moreover, this method is problem-independent and potentially can be applied in similar contexts. Thus, clustering those neighborhoods offers better opportunities for parameter tuning algorithms, improving the development process and resulting in the generation of more efficient algorithms. This can be considered as a gray box approach, allowing the designer to enrich the environment with more information and stimulating new ideas.

WP 1.4.4 Algorithm selection

A fundamental algorithm selection framework has been designed and preliminary results have been presented in two workshops. A limitation of most metaheuristics is that they are designed to handle only one kind of performance: minimisation or maximisation with the performance-value-interpretation increasing linearly in function of the actual value. At the student workshop of GECCO 2015 a more general model for performance has been presented, as well as

a method to define new metaheuristics in terms of this model [18] A preliminary implementation of the model has been created in Java. This model facilitates broad applicability of any metaheuristic or general algorithm framework. At the informal COSEAL workshop a poster has been presented in which a next step in the research on automatic algorithm selection is proposed. Current approaches train a selection model offline and keep the selection model static while it is used during the online phase to select algorithms for new problem instances. However, after every selection during the offline phase additional information is obtained: the performance of the selected algorithm on the instance. The poster proposes a method to use this additional information to continue learning during the online phase, thereby continuously improving the selection model. Audience feedback was positive and has led to a collaboration with researchers from UBC, Canada and LMU, München on empirically investigating the possibilities of an alternative method to continue learning during the online phase.

WP 1.4.5 Advanced experimental methodologies

Palhazi Cuervo et al. [50] focus on stated choice experiments, which are conducted to identify the attributes that drive people's preferences when choosing between competing options of products or services. They are widely used in transportation in order to support the decision making of companies and governmental authorities. A large number of attributes might increase the complexity of the choice task in a choice experiment, and have a detrimental effect on the quality of the results obtained. In order to reduce the cognitive effort required by the experiment, researchers may resort to experimental designs where the levels of some attributes are held constant within a choice situation. These designs are called partial profile designs.The authors propose an integrated algorithm for the generation of D-optimal designs for stated choice experiments with partial profiles. This algorithm optimizes the set of constant attributes and the levels of the varying attributes simultaneously. An extensive computational experiment shows that the designs produced by the integrated algorithm outperform those obtained by existing algorithms, and match the optimal designs that have been analytically derived for a number of benchmark instances. It follows an evaluation of the performance of the algorithm under varying experimental conditions and study the structure of the designs generated.

Advanced experimental methodologies have been used to study the scaling behavior of the scaling behaviour of state-of-the-art local search algorithms for the TSP [20]. In particular, Dubois-Lacoste et al. study the scaling of running time required for finding optimal solutions to Euclidean TSP instances. They use a recently introduced bootstrapping approach to assess the statistical significance of the scaling models thus obtained and contrast these models with those recently reported for the Concorde algorithm. In particular, they answer the question whether the scaling behaviour of state-of-the-art local search algorithms for the TSP differs by more than a constant from that required by Concorde to find the first optimal solution to a given TSP instance. Current work is ongoing to study the impact automatic algorithm configuration has on the scaling behavior of the state-of-the-art local search algorithms studied in [20].

WP 2.1 Networks

This section describes the work that was carried out by the COMEX consortium in the field of Networks. We distinguish research in the domain of Telecommunications (Section 2.1.1), Security (Section 2.1.2), and Miscellaneous (2.1.3)

2.1.1. Telecom

B. Fortz (ULB-GOM), L. Gouveia (FCUL, Portugal), and M. Joyce-Moniz (GOM, ULB) study the multi-commodity flow problem with unsplittable flows, and piecewise-linear costs on the arcs. They show that this problem is NP-hard when there is more than one commodity. They propose a new MILP models for this problem, that was compared to two formulations commonly used in the literature. The computational experiments reveal that the new model is able to obtain very strong lower bounds, and is very efficient to solve the considered problem.

M. Leitner (ULB-GOM and UV, Austria) and L. Gouveia (CMAF+CIO, Portugal) study the Network Design Problem with Vulnerability Constraints (NDPVC) which simultaneously addresses resilience against failures (network survivability) and bounds on the lengths of each communication path (hop constraints). Solutions to the NDPVC are subgraphs containing a path of length at most H_{st} for each commodity $\{s, t\}$ and a path of length at most H'_{st} between s and t after at most k edge failures. They first show that a related and well known problem from the literature, the Hop-Constrained Survivable Network Design Problem (kHSNDP), that addresses the same two measures produces solutions that are too conservative in the sense that they might be too expensive in practice or may even fail to provide feasible solutions. They also explain that the reason for this difference is that hop-constrained Mengerian theorems do not hold in general. Three graph theoretical characterizations of feasible solutions to the NDPCV are derived and used to propose integer linear programming formulations. In a computational study we compare these alternatives with respect to the lower bounds obtained from their linear programming relaxation and their capability of solving instances to proven optimality. In addition, it is shown that in many cases, the obtained solutions are cheaper than those obtained by the related problem previously suggested.

M. Leitner (ULB-GOM and UV, Austria) [33] studies the generalized hop-constrained minimum spanning tree problem (GHMSTP) which has applications in backbone network design subject to quality-of-service constraints that restrict the maximum number of intermediate routers along each communication path. Different possibilities to model the GHMSTP as an integer linear program and strengthening valid inequalities are studied. The obtained formulations are compared theoretically, i.e., by means of their linear programming relaxation. In addition, branch-and-cut approaches based on these formulations are developed and compared in a computational study. B. Fortz (ULB-GOM) and M. Leitner (ULB-GOM and UV, Austria) study Benders decomposition approaches for fixed-charge multi-commodity flow problems. The main point is to start from an aggregated formulation and re-introduce the strength of the disaggregated formulation via Benders cuts. This approach is also studied for problem variants involving commodity-dependent flow costs and a complex variant involving multi-period decision. M. Leitner (ULB-GOM and UV, Austria) and B. Gendron (CIRRELT) study Branch-price-and-cut algorithms for an undirected variant of the multi-commodity fixed-charge network design problem in which at most one among a large set of modules shall be installed at each edge such that all commodities can be routed at minimum overall costs. The goal is to dynamically generate both flow and module variables as well as consider different strengthening constraints that have been proposed in the literature.

H. Calik (ULB-GOM) and M. Leitner (ULB-GOM and UV, Austria) study different variants of the p-Cable Trench Problem. One particular focus is the recently proposed p-Cable Trench Problem with Covering as well as a new variant also involving capacity constraints. A compact MILP formulation is the starting point for the study of a Benders decomposition ap-

proach that can be directly used for all considered problem variants. In addition, the combination of Benders decomposition with Branch-and-Price is analyzed for the variant with capacity constraints. B. Fortz (ULB/GOM), M. Labbé (ULB/GOM) and F. Sciamannini (ULB/GOM) studied a column generation approach for the resolution of a particular vertex coloring problem, the b-Coloring, that has been already proved to be NP-hard. A b-Coloring of a graph is an assignment of colors to each vertex of a graph in such a way that colors on adjacent vertices are different with the additional constraint that subsets of vertices receiving the same color, called color classes, admit at least one node (called dominating vertex) adjacent to every other color used. The goal of this problem is to maximize the number of colors needed to color the graph. They proposed Dantzig-Wolfe decompositions of the classical formulation of the b-Coloring problem introduced by Campelo. Then, they exhaustively compared them in order to determine the one that provide the strongest LP relaxation and allow to remove the symmetry that affect the classical formulation of the problem. Furthermore, they derived and analysed the subproblem associated with the Dantzig-Wolfe reformulation selected and studied its complexity. They plan to develop a Branch-and-Price algorithm to solve the b-Coloring and thoroughly validate its performance through extensive computational experiments. Moreover, the research will be devoted to the development of general methods and algorithms exploiting a column generation approach for the resolution of two other NP-hard vertex coloring problems: the minimum entropy coloring and the the equitable coloring. A. Frangioni, E. Gorgone (ULB/GOM) and B. Gendron (CIRRELT) [23] studied the tuning and the testing of a (generalized) subgradient method combined with different rules for the stepsize and the search direction, for the standard network design problem. The algorithm includes the Primal-Dual variant designed by Yu. Nesterov and the incremental versions designed by D. Bertsekas. B. Fortz (ULB/GOM) and D. Papadimitriou studied a new combined optimization model for telecommunications networks that integrates network design decisions and routing decisions, with time-dependent demands. They compared a basic, aggregated model to a disaggregated, extended formulation that provides much tighter lower bounds at the cost of a very high solving time [52, 21]. A variant of the problem taking into account the ageing of links was studied in [53]. Together with E. Gorgone (ULB/GOM), they also developed a Lagrangean decomposition approach to solve the problem [54]. The Lagrangian Dual is solved by means of a non-smooth algorithm, the bundle method. The bundle code was enhanced with a specialized quadratic solver to handle the master problem.

2.1.2. Security

Reliability and security measures are of great importance in many industrial scenarios. These kinds of measures are usually enforced with the purpose of ensuring a good-quality service and/or containing any detrimental effects due to unexpected accidents. For instance, utility distribution networks (like electricity, gas, water, ...) should provide a continuous and dependable service to their customers. As a result, most of these networks implement several mechanisms to minimize the number of customers that are affected when there is a failure. Chemical companies, on the other hand, are usually very concerned about the safety of their employees. For that reason, most of these companies implement different security barriers in their production plants to quickly control any unforeseen accident. In these scenarios, the main goal is to generate a plan (deciding on the measures to implement and the components of the plant/network to host them) with minimum cost such that the security/reliability requirements are satisfied.

We now describe specific contributions in this field.

Janssens, Talarico, and Sörensen [30] propose a decision model aimed at increasing security in a utility network (e.g., electricity, gas, water or communication network). The network is modelled as a graph, the edges of which are unreliable. We assume that all edges (e.g., pipes, cables) have a certain, not necessarily equal, probability of failure, which can be reduced by selecting edge-specific security strategies. We develop a mathematical programming model and a metaheuristic approach that uses a greedy random adaptive search procedure to find an initial solution and uses tabu search hybridised with iterated local search and a variable neighbourhood descend heuristic to improve this solution. The main goal is to reduce the risk of service failure between an origin and a destination node by selecting the right combination of security measures for each network edge given a limited security budget.

Janssens et al. [29] present a model to support decision-makers about where to locate safety barriers and mitigate the consequences of an accident triggering domino effects. Based on the features of an industrial area that may be affected by domino accidents, and knowing the characteristics of the safety barriers that can be installed to stall the fire propagation between installations, the decision model can help practitioners in their decision-making. The model can be effectively used to decide how to allocate a limited budget in terms of safety barriers. The goal is to maximize the time-to-failure of a chemical installation ensuring a worst case scenario approach. The model is mathematically stated and a flexible and effective solution approach, based on metaheuristics, is developed and tested on an illustrative case study representing a tank storage area of a chemical company. We show that a myopic optimization approach, which does not take into account knock-on effects possibly triggered by an accident, can lead to a distribution of safety barriers that are not effective in mitigating the consequences of a domino accident. Moreover, the optimal allocation of safety barriers, when domino effects are considered, may depend on the so-called cardinality of the domino effects.

Talarico et al. [73] present a multi-modal security-transportation model to allocate security resources within a chemical supply chain which is characterized by the use of different transport modes, each having their own security features. We consider security-related risks so as to take measures against terrorist acts which could target critical transportation systems. The idea of addressing security-related issues, by supporting decisions for preventing or mitigating intentional acts on transportation infrastructure, has gained attention in academic research only recently. The decision model presented in this paper is based on game theory and it can be employed to organize intelligence capabilities aimed at securing chemical supply chains. It enables detection and warning against impending attacks on transportation infrastructures and the subsequent adoption of security countermeasures. This is of extreme importance for preventing terrorist attacks and for avoiding (possibly huge) human and economic losses. In our work, data sources and numerical simulations are provided by applying the proposed model to a illustrative multi-modal chemical supply chain.

Talarico et al. [74] investigate security issues related to intentional acts, such as terrorist and criminal attacks, to pipeline systems. A classification of malicious threats is proposed, and several episodes of intentional attacks against pipelines are mentioned for each of the categories identified in the classification. Traditional and advanced security measures that are used by pipeline operators to prevent and mitigate the consequences of intentional attacks are presented. Future developments of new emerging technologies and recent applications in the field of pipeline security are also discussed. Finally, within a general framework for a pipeline security risk assessment, a support decision model aimed at increasing the effectiveness of the

set of selected countermeasures for the pipeline infrastructure security within a limited budget is also described, and it is applied to a realistic scenario.

2.1.3. Miscellaneous

Consider, as a network, a set of inland waterways. Very often, locks are needed in inland waterways, as well as in many ports, to regulate the water level while still allowing ships to pass. Specifically along many canals and inland waterways, and with increasing waterway traffic density, locks become a source of waiting time for ships traveling these waterways. Characteristic of this problem setting is that ships may travel in both directions and each lock acts as a single server which handles both the upstream and the downstream traffic. In addition, lock operations must alternate between upwards (downstream to upstream) and downwards (upstream to downstream) movements. Results exist on scheduling a single lock in order to minimize ship waiting times. In Passchyn et al. [58], the potential benefits that can be gained from coordinating the lock scheduling on waterways with multiple locks in sequence is investigated. The first contribution of this work is to provide two general mixed integer linear programming (MIP) models that consider multiple locks in sequence. Indeed, by scheduling the system of locks as a whole, a global schedule can be obtained that minimizes the ships flow times over the entire length of the canal (where the flow time of a ship is the total time that the ship spends in the canal). Moreover, these models can deal with an alternative objective function reflecting minimization of fuel cost or pollutant emissions. In both cases, communicating the outcome of the models to the ships allows them to lower their movement speed when locks are known to be unavailable. This avoids unnecessary idle time where ships would arrive at a lock before it is available. At the same time, this yields a reduction in fuel cost as well as pollutant emissions. The second contribution of this paper is a computational study evaluating the performance of the models. The parameters used in the instances are derived from a real-world dataset. It is reasonable to expect a trade-off between reducing emissions on the one hand, and minimizing the total flowtime on the other hand. The computational study confirms the existence of this trade-off and allows one to analyze this trade-off quantitatively. Finally, the impact of an integrated model is compared to a heuristic that is based on scheduling each lock individually.

In De Causmaecker and Pham [59] the Intermittent Traveling Salesman Problem is introduced. The Intermittent Traveling Salesman Problem arises from the practical Energy Beam Technology drilling/ polishing where the temperature of the workpiece is taken into account. The machining generates heat which might causes the workpiece to melt down if the temperature exceeds a certain point. The problem consists of finding the optimal processing path to process the whole workpiece while ensuring the temperature constraints. They modeled the problem as a variant of the Traveling Salesman Problem and propose a Variable Neighborhood Search algorithm for the problem.

WP 2.2 Transportation & Logistics

WP 2.2.1 Intermodal transportation

Intermodal transport is promoted by Europe as an environmentally friendly alternative to road. In [66], B.F. Santos, S. Limbourg (ULg) and J.S. Carreira discuss the impact of three freight transport policies aiming to promote railroad intermodal transport in Europe, and examine the

case of Belgium as a testing ground.

The location of intermodal terminals, where the transfer of goods between modes occurs, is a key issue for achieving economic and environmental competitiveness. M. Mostert (ULg), A. Caris (Hasselt) and S. Limbourg (ULg) have proposed a bi-objective model for the intermodal terminal location-allocation problem. Operational costs and CO_2 emissions are minimized using three modes: road, intermodal rail and intermodal inland waterways transport. Economies of scale are modeled by nonlinear cost and emission functions. Intermodal global performances are assessed through a Belgian case study. This research has been presented at ORBRL [47] and is described in more detail in the working paper [46].

WP 2.2.2 Rich vehicle routing problems

Home care routing and scheduling

P.A. Maya Duque (UA), M. Castro (UA), K. Sörensen (UA) and P. Goos (UA) [42] have been studying the planning of home care services at Landelijke Thuiszorg, a “social profit" organization that provides home care services in several Belgian regions. The underlying problem is a routing and scheduling problem that aims to maximize the service level and to minimize the distance traveled by the caregivers of the organization. This problem is formulated as a bi-objective mathematical program, based on a set partitioning problem formulation. A flexible two-stage solution strategy is designed to efficiently tackle the problem. Computational tests, as well as extensive pilot runs performed by the organizationís personnel, show that this approach achieves excellent performance, both in terms of the service level and total traveled distance. Moreover, computation times are small, allowing for the weekly planning to be largely automated. The organization is currently in the process of implementing the solution approach in collaboration with an external software company.

Another bi-objective routing and scheduling problem in the context of home care services is studied by K. Braekers (UH), R.F. Hartl, S.N. Parragh and F. Tricoire (University of Vienna) [11]. The trade-off between minimizing costs and maximizing patient convenience is analyzed. A mixed integer program is proposed, together with several valid inequalities which considerably increase the efficiency of commercial solvers like CPLEX. Additionally, the authors propose a meta-heuristic algorithm which is based on the Multi-Directional Local Search framework and uses a Large Neighborhood Search heuristic as a subroutine.

Integrating VRP and loading problems

Distributors are faced with loading constraints in their route planning, e.g., multi-dimensional packing constraints, unloading sequence constraints, stability constraints and axle weight limits. Ignoring these constraints impairs planning and induces last-minute changes resulting in additional costs. Developing vehicle routing models incorporating loading constraints is critical to more efficient route planning. H. Pollaris (UH), K. Braekers (UH), A. Caris (UH), G.K. Janssens (UH) and S. Limbourg (ULg) [61] provide an overview of recent developments on all transport modes in which loading constraints play a key role (trucks, airplanes, ships, and automated guided vehicles). They also identify research gaps and opportunities for future research.

The same authors are studying a vehicle routing problem with sequence-based pallet loading and axle weight restrictions. A mathematical formulation for the problem was already presented in a joint paper which was mentioned in the report of last year. In the past months, an Iterated Local Search heuristic has been developed to solve larger instances of the problem.

The main goal is to analyze the extent to which axle weight limits are violated when ignored in the planning process and the additional costs that are incurred to avoid these violations. The irace package, developed at ULB/IRIDIA, was applied to tune the parameters of the algorithm. Preliminary results of the heuristic have been presented at the VeRoLog 2015 conference. Additionally, H. Pollaris (UH) attended the PhD School on Routing and Logistics in Brescia (Italy) from June 24 to July 3, 2015.

Dial-a-ride problems

In the past year, several research activities have focused on dial-a-ride problems, routing problems in the context of demand-responsive transportation.

S. Deleplanque (ULB-GOM) and A. Quilliot [19] consider a dial-a-ride problem with transfers. The problem is solved with a Monte Carlo procedure. It consists of several replications of a greedy insertion algorithm based on constraint propagation of the main time constraints (time windows, maximum ride times and maximum route times). The constraints related to passenger transfer from one vehicle to another are also propagated. The computational experiments of the proposed heuristic consider clusters of vehicle fleets satisfying a set of demands. The algorithm automatically determines if a transfer between two vehicles is merited.

Y. Molenbruch, K. Braekers and A. Caris (UH) [45] have been studying the effect of service level variations on the operating costs of dial-a-ride service providers. A single objective dial-a-ride problem has been solved for different levels of service quality with respect to time window lengths and the maximum time users can spend in a vehicle. The same authors have reviewed the existing literature on dial-a-ride problems and have proposed a typology to classify this literature. This review paper is currently in review at an academic journal. Finally, together with G. Vanden Berghe (KUL), the same authors have been studying a bi-objective version of the dial-a-ride problem, in which both costs and user ride times are minimized. A meta-heuristic algorithm, which embeds a Variable Neighborhood Search in a Multi-Directional Local Search framework, has been proposed to solve the problem. Preliminary results have been presented at two international conferences (Odysseus, VeRoLog) and the corresponding paper has been submitted as well.

K. Braekers (UH) and A.A. Kovacs (University of Southampton) have been studying a multi-period variant of the dial-a-ride problem. The goal is to investigate how driver consistency can be modeled in these problems, to account for the fact that users typically appreciate being transported by a familiar driver. Both an exact Branch-and-Cut algorithm and a Large Neighborhood Search meta-heuristic have been proposed to solve the problem. The work has been presented at the EURO 2015 conference. A paper on this work is currently in review.

Finally, K. Braekers (UH) studied the resource requirements for a demand-responsive transportation system under different policy scenarios, together with several colleagues from the Transportation Research Institute of Hasselt University [48]. A large number of dial-a-ride problems are solved using an existing meta-heuristic algorithm to assess the number of vehicles required and total distance to be traveled.

Other vehicle routing problems

Several other variants of the classical Vehicle Routing Problem (VRP) have been studied by different researchers.

Distribution companies that serve a very large number of customers often partition the geographical region served by a depot into zones. Each zone is assigned to a single vehicle and each vehicle serves a single zone. J. Janssens (UA), J. Van den Bergh (UA), K. Sörensen (UA) and D. Cattrysse (KUL) [31] study an alternative approach in which the distribution region is

partitioned into smaller microzones which are then assigned to a preferred vehicle in a so-called tactical plan. The moment the workload in each microzone is known, the microzones can be reassigned to vehicles in such a way that the total distance traveled is minimized, the workload of the different vehicles is balanced, and as many microzones as possible are assigned to their preferred vehicle. The authors model the resulting microzone-based vehicle routing problem as a multi-objective optimization problem and develop a simple yet effective algorithm to solve it.

L. Talarico (UA), F. Meisel (Christian-Albrechts-University Kiel) and K. Sörensen (UA) [72] consider a routing problem for ambulances in a disaster response scenario, in which a large number of injured people require medical aid at the same time. The ambulances are used to carry medical personnel and patients. Two mathematical formulations are proposed to obtain route plans that minimize the latest service completion time among the people waiting for help. A large neighborhood search metaheuristic which can be applied at high frequency to cope with the dynamics and uncertainties in a disaster situation is proposed as well. Experiments show that the metaheuristic produces high quality solutions for a large number of test instances within very short response time. The effect of various structural parameters of a problem, like the number of ambulances, hospitals, and the type of patients, on both running time of the heuristic and quality of the solutions is analyzed as well. This information can additionally be used to determine the required fleet size and hospital capacities in a disaster situation.

L. Talarico (UA), K. Sörensen (UA) and J. Springael (UA) [75] define a variant of the VRP, the aim of which is to find a set of k dissimilar solutions on a single instance. This problem has several practical applications in the cash-in-transit sector and in the transportation of hazardous materials. A minñmax mathematical formulation is proposed which requires a maximum similarity threshold between VRP solutions, and the number k of dissimilar VRP solutions that need to be generated. An index to measure similarities between VRP solutions is defined based on the edges shared between pairs of alternative solutions. An iterative metaheuristic to generate k dissimilar alternative solutions is also presented. The solution approach is tested using large and medium size benchmark instances for the capacitated vehicle routing problem. The same authors propose another variant that models the routing of vehicles in the cash-in-transit industry by introducing a risk constraint [76]. In the Risk-constrained Cash-in-Transit Vehicle Routing Problem (RCTVRP), the risk of being robbed, which is assumed to be proportional both to the amount of cash being carried and the time or the distance covered by the vehicle carrying the cash, is limited by a risk threshold. A mathematical formulation is developed and small instances of the problem are solved by using IBM CPLEX. Four constructive heuristics as well as a local search block composed of six local search operators are developed and combined using two different metaheuristic structures: a multistart heuristic and a perturb-and-improve structure. In a statistical experiment, the best parameter settings for each component are determined, and the resulting heuristic configurations are compared in their best possible setting. The resulting metaheuristics are able to obtain solutions of excellent quality in very limited computing times.

Ch. Defryn (UA) and K. Sörensen (UA) are studying the Clustered VRP (CluVRP), in which customers are grouped into predefined clusters. When serving all these customers with a given fleet of vehicles it should be ensured that customers belonging to the same cluster are served by one vehicle, sequentially in the same path (CluVRP with hard cluster constraints). In a second phase, these constraints will be relaxed by defining the CluVRP with soft cluster constraints. A metaheuristic approach is proposed which tries to find the optimal solution for

both problems by combining two variable neighbourhood search algorithms, exploring the distribution area at two different levels. The algorithm is tested on different benchmark instances from the literature with up to 484 nodes, obtaining high quality solutions. A working paper on this research is available [15].

Y. Arda (ULg), Y. Crama (ULg), V. François (ULg) and G. Laporte (Cirrelt, Montreal) [22] have developed heuristic solution procedures for multi-trip vehicle routing problems (MTVRP) where each vehicle is allowed to perform one or more trips without exceeding a maximum duration. The authors compare the use of multi-trip local search operators with more common solution methods for the MTVRP which consist in using VRP heuristics in combination with bin packing techniques. These two approaches are implemented within two different metaheuristic frameworks: the adaptive large neighborhood search (ALNS) and the tabu search (TS). A special focus is put on understanding the interactions between heuristic components through experimentation. Since both ALNS algorithms have various implementation options and each more than 30 parameters to tune, collaboration with the research center IRIDIA (ULB) was initiated. The iRace package was used to perform the automatic tuning of ALNS algorithms. This work was presented at VeRoLog 2014 and at IFORS 2014. Y. Arda (ULg), Y. Crama (ULg), V. François (ULg) are currently extending this study by developing heuristic solution procedures for vehicle routing problems with multiple trips and time windows (MTVRPTW). Since the problem definition involves a maximum duration for each vehicle while customers have delivery time windows, the starting time of each vehicle is a decision variable. Again, the use of specific operators is compared with the methods that combine VRPTW heuristics with bin packing techniques. The ALNS metaheuristic is used as the common framework for implementing both approaches.

Y. Arda (ULg) and S. Michelini (ULg) are improving the exact solution method developed by H. Küçükaydin (MEF), Y. Arda (ULg) and Y. Crama (ULg) for an elementary shortest path problem with resource constraints (ESPPRC), where a capacitated single vehicle serves customers within specified time windows and can start its service at any desired time. The solution method, an exact bidirectional dynamic programming algorithm, is being improved with techniques such as duplicate elimination and decremental state space relaxation. In addition, this method is being included in the design of a matheuristic, i.e., an integration of (meta)heuristics and MIP solving techniques. This work was presented at VeRoLog 2015 and at ORBEL29.

M. Schyns (ULg) [67] presents an algorithm based on an Ant Colony System to deal with a broad range of Dynamic Capacitated Vehicle Routing Problems with Time Windows, (partial) Split Delivery and Heterogeneous fleets (DVRPTWSD). The paper addresses the important case of responsiveness. Responsiveness is defined here as the ability to complete a delivery as soon as possible, within the time window, such that the client or the vehicle may restart its activities. The paper develops an interactive solution to allow dispatchers to take new information into account in real-time. The algorithm and its parametrization have been tested on a problem submitted by Liege Airport, where the goal is to optimize the journey of the refueling trucks. It is also tested on some classical VRP benchmarks with extensions to the responsiveness context.

Y. Crama (ULg), M. Rezaei (ULg) and T. Van Woensel (TU Eindhoven) [13] consider a VRP with deterministic orders in two periods from a set of stores. Orders in period 1 (2) can be postponed (advanced) to the other period but any diversion from the initial orders incurs a penalty. From the perspective of a Logistics Service Provider (LSP), such diversions could be beneficial if savings in the routing costs outweigh the penalties. So could they be from a store's view, as the store can set a high enough penalty to compensate the diversion from its

own optimal orders. In this paper, the authors introduce a new model where they seek a better solution for the LSP, compared to solving two independent VRPs with fixed orders, by allowing orders to be fully postponed or advanced. They apply a branch-and-price algorithm to solve this model to optimality. Many cutting-edge techniques are implemented to have an efficient branch-and-price algorithm, and two ideas to possibly improve the upper bound are tested.

In [6], [7], and [8], M. Bay (ULg) and S. Limbourg (Ulg) define the electric vehicle travelling salesman problem (EV-TSP) and the electric vehicle routing problem (E-VRP) and present models and preliminary results for those problems. The objective usually considered in sustainable transportation is to *minimize pollution* due to emissions, and equivalently energy consumption. Turning to electric mobility, pollution is related to electricity production technology, not considered in this research; driving range is the major concern nowadays, due to the limited capacity of batteries and long recharge times. Maximizing the driving range or the level of energy (state of charge of the battery) at destination leads to consider the main factors of energy consumption, namely: vehicle weight, engine efficiency and consumption models, drive speed and acceleration, drive pattern, road grade, and payload.

Reducing environmental impact, related regulations and potential for operational benefits are the main reasons why companies share their returnable transport items (RTIs) among the different partners of a closed-loop supply chain. G. Iassinovskaia, S. Limbourg (ULg) and F. Riane [27] consider a producer, located at a depot, who has to distribute his products packed in RTIs to a set of clients. Clients define a time window wherein the service can begin. The producer is also in charge of the collection of empty RTIs for reuse in the next production cycle. Each partner has a storage area composed of both empty and loaded RTI stock, as characterized by initial levels and maximum storage capacity. As deliveries and returns are performed by a homogeneous fleet of vehicles that can carry simultaneously empty and loaded RTIs, this research addresses a pickup and delivery inventory-routing problem within time windows (PDIRPTW) over a planning horizon. A mixed-integer linear program is developed and tested on small-scale instances. To handle more realistic large-scale problems, a cluster first-route second matheuristic is proposed in [27].

In [12], Y. Crama (ULg) and Th. Pironet (ULg) investigate optimization techniques for a multi-period vehicle allocation problem with uncertain requests. A company owning a limited fleet of trucks attempts to maximize its operational profit over an infinite horizon by optimally assigning transportation orders to the vehicles. Its profit stems from profits collected when transporting full truckloads, minus costs incurred when waiting or when moving unladen. The stochastic component of the problem arises from the uncertainty on the realization of each transportation order. The methodology is based on optimizing decisions for deterministic scenarios. Several policies are generated in this way, either by simple heuristics, or by more complex approaches, such as consensus and restricted expectation algorithms, or from network flow formulations over subtrees of scenarios. Myopic and a-posteriori deterministic optimization models are used to compute bounds allowing for performance evaluation. Numerical experiments are performed on various instances featuring different numbers of orders, graph sizes, sparsity, and probability distributions, and the performance of the algorithms is assessed by statistical tests. The robustness of various policies with respect to erroneous evaluations of the probability distributions is also analyzed.

K. Braekers (UH), K. Ramaekers (UH) and Inneke Van Nieuwenhuyse (KUL) reviewed and classified the vehicle routing literature of the past six years, using an adapted version of an existing taxonomy. Trends are analyzed and future research directions are proposed. The

corresponding paper is currently under review.

T. Manisri (Sripatum University, Thailand) Mungwattana (Kasetsart University, Thailand), G.K. Janssens (UH) and A. Caris (UH) [41], study a vehicle routing problem with soft time windows and several hierarchical objectives. The problem is solved using a hybrid heuristic algorithm. Results show a trade-off can be made between total cost and service when considering soft time windows. Additionally, G.K. Janssens (UH), K. Soonpracha (Kasetsart University, Thailand), T. Manisri (Sripatum University, Thailand), A. Mungwattana (Kasetsart University, Thailand) [28] study a vehicle routing problem with time windows and uncertain travel times. A solution concept to obtain robust solutions, performing well in worst-case scenarios is proposed.

Finally, K. Ramaekers (UH), A. Caris (UH), G.K. Janssens (UH) and T. Maes [65] have studied the pickup and delivery selection problem. This problem models the situation in which transportation companies have a limited fleet of vehicle, and they have to decide which pickup and delivery requests to perform and which to reject. The goal is to find the selection of requests and a corresponding routing plan that maximize the profit. A hybrid tabu search and simulated annealing algorithm is proposed to solve the problem. The work has been presented at the joint ECEC - FUBUTEC - EUROMEDIA conference.

WP 2.2.3 Loading problems

Several participants in the project have continued investigating various types of loading problems arising in transportation management.

V. Lurkin (Ulg) and M. Schyns (ULg) [37] consider the loading optimization problem for a set of containers and pallets transported in a cargo aircraft that serves multiple airports. Because of pickup and delivery operations that occur at intermediate airports, this problem is simultaneously a Weight & Balance Problem and a Sequencing Problem. The objective is to minimize fuel and handling operation costs. The problem is shown to be NP-hard. The authors formulate it as a mixed integer linear program. Based on real-world data provided by an industrial partner (TNT Airways), they perform numerical experiments using a standard B&C library. Their approach yields better solutions than traditional manual planning, and it results in substantial cost savings. This work has been awarded the gold medal of the Airline Group of the International Federation of Operational Research Societies (AGIFORS).

In an article presented at [56] and submitted to Computers and Operations Research [55], C. Paquay (Ulg), S. Limbourg (Ulg), J. Oliveira and M. Schyns (Ulg) deal with finding a good feasible solution in a reasonable amount of computation time for the three dimensional Multiple Bin Size Bin Packing Problem (MBSBPP). The MBSBPP variant considered is one with additional constraints encountered in real-world air transportation situations such as the stability of the cargo or the particular shape of containers in air transportation. This extended MBSBPP has been formulated as a mixed integer linear programming problem (MIP), but currently only poor results are achieved for even fairly small problem sizes. The goal of this work is to develop heuristics that may be able to provide better quality solutions, to then be used - if sufficiently good - as final solutions for the problem or as initial feasible solutions that may speed-up the mathematical programming model resolution. Three methodologies based on the decomposition of the original problem into easier subproblems are considered: the Relax-and-Fix, the Insert-and-Fix and the Fractional Relax-and-Fix matheuristics. They were tested on real data sets to determine the best parameters for each technique and then compared to the

results of the Branch-and-Bound. Finally, deeper experiments are carried out on the two best approaches to find their limitations. A best fit decreasing algorithm for the three-dimensional bin-packing problem with transportation constraints, currently under development, has been presented at [57].

WP 2.2.4 Location problems

M. Leitner (ULB-GOM and UV, Austria), I. Ljubic (ESSEC Business School, Paris), M. Riedler (TU Wien, Austria) and M. Ruthmair (UV, Austria) [34] study the Network Design Problem with Relays (NDPR) which gives answers to some important strategic design questions in context of e-mobility. Given a family of origin-destination pairs electric vehicles need to travel, and given the existing links that can be traversed, these questions are: (1) What are the optimal locations for placing the charging stations and how many of them are needed? (2) Could the available infrastructure be enhanced by including additional links (shortcuts), to reduce the travel distances? In contrast to previous work on the NDPR which mainly focused on heuristic approaches, exact methods based on different mixed integer linear programming formulations for the problem are considered. Branch-and-Price and Branch-Price-and-Cut algorithms that build upon models with an exponential number of variables (and constraints) are developed. In an extensive computational study, the performance of these approaches for instances that reflect different real-world settings is analyzed.

H. Calik (ULB-GOM), I. Contreras (CIRRELT and Concordia University, Montreal), J.F. Cordeau (CIRRELT and HEC Montreal, Montreal), and G. Laporte (CIRRELT and HEC Montreal, Montreal) work on a two-echelon hub location-routing problem with multiple levels of hubs. The network structure of the problem consists of three levels of nodes: main hubs, regional hubs, and customers. Each customer wishes to send a positive amount of flow to every other customer. The flows of customers are collected and distributed by the vehicles originating from regional hubs. So, each customer needs to be assigned to a regional hub. The flows collected from the customers are sorted at the regional hubs and these hubs are not directly connected to each other. Therefore, they have to be served by vehicles originating from main hubs and each regional hub is assigned to a main hub. The problem under consideration requires the location of regional hubs, allocation of customers to regional hubs and regional hubs to main hubs, and the vehicle trips at both levels with minimum cost of operation. The authors developed a path based mathematical formulation and tested this formulation on problems with up to 50 nodes constructed from the Australian Post (AP) data set which is commonly used in the hub location literature. The results are promising in terms of the solution time. As the authors wish to solve larger problems, they are at the phase of developing an adaptive large neighborhood search heuristic for solving the problem. This heuristic algorithm utilizes several neighborhood structures obtained by hub addition, hub removal, hub exchange, node addition and removal to the vehicle trips etc. Another idea is to develop a math-heuristic that finds the second level vehicle trips (between regional hubs and customers) heuristically and then find the first level trips (between main hubs and regional hubs) optimally by inserting the second level information into proposed formulation. After the completion of the heuristic algorithms, the authors plan to conduct experiments on problems with nodes of 100-200 range.

H. Calik (ULB-GOM) and O. Karasan (Bilkent University, Ankara) study the capacitated p-center problem under multiple and single allocation strategies. The p-center problem is an NP-Hard combinatorial optimization problem that requires location of p facilities (centers)

on a given network so that the maximum of the distances between a demand point and its assigned facility is minimum. The capacitated p-center problem is a generalization of the p-center problem with the additional restriction on the capacities of the facilities. The studies in the literature are mainly focused on the single allocation version of the problem which restricts the assignment of each demand point to a single facility. H. Calik and O. Karasan proposed new mathematical formulations and exact algorithms for both the single allocation and the multiple allocation version where any demand point can take service from multiple facilities. The algorithms proposed work within a branch-and-cut framework and extensive computational experiments reveal that they can solve problems with sizes not attempted before in reasonable amount of time. The authors plan to send the findings of this study as a research article to Transportation Science journal of INFORMS by finalizing the computational experiments in the upcoming weeks.

H. Calik (ULB-GOM) and B. Kara (Bilkent University, Ankara) work on the development of exact methods for solving the absolute p-center problem on large networks. The p-center problem can be categorized into two depending on the location of the facilities on the network. In the vertex restricted version, the facilities can be placed only on the vertices while in the absolute version, they can be placed on both vertices and edges of the given network. The studies in the literature are mostly focused on solving the vertex restricted version of the problem. H. Calik and B. Kara developed an algorithm to obtain a transformation of the absolute p-center problem into a vertex p-center problem so that the absolute version of the problem can be solved by using any of the state of the art methods proposed for the vertex restricted version in the literature. The authors conducted computational experiments by integrating their algorithm with one of the existing algorithms for the vertex p-center problem and they were able to solve problems on networks with up to 900 nodes in reasonably short amount of time. The authors plan to develop a new algorithm for solving the vertex p-center problem and integrate that with the proposed transformation method to solve the absolute p-center problem with a totally new approach.

WP 2.2.5 Miscellaneous

Airline itinerary choice models support many multi-million dollar decisions, as they are used to evaluate potential route schedules. Classic models suffer from major limitations, most notably they use average fare information but do not correct for price endogeneity. V. Lurkin (ULg), L.A. Garrow (Georgia Tech), M.J. Higgins (Georgia Tech) and M. Schyns (ULg) use a novel database of airline tickets to estimate itinerary choice models using detailed fare data and compare these to classic itinerary choice models. A preliminary short version of their work appears as [36].

S. Deleplanque and M. Labbé (ULB-GOM) work on a specific Railway Problem in collaboration with INFRABEL. The Belgian railway company needs a new tool for the trains which have to be rescheduled when the company must do some maintenance operations on the network. The difficulties are the number of constraints, the size of the network, the quantity of trains and many other features related to the Belgian railway system. These difficulties imply that some choices have to be made to balance the quantity of work feasible in the remaining 2 years. After developing an interface between the INFRABEL database and the framework used in this project, a first model (MIP) has been implemented and some experiments has been already made.

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. Members of the IAP working in this domain are in the steering committee of the PATAT conference (York 2014) and the EURO/WATT working group on timetabling.

WP 2.3.1 Health care

Spanning the conferences PATAT 2014 (York) and MISTA 2015 (Prague), we organised the second nurse rostering competition (`http://mobiz.vives.be/inrc2/`) in cooperation with university of UDINE. The contest attracted 15 participants from which 7 finalists were selected. They came from 7 different countries. The three winners were Martin Römer from Martin Luther University Halle-Wittenberg, Germany, Legrain Antoine, Omer Jérémy, Rosat Samuel from Polytechnique Montreal in Canada and Ahmed Kheiri from University of York, UK. The subject of the competition combined a rostering challenge on short spans of one or two weeks, with forecasting where in total four consecutive spans had to be rostered. Information about the next phase only became available after the roster for the current phase was released. This problem definition is new to the domain and matches real world situations.

In two PhD thesises [68, 78], different facets of the nurse rostering problems were tackled. Pieter Smet discusses Nurse rostering: models and algorithms for theory, practice and integration with other problems. In 2015, Pieter mainly worked on simplified nurse rostering problems, establishing a basic understanding of the problem's complexity. These new insights identify a boundary between easy and hard problems, which strongly influences computational search approaches to the problem. In his PhD thesis on Operational Decision Support Models and Algorithms for Hospital Admission Planning and Scheduling, Wim Vancroonenburg focuses on developing operational decision support models and algorithms for hospital admission planning and scheduling. The aim is to increase efficient usage of key hospital resources by supporting human planners at hospital admission offices with automated tools for their daily and weekly decision making. Both scientists worked intensively together in many different settings. This resulted in a number of scientific publications: [79, 80, 44, 43, 69].

Apart from the work on Nurse rostsring, general manpower planning was investigated at a more strategic level in [32]. A Markov manpower planning model with fixed internal transition probabilities, enables assessing the feasibility to attain the most desirable personnel structure. This paper focuses on a model that balances three criteria, that is, the desirability degree, the attainability degree and the promotion steadiness degree, formulated by fuzzy membership functions. A new set of instances is introduced, and the algorithms are evidenced in a set of experiments.

H. Calik (ULB-GOM) and M. Labbé (ULB-GOM) work on a network approach for detecting the key symptoms of major depression. It is a collaborative work with P. Linkowski and P. Hubain who are Professors in Psychiatry Department of Erasme Hospital of ULB. The Hamilton rating scale, which is used to rate the severity of depression in patients diagnosed as depressed, has 24 criteria (symptoms) such as anxiety, insomnia (early, middle, or late), suicide etc. and each patient is given a score for each of these criteria. The existing approaches obtain the level of depression by summing these scores. However, recent approaches reveal that sum scores do not reflect the reality because some of the symptoms are triggered by the existence of

other symptoms. Therefore, a network approach that shows the relation between the symptoms in considered as a promising advance in the area.

WP 2.3.2 Production scheduling

Decision making in production concerns building good responsive scheduling applications under dynamically changing conditions. Tony Wauters investigated 'A learning-based optimization approach to multi-project scheduling'. He introduces a learning-based optimization approach to the resource-constrained multi-project scheduling problem [85]. Furthermore, by generalizing various aspects of project scheduling, he improved capabilities of decision makers to capture reality. He continued on the work for the MISTA 2013 challenge organised by our group CODeS at KU Leuven to introduce such a general problem model [84].

In [86], Laurence Wolsey (UCL) gives a tight extended formulation for an n-period uncapacitated lot-sizing problem with stock upper bounds, stock fixed costs, stock overload and backlogging with $O(n^2)$ variables and constraints. This corrects and extends a formulation in Wolsey (2006) for the problem with just stock upper bounds.

WP 2.3.3 Other problems

Tulio Toffolo studied a problem from sports scheduling. [77]. The Traveling Umpire Problem (TUP) is an optimization problem in which umpires have to be assigned to games in a double round robin tournament. The objective is to obtain a solution with minimum total travel distance over all umpires, while respecting hard constraints on assignments and sequences. Up till now, no general nor dedicated algorithm was able to solve all instances with 12 and 14 teams. We present a novel branch-and-bound approach to the TUP, in which a decomposition scheme coupled with an efficient propagation technique produces the lower bounds. The algorithm is able to generate optimal solutions for all the 12- and 14-team instances as well as for 11 of the 16-team instances. In addition to the new optimal solutions, some new best solutions are presented and other instances have been proven infeasible.

WP 2.4 Bio-informatics

L. Porretta (ULB/GOM), D. Catanzaro, B. Halldórsson, and B. Fortz (ULB/GOM) study the Polymorphic Alu Insertion Recognition Problem (PAIRP) Alu (Arthrobacter luteus) forms a major component of repetitive DNA and are frequently encountered during the genotyping of individuals. The basic approach to find Alus consists of (i) aligning sequence reads from a set of individual(s) with respect to a reference genome and (ii) comparing the possible Alu insertion induced by the alignment with the Alu insertions positions already known for the reference genome. The sequence genome of the reference individual is known and will be highly similar, but not identical, to the genome of the individual(s) being sequenced. Hence, at some locations they will diverge. Some of this divergence is due to the insertion of Alu polymorphisms.

Detecting Alus has a central role in the field of Genetic Wide Association Studies because basic elements are a common source of mutation in humans. Poretta et al. [62] investigate the PAIRP relationship with the the Clique Partitioning of Interval Graphs (CPIG). Their results provide insights of the complexity of the problem, a characterization of its combinatorial structure and an exact approach based on Integer Linear Programming to exactly solve the correspond instances.

WP 2.5 Economics

2.5.1. Pricing problems

Several COMEX researchers are investigating *pricing problems* and the associated optimization models, as they arise in various economic frameworks.

B. Fortz (ULB/GOM), M. Labbé (ULB/GOM) and A. Violin (ULB/GOM) studied the Network Pricing Problem with Connected Toll Arcs. They consider a road network where there are two types of arcs: a subset of arcs is owned by a company imposing tolls for using them, and a subset of remaining arcs which are toll-free. Toll arcs are connected such that they constitute a single path, as it occurs for instance in a highway network. The company attempts to set up *tolls* so as to maximize its revenues, whilst users seek for their minimum cost path between their origin and destination. This problem can be modeled in a bilevel programming framework and proved to be strongly NP-hard.

The authors proposed a Dantzig-Wolfe reformulation for this problem, and showed that the linear relaxation is stronger than the mixed integer formulation from the literature, and easily solvable. They then extended this framework by including more advanced techniques: initialisation alternatives, stabilisation of dual variables values and early stopping criteria. Furthermore, they proposed a full Branch-and-Cut-and-Price scheme to solve the integer problem, with an ad-hoc branching algorithm using pseudo-costs to guide the choices, some rounding heuristics and the inclusion of efficient valid inequalities.

With S. Deleplanque (ULB-GOM), new strategies have been implemented to reduce the number of nodes in the tree by fixing variables based on the Lagrangian relaxation of the Master Problem.

Numerical experiments, on both random and realistic instances, have been run under the SCIP framework. Within a collaboration with ULB/IRIDIA, both the column generation and the Branch-and-Cut-and-Price algorithms were tuned with an automatic tuner of parameters (irace), to find the best performing configurations. There was a large difference in the performance of the algorithms depending on the configuration chosen, and given the large number of parameters to be set, using an automatic tuner revealed to be very useful.

Various pricing problems also play a crucial role in the airline industry. As part of the SATURN project, E. Marcotte (ULB/GOM) collaborated on the design on a *pure-pricing mechanism* with the goal of reducing congestion in the European airpace. He also developed an heuristic algorithm to find approximate solutions to the mathematical model describing this mechanism, on the complete European airspace network. This algorithm was developed in response to the exact mixed-integer programming approach being found intractable for a problem of that size. The fast results obtained through this algorithm allowed him to test multiple variants of the pricing mechanism.

V. Lurkin (ULg), L.A. Garrow (Georgia Tech), M.J. Higgins (Georgia Tech) and M. Schyns (ULg) [36] are investigating airline itinerary choice models. Such models support many decisions with far-reaching economic consequences for the airlines, as they are used to evaluate potential route schedules. Classic models, however, suffer from major limitations, most notably because they use average fare information but do not correct for *price endogeneity*. Lurkin et al. use a novel database of airline tickets to estimate itinerary choice models using detailed fare data and compare these to classic itinerary choice models.

Several COMEX members are also interested in pricing problems related to the operations of electricity markets. M. Labbé (ULB/GOM), E. Marcotte (ULB/GOM) and P. Marcotte

(UdeM/DIRO), in particular, developed an exact, polynomial-time, algorithm to solve an electricity *bidding* problem where an electricity provider must chose values and quantities for bids to be sent to centralized buyer, where the competitors' bids and the total demand are uncertain. They constructed a proof of the algorithm validity and polynomial runtime when the uncertainty is represented through a finite number of distinct scenarios.

Another type of bidding situations, called *combinatorial auctions*, are considered by B. Vangerven, D. Goossens and F. Spieksma (KUL) [81]. More specifically, the subject of their work are auctions of goods that can be arranged in rows. Examples appear in allocating seats in a theater or stadium, or pieces of land for real estate development. Bidders bid on a subset of goods. The objective is to compute a subset of bids that maximizes auction revenue (often referred to as the winner determination problem). A dynamic programming algorithm is described, which, for a 2-row problem with connected and gap-free bids, solves the winner determination problem in polynomial time. This dynamic programming algorithm is extended in order to solve the case where bidders submit connected bids in a 3-row problem. The authors also establish the complexity for bids in a grid, thereby complementing previously known results.

2.5.2. Decision-making and game-theoretic models

Revealed preferences

An interesting topic in computational economics is the complexity of testing different axioms of revealed preference. This topic has been investigated for a number of years by a joint team involving IAP researchers as well as several other researchers at KULAK and ULB.

Probably, the best-known axiom is the so-called Generalized Axiom of Revealed Preferences, known as GARP. In a recent paper, Talla Nobibon, Smeulders and Spieksma [49] show how to speed up testing GARP to $O(n^2)$ (where n refers the number of observations). They also give lower bounds on the complexity of testing other axioms such as the Weak Axiom of Revealed Preferences (WARP) and the Strong Axiom of Revealed Preferences (SARP).

It is well-known that, for single-member households, WARP and SARP are equivalent when there are only two goods. In a paper by Smeulders, Cherchye, De Rock, Spieksma, and Talla Nobibon [71], this result is extended towards households consisting of L members, for which the authors introduce the concepts L-WARP and L-SARP. They demonstrate that L-WARP and L-SARP are not equivalent if there are at least $L + 1$ goods. However, they also show that L-WARP and L-SARP do become equivalent for the restricted "labor supply" setting where each single good is exclusively assigned to a different household member, i.e., in a setting where L (out of $L + 1$) goods are exclusive.

In another paper [70], the same authors establish the complexity of alternative versions of the weak axiom of revealed preference (WARP) for collective consumption models. In contrast to the unitary consumption model, these collective models explicitly take the multi-member nature of the household into account. Smeulders et al. consider the three collective settings that a re most often considered in the literature, namely: the private setting in which all goods are privately consumed by the household members; the public setting in which all goods are publicly consumed inside the household; and the general setting where no information on the (private or public) nature of goods consumed in the household is available. The authors prove that the collective version of WARP is NP-hard to test for both the private and public settings. Surprisingly, they find for the general setting that the collective version of WARP is easy to test

for two-member households.

Collaborative decisions

Game-theoretic models can be used to support decisions logistics, a main topic of interest for many participants in the IAP project. In particular, a recent trend in supply chain management, called horizontal collaboration, sees companies join forces to perform their distribution jointly. The principle behind this trend is straightforward: companies can achieve higher efficiency levels by forming a coalition and carrying out a joint operational plan. Several studies show that this close cooperation can lead to major reductions in the total logistic cost and in the CO2 emissions. For instance, a recent alliance between the pharmaceutical companies UCB and Baxter to transport their orders from Belgium to Romania has proved to be very fruitful. By collaborating, these companies were able to achieve a double-digit profit gain and a reduction in the greenhouse gas emissions of almost 50%. Despite the many potential advantages, the collaborative aspect makes creating a joint operational much more complex and demanding. Which companies offer the greatest potential for collaboration? How should the savings in the logistic cost be distributed among the coalition members? Giving answers to these questions requires facing the distribution problems from a new "collaborative" angle.

In a recent study, Ch. Defryn, Ch. Vanovermeire, and K. Sörensen (UA) [17] focus on the challenge of dividing the total coalition gain among all partners. They show that significant differences exist between allocation methods and they examine the impact of defining gain sharing on a short term (daily) or a long term (monthly) basis. Too often, the selection of an appropriate allocation mechanism is considered as an independent decision with fairness as the single criterion. The companies involved, however, should realize what the impact of a certain allocation method might be, when applied in the broader context of horizontal co-operation. Defryn et al. introduce a selection of well-known allocation methods and concepts and apply them to a real life case study of fresh produce traders, jointly organizing their transportation from the auction to a joint transport platform.

D. Palhazi Cuervo, Ch. Vanovermeire, and K. Sörensen (UA) [51] observed that the extent of the profit reaped from horizontal collaboration is highly dependent on the partners that form the coalition and on the characteristics of their operations. Different companies might have different requirements and could enforce different restrictions on the joint operational plan. In this work, they discuss a simulation study carried out to analyze the effects of different partner characteristics on the coalitionís performance. Contrary to most of the previous research, they evaluate coalitions formed by partners with different characteristics, and they analyze how these complement each other. This allows them to identify opportunities for very profitable collaborations that are missed by other studies.

Ch. Defryn, K. Sörensen, and T. Cornelissens (UA) [16] consider a selective vehicle routing problem, in which customers belonging to different partners in a logistic coalition are served in a single logistic operation with multiple vehicles. Each partner determines a cost of non-delivery (CND) for each of its customers, and a central algorithm creates an operational plan, including the decision on which customers to serve and in which trip. The total transportation cost of the coalition is then divided back to the partners through a cost allocation mechanism. This paper investigates the effect on the cost allocation of a partnerís strategy on non-delivery penalties (high/low) and the properties of its customer locations (distance to the depot, degree of clustering). The effect of the cost allocation method used by the coalition is also investigated. The authors compare the well-known Shapley value cost allocation method to their novel problem-specific method: the CND-weighted cost allocation method. They prove that an

adequate cost allocation method can provide an incentive for each partner to behave in a way that benefits the coalition. Further, they develop a transformation that is able to transform any cost allocation into an individually rational one without losing this incentive.

L. Verdonck (UH), P. Beullens (University of Southampton), A. Caris, K. Ramaekers and G.K. Janssens (UH) [82] studied a new approach for the horizontal collaboration of transportation companies, i.e., sharing distribution centers with partnering organizations. The resulting problem is denoted the cooperative facility location problem and is formulated as a mixed integer program. Numerical results of an experimental design on a case study are used to analyze the benefits of cooperative facility location and the effects of different cost allocation techniques. Results indicate that sharing distribution centers may lead to significant cost savings, diseconomies of scale may exist in terms of the number of partners, and more collaborative benefit can be expected when partners are unequal in size.

Adversarial situations

As opposed to the collaborative frameworks described in the previous subsection, adversarial situations where the actors "play" against each other or against nature are also frequently encountered. They give rise to noncooperative game models, such as Stackelberg games.

C. Casorrán (ULB/GOM), B. Fortz (ULB/GOM), M. Labbé (ULB/ GOM) and F. Ordónez have performed a thorough polyhedral analysis of mixed-integer programming formulations used to solve Stackelberg Games. They have compared previously known formulations from the literature and they have presented a novel formulation. From a theoretical standpoint, they have provided a ranking of all formulations in terms of the strength of their linear programming relaxations. These theoretical findings have been confirmed by computational experiments where running times, number of nodes in the branch-and-bound tree and gap between the optimal integer solution and the solution of each formulation's linear relaxation, have been compared. From both the theoretical and computational approach, they have surmised that the novel formulation, which is an ideal formulation when restricted to a single type of follower, significantly outperforms previous formulations.

In addition, the same authors have concentrated on extending the results obtained for Stackelberg Games to the specific subclass of Stackelberg Security Games, commonly used in many real life applications. The work done has led to successfully adapting general Stackelberg formulations to the security setting. This has involved redefining variables, developing a careful understanding of payoff structure in both settings, which in turn has led to the realization that they could establish a theoretical projection link between all the formulations in the general and the security setting. This has been key in adapting their previously obtained theoretical results to the specifics of Stackelberg Security Games. In particular, a novel formulation – which is ideal when the game involves a single type of attacker – has been obtained. Computational tests show that it responds significantly better than previously known formulations for this setting.

L. Talarico, G. Reniers, K. Sörensen, and J. Springael (UA) [73] have proposed a multimodal security-transportation model (called MISTRAL) to allocate security resources within a chemical supply chain which is characterized by the use of different transport modes, each having their own security features. The authors have considered security-related risks so as to take measures against terrorist acts which could target critical transportation systems. The idea of addressing security-related issues, by supporting decisions for preventing or mitigating intentional acts on transportation infrastructure, has gained attention in academic research only recently. The decision model presented in this paper is based on game theory and it can be employed to organize intelligence capabilities aimed at securing chemical supply chains. It en-

ables detection and warning against impending attacks on transportation infrastructures and the subsequent adoption of security countermeasures. This is of extreme importance for preventing terrorist attacks and for avoiding (possibly huge) human and economic losses. In this work, Talarico et al. also provide data sources and numerical simulations by applying the proposed model to an illustrative multi-modal chemical supply chain.

The modelling of electricity markets, modelled as locational two-sided auctions, has also attracted substantial attention.

Mehdi Madani and Mathieu Van Vyve (UCL) [38] consider the optimization problem implementing current market rules for European day-ahead electricity markets. They propose improved algorithmic approaches for that problem. First, a new MIP formulation is presented which avoids the use of complementarity constraints to express market equilibrium conditions, and also avoids the introduction of auxiliary continuous or binary variables. Instead, we rely on strong duality theory for linear or convex quadratic optimization problems to recover equilibrium constraints. Second, the new formulation suggests a Benders-like decomposition procedure. This helps in the case of piecewise linear bid curves that yield quadratic primal and dual objective functions leading to a dense quadratic constraint in the formulation. Computational experiments using 2011 historical instances for the Central Western Europe region show excellent results.

It is well known that a market equilibrium with uniform prices often does not exist in non-convex day-ahead electricity auctions. In [39] Mehdi Madani and Mathieu Van Vyve (UCL) consider the case of the non-convex, uniform-price Pan-European day-ahead electricity market "PCR" (Price Coupling of Regions), with non-convexities arising from so-called complex and block orders. They propose a new primal-dual framework for these auctions, which has applications in both economic analysis and algorithm design. This leads to better formulations and better algorithms for soving this type of problems. Moreover, from the economic analysis point of view, they give the first MILP formulations of optimization problems such as the maximization of the traded volume, or the minimization of opportunity costs of paradoxically rejected block bids. They illustrate the efficiency of the approach, as well as the economics trade-offs that may occur in practice.

Madani and Van Vyve (UCL) [40] examine the specific problem of clearing day-ahead electricity market auctions where each bidder, whether a producer or consumer, can specify a minimum profit or maximum payment condition constraining the acceptance of a set of bid curves spanning multiple time periods in locations connected through a transmission network with linear constraints. This helps describing e.g. the recovery of start-up costs of a power plant, or analogously for a large consumer, utility reduced by a constant term. They propose here a new market model with a corresponding MILP formulation for uniform locational price day-ahead auctions, handling bids with a minimum profit or maximum payment condition, which we call MP bids, in a uniform and computationally-efficient way. They compare these MP bids to previous models for minimum profit conditions proposed in the academic literature, and to the model for minimum income conditions used by the Spanish power exchange OMIE, now integrated to the pan-European PCR market.

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5 Network organisation and operation

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 Sections 3 and 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 this year: during the annual meeting at ULB (December 4, 2014) and during the COMEX Belgian Workshop on Mathematical Optimization in La-Roche-en-Ardenne (April 23-24, 2015).

Several scientific and networking joint meetings took place during the year. These are reported in Subsection 3.1.

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