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Project-Team REALOPT

Reformulations based algorithms for Combinatorial Optimization

IN COLLABORATION WITH: Institut de Mathématiques de Bordeaux (IMB)

RESEARCH CENTER
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THEME
Optimization, machine learning and statistical methods

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Project-Team REALOPT

Keywords: Combinatorial Optimization, Mixed Integer Linear Programming, Operations Research

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2. Overall Objectives

2.1. Overall Objectives

Quantitative modeling is routinely used in both industry and administration to design and operate transportation, distribution, or production systems. Optimization concerns every stage of the decision-making process: long term investment budgeting and activity planning, tactical management of scarce resources, or the control of day-to-day operations. In many optimization problems that arise in decision support applications the most important decisions (control variables) are discrete in nature: such as on/off decision to buy, to invest, to hire,

to send a vehicle, to allocate resources, to decide on precedence in operation planning, or to install a connection in network design. Such *combinatorial optimization* problems can be modeled as linear or nonlinear programs with integer decision variables and extra variables to deal with continuous adjustments. The most widely used modeling tool consists in defining the feasible decision set using linear inequalities with a mix of integer and continuous variables, so-called Mixed Integer Programs (MIP), which already allow a fair description of reality and are also well-suited for global optimization. The solution of such models is essentially based on enumeration techniques and is notoriously difficult given the huge size of the solution space.
Commercial solvers have made significant progress but remain quickly overwhelmed beyond a certain problem size. A key to further progress is the development of better problem formulations that provide strong continuous approximations and hence help to prune the enumerative solution scheme. Effective solution schemes are a complex blend of techniques: cutting planes to better approximate the convex hull of feasible (integer) solutions, extended reformulations (combinatorial relations can be formulated better with extra variables), constraint programming to actively reduce the solution domain through logical implications, Lagrangian and Bender's decomposition methods to produce powerful relaxations, multi-level programming to model a hierarchy of decision levels or recourse decision in the case of data adjustment, heuristics and meta-heuristics (greedy, local improvement, or randomized partial search procedures) to produce good candidates at all stage of the solution process, and branch-and-bound or dynamic programming enumeration schemes to find a global optimum. The real challenge is to integrate the most efficient methods in one global system so as to prune what is essentially an enumeration based solution technique. The progress are measured in terms of the large scale of input data that can now be solved, the integration of many decision levels into planning models, and not least, the account taken for random data by way of modeling expectation (stochastic approaches) or worst-case bahavior (robust approaches).

Building on complementary expertise, our team's overall goals are threefold:

(i) Methodologies: To design tight formulations for specific problems and generic models, relying on delayed cut and column generation, decomposition, extended formulations and projection tools for linear and nonlinear mixed integer programming models. More broadly, to contribute to theoretical and methodological developments of exact approaches in combinatorial optimization, while extending the scope of applications.

(ii) Problem solving: To demonstrate the strength of cooperation between complementary exact mathematical optimization techniques, dynamic programming, robust and stochastic optimization, constraint programming, combinatorial algorithms and graph theory, by developing "efficient" algorithms for specific mathematical models. To tackle large-scale real-life applications, providing provably good approximate solutions by combining exact methods and heuristics.

(iii) Software platform: To provide prototypes of specific model solvers and generic software tools that build on our research developments, writing proof-of-concept code, while transferring our research findings to internal and external users.

3. Research Program

3.1. Introduction

Combinatorial optimization is the field of discrete optimization problems. In many applications, the most important decisions (control variables) are binary (on/off decisions) or integer (indivisible quantities). Extra variables can represent continuous adjustments or amounts. This results in models known as *mixed integer programs* (MIP), where the relationships between variables and input parameters are expressed as linear constraints and the goal is defined as a linear objective function. MIPs are notoriously difficult to solve: good quality estimations of the optimal value (bounds) are required to prune enumeration-based global-optimization algorithms whose complexity is exponential. In the standard approach to solving an MIP is so-called *branch-and-bound algorithm* : (i) one solves the linear programming (LP) relaxation using the simplex method; (ii) if the LP solution is not integer, one adds a disjunctive constraint on a factional component (rounding it up or down) that defines two sub-problems; (iii) one applies this procedure recursively, thus defining a binary enumeration tree that can be pruned by comparing the local LP bound to the best known integer solution. Commercial MIP solvers are essentially based on branch-and-bound (such IBM-CPLEX, FICO-Xpress-mp, or GUROBI). They have made tremendous progress over the last decade (with a speedup by a factor of 60). But extending their capabilities remains a continuous challenge; given the combinatorial explosion inherent to enumerative solution techniques, they remain quickly overwhelmed beyond a certain problem size or complexity.

Progress can be expected from the development of tighter formulations. Central to our field is the characterization of polyhedra defining or approximating the solution set and combinatorial algorithms to identify "efficiently" a minimum cost solution or separate an unfeasible point. With properly chosen formulations, exact optimization tools can be competitive with other methods (such as meta-heuristics) in constructing good approximate solutions within limited computational time, and of course has the important advantage of being able to provide a performance guarantee through the relaxation bounds. Decomposition techniques are implicitly leading to better problem formulation as well, while constraint propagation are tools from artificial intelligence to further improve formulation through intensive preprocessing. A new trend is robust optimization where recent progress have been made: the aim is to produce optimized solutions that remain of good quality even if the problem data has stochastic variations. In all cases, the study of specific models and challenging industrial applications is quite relevant because developments made into a specific context can become generic tools over time and see their way into commercial software.

Our project brings together researchers with expertise in mathematical programming (polyhedral approaches, Dantzig-Wolfe decomposition, mixed integer programing, robust and stochastic programming, and dynamic programming), graph theory (characterization of graph properties, combinatorial algorithms) and constraint programming in the aim of producing better quality formulations and developing new methods to exploit these formulations. These new results are then applied to find high quality solutions for practical combinatorial problems such as routing, network design, planning, scheduling, cutting and packing problems.

3.2. Polyhedral approaches for MIP

Adding valid inequalities to the polyhedral description of an MIP allows one to improve the resulting LP bound and hence to better prune the enumeration tree. In a cutting plane procedure, one attempt to identify valid inequalities that are violated by the LP solution of the current formulation and adds them to the formulation. This can be done at each node of the branch-and-bound tree giving rise to a so-called *branch-and-cut algorithm* [73]. The goal is to reduce the resolution of an integer program to that of a linear program by deriving a linear description of the convex hull of the feasible solutions. Polyhedral theory tells us that if X is a mixed integer program: $X = P \cap \mathbb{Z}^n \times \mathbb{R}^p$ where $P = \{x \in \mathbb{R}^{n+p} : Ax \leq b\}$ with matrix $(A, b) \in \mathbb{Q}^{m\times(n+p+1)}$, then $conv(X)$ is a polyhedron that can be described in terms of linear constraints, i.e. it writes as $conv(X) = \{x \in \mathbb{R}^{n+p} : C\,x \leq d\}$ for some matrix $(C, d) \in \mathbb{Q}^{m'\times(n+p+1)}$ although the dimension m' is typically quite large. A fundamental result in this field is the equivalence of complexity between solving the combinatorial optimization problem $\min\{cx : x \in X\}$ and solving the *separation problem* over the associated polyhedron $conv(X)$: if $\widetilde{x} \notin conv(X)$, find a linear inequality $\pi\, x \geq \pi_0$ satisfied by all points in $conv(X)$ but violated by $\widetilde{x}$. Hence, for NP-hard problems, one can not hope to get a compact description of $conv(X)$ nor a polynomial time exact separation routine. Polyhedral studies focus on identifying some of the inequalities that are involved in the polyhedral description of $conv(X)$ and derive efficient *separation procedures* (cutting plane generation). Only a subset of the inequalities $C\,x \leq d$ can offer a good approximation, that combined with a branch-and-bound enumeration techniques permits to solve the problem. Using *cutting plane algorithm* at each node of the branch-and-bound tree, gives rise to the algorithm called *branch-and-cut*.

3.3. Decomposition and reformulation approaches

An hierarchical approach to tackle complex combinatorial problems consists in considering separately different substructures (subproblems). If one is able to implement relatively efficient optimization on the substructures, this can be exploited to reformulate the global problem as a selection of specific subproblem solutions that together form a global solution. If the subproblems correspond to subset of constraints in the MIP formulation, this leads to Dantzig-Wolfe decomposition. If it corresponds to isolating a subset of decision variables, this leads to Bender's decomposition. Both lead to extended formulations of the problem with either a huge number of variables or constraints. Dantzig-Wolfe approach requires specific algorithmic approaches to generate subproblem solutions and associated global decision variables dynamically in the course of the optimization. This procedure is known as *column generation*, while its combination with branch-and-bound enumeration is called *branch-and-price*. Alternatively, in Bender's approach, when dealing with exponentially many constraints in the reformulation, the *cutting plane procedures* that we defined in the previous section are well-suited tools. When optimization on a substructure is (relatively) easy, there often exists a tight reformulation of this substructure typically in an extended variable space. This gives rise powerful reformulation of the global problem, although it might be impractical given its size (typically pseudo-polynomial). It can be possible to project (part of) the extended formulation in a smaller dimensional space if not the original variable space to bring polyhedral insight (cuts derived through polyhedral studies can often be recovered through such projections).

3.4. Integration of Artificial Intelligence Techniques in Integer Programming

When one deals with combinatorial problems with a large number of integer variables, or tightly constrained problems, mixed integer programming (MIP) alone may not be able to find solutions in a reasonable amount of time. In this case, techniques from artificial intelligence can be used to improve these methods. In particular, we use primal heuristics and constraint programming.

Primal heuristics are useful to find feasible solutions in a small amount of time. We focus on heuristics that are either based on integer programming (rounding, diving, relaxation induced neighborhood search, feasibility pump), or that are used inside our exact methods (heuristics for separation or pricing subproblem, heuristic constraint propagation, ...).

Constraint Programming (CP) focuses on iteratively reducing the variable domains (sets of feasible values) by applying logical and problem-specific operators. The latter propagates on selected variables the restrictions that are implied by the other variable domains through the relations between variables that are defined by the constraints of the problem. Combined with enumeration, it gives rise to exact optimization algorithms. A CP approach is particularly effective for tightly constrained problems, feasibility problems and min-max problems Mixed Integer Programming (MIP), on the other hand, is known to be effective for loosely constrained problems and for problems with an objective function defined as the weighted sum of variables. Many problems belong to the intersection of these two classes. For such problems, it is reasonable to use algorithms that exploit complementary strengths of Constraint Programming and Mixed Integer Programming.

3.5. Robust Optimization

Decision makers are usually facing several sources of uncertainty, such as the variability in time or estimation errors. A simplistic way to handle these uncertainties is to overestimate the unknown parameters. However, this results in over-conservatism and a significant waste in resource consumption. A better approach is to account for the uncertainty directly into the decision aid model by considering mixed integer programs that involve uncertain parameters. Stochastic optimization account for the expected realization of random data and optimize an expected value representing the average situation. Robust optimization on the other hand entails protecting against the worst-case behavior of unknown data. There is an analogy to game theory where one considers an oblivious adversary choosing the realization that harms the solution the most. A full worst case protection against uncertainty is too conservative and induces very high over-cost. Instead, the realization of random data are bound to belong to a restricted feasibility set, the so-called uncertainty set. Stochastic and robust optimization rely on very large scale programs where probabilistic scenarios are enumerated. There is hope of a tractable solution for realistic size problems, provided one develops very efficient ad-hoc algorithms.

The techniques for dynamically handling variables and constraints (column-and-row generation and Bender's projection tools) that are at the core of our team methodological work are specially well-suited to this context.

3.6. Polyhedral Combinatorics and Graph Theory

Many fundamental combinatorial optimization problems can be modeled as the search for a specific structure in a graph. For example, ensuring connectivity in a network amounts to building a *tree* that spans all the nodes. Inquiring about its resistance to failure amounts to searching for a minimum cardinality *cut* that partitions the graph. Selecting disjoint pairs of objects is represented by a so-called *matching*. Disjunctive choices can be modeled by edges in a so-called *conflict graph* where one searches for *stable sets* – a set of nodes that are not incident to one another. Polyhedral combinatorics is the study of combinatorial algorithms involving polyhedral considerations. Not only it leads to efficient algorithms, but also, conversely, efficient algorithms often imply polyhedral characterizations and related min-max relations. Developments of polyhedral properties of a fundamental problem will typically provide us with more interesting inequalities well suited for a branch-and-cut algorithm to more general problems. Furthermore, one can use the fundamental problems as new building bricks to decompose the more general problem at hand. For problem that let themselves easily be formulated in a graph setting, the graph theory and in particular graph decomposition theorem might help.

4. Application Domains

4.1. Introduction

Our group has tackled applications in logistics, transportation and routing [72], [71], [67], [69], in production planning [93] and inventory control [67], [69], in network design and traffic routing [49], [58], [65], [96], [47], [59], [79], [86], in cutting and placement problems [74], [75], [90], [91], [92], [94], and in scheduling [5], [80], [45].

4.2. Network Design and Routing Problems

We are actively working on problems arising in network topology design, implementing a survivability condition of the form "at least two paths link each pair of terminals". We have extended polyhedral approaches to problem variants with bounded length requirements and re-routing restrictions [58]. Associated to network design is the question of traffic routing in the network: one needs to check that the network capacity suffices to carry the demand for traffic. The assignment of traffic also implies the installation of specific hardware at transient or terminal nodes.

To accommodate the increase of traffic in telecommunication networks, today's optical networks use grooming and wavelength division multiplexing technologies. Packing multiple requests together in the same optical stream requires to convert the signal in the electrical domain at each aggregation of disaggregation of traffic at an origin, a destination or a bifurcation node. Traffic grooming and routing decisions along with wavelength assignments must be optimized to reduce opto-electronic system installation cost. We developed and compared several decomposition approaches [98], [97], [96] to deal with backbone optical network with relatively few nodes (around 20) but thousands of requests for which traditional multi-commodity network flow approaches are completely overwhelmed. We also studied the impact of imposing a restriction on the number of optical hops in any request route [95]. We also developed a branch-and-cut approach to a problem that consists in placing sensors on the links of a network for a minimum cost [65], [66].

We studied several time dependent formulations for the unit demand vehicle routing problem [51], [50] [30]. We gave new bounding flow inequalities for a single commodity flow formulation of the problem. We described their impact by projecting them on some other sets of variables, such as variables issued of the Picard and Queyranne formulation or the natural set of design variables. Some inequalities obtained by projection are facet defining for the polytope associated with the problem. We are now running more numerical experiments in order to validate in practice the efficiency of our theoretical results.

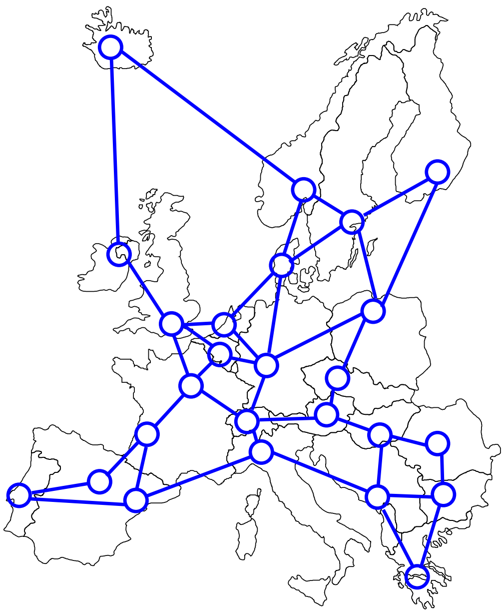

Figure 1. Design of a SDH/SONET european network where demands are multiplexed.

We also worked on the p-median problem, applying the matching theory to develop an efficient algorithm in Y-free graphs and to provide a simple polyhedral characterization of the problem and therefore a simple linear formulation [85] simplifying results from Baiou and Barahona.

We considered the multi-commodity transportation problem. Applications of this problem arise in, for example, rail freight service design, "less than truckload" trucking, where goods should be delivered between different locations in a transportation network using various kinds of vehicles of large capacity. A particularity here is that, to be profitable, transportation of goods should be consolidated. This means that goods are not delivered directly from the origin to the destination, but transferred from one vehicle to another in intermediate locations. We proposed an original Mixed Integer Programming formulation for this problem which is suitable for resolution by a Branch-and-Price algorithm and intelligent primal heuristics based on it.

For the problem of routing freight railcars, we proposed two algorithmes based on the column generation approach. These algorithmes have been testes on a set of real-life instances coming from a Russian freight real transportation company. Our algorithmes have been faster on these instances than the current solution approach being used by the company.

4.3. Packing and Covering Problems

Realopt team has a strong experience on exact methods for cutting and packing problems. These problems occur in logistics (loading trucks), industry (wood or steel cutting), computer science (parallel processor scheduling).

We developed a branch-and-price algorithm for the Bin Packing Problem with Conflicts which improves on other approaches available in the literature [84]. The algorithm uses our methodological advances like the generic branching rule for the branch-and-price and the column based heuristic. One of the ingredients which contributes to the success of our method are fast algorithms we developed for solving the subproblem which is the Knapsack Problem with Conflicts. Two variants of the subproblem have been considered: with interval and arbitrary conflict graphs.

We also developped a branch-and-price algorithm for a variant of the bin-packing problem where the items are fragile. In [43] we studied empirically different branching schemes and different algorithms for solving the subproblems.

We studied a variant of the knapsack problem encountered in inventory routing problem [69]: we faced a multiple-class integer knapsack problem with setups [68] (items are partitioned into classes whose use implies a setup cost and associated capacity consumption). We showed the extent to which classical results for the knapsack problem can be generalized to this variant with setups and we developed a specialized branch-and-bound algorithm.

We studied the orthogonal knapsack problem, with the help of graph theory [62], [60], [64], [63]. Fekete and Schepers proposed to model multi-dimensional orthogonal placement problems by using an efficient representation of all geometrically symmetric solutions by a so called *packing class* involving one *interval graph* for each dimension. Though Fekete & Schepers' framework is very efficient, we have however identified several weaknesses in their algorithms: the most obvious one is that they do not take advantage of the different possibilities to represent interval graphs. We propose to represent these graphs by matrices with consecutive ones on each row. We proposed a branch-and-bound algorithm for the 2d knapsack problem that uses our 2D packing feasibility check. We are currently developping exacti optimization tools for glass-cutting problems in a collaboration with Saint-Gobain. This 2D-3stage-Guillotine cut problems are very hard to solve given the scale of the instance we have to deal with. Moreover one has to issue cutting patterns that avoid the defaults that are present in the glass sheet the are used as raw material. They are extra sequencing constraints regarding the production that make the problem even more complex.
Finally, let us add that we are now organizing a european challenge on packing with society Renault: see http://challenge-esicup-2015.org/. This challenge is about loading trucks under practical constraints. The final results will be announced in March 2015.

4.4. Planning, Scheduling, and Logistic Problems

Inventory routing problems combine the optimization of product deliveries (or pickups) with inventory control at customer sites. We considered an industrial application where one must construct the planning of single product pickups over time; each site accumulates stock at a deterministic rate; the stock is emptied on each visit. We have developed a truncated branch-and-price algorithm: periodic plans are generated for vehicles by solving a multiple choice knapsack subproblem; the global planning of customer visits is generated by solving a master program. Confronted with the issue of symmetry in time, we used a state-space relaxation idea. Our algorithm provides solutions with reasonable deviation from optimality for large scale problems (260 customer sites, 60 time periods, 10 vehicles) coming from industry [70]. We previously developed approximate solutions to a related problem combining vehicle routing and planning over a fixed time horizon (solving instances involving up to 6000 pick-ups and deliveries to plan over a twenty day time horizon with specific requirements on the frequency of visits to customers [72].

Together with our partner company GAPSO from the associate team SAMBA, we worked on the equipment routing task scheduling problem [78] arising during port operations. In this problem, a set of tasks needs to be performed using equipments of different types with the objective to maximum the weighted sum of performed tasks.

We participated to the project on an airborne radar scheduling. For this problem, we developed fast heuristics [57] and exact algorithms [45]. A substantial research has been done on machine scheduling problems. A new compact MIP formulation was proposed for a large class of these problems [44]. An exact decomposition algorithm was developed for the NP-hard maximizing the weighted number of late jobs problem on a single machine [80]. A dominant class of schedules for malleable parallel jobs was discovered in the NP-hard problem to minimize the total weighted completion time [82]. We proved that a special case of the scheduling problem at cross docking terminals to minimize the storage cost is polynomially solvable [83], [81].

Another application area in which we have successfully developed MIP approaches is in the area of tactical production and supply chain planning. In [42], we proposed a simple heuristic for challenging multi-echelon problems that makes effective use of a standard MIP solver. [41] contains a detailed investigation of what makes solving the MIP formulations of such problems challenging; it provides a survey of the known methods for strengthening formulations for these applications, and it also pinpoints the specific substructure that seems to cause the bottleneck in solving these models. Finally, the results of [46] provide demonstrably stronger formulations for some problem classes than any previously proposed.

We have been developing robust optimization models and methods to deal with a number of applications like the above in which uncertainty is involved. In [53], [52], we analyzed fundamental MIP models that incorporate uncertainty and we have exploited the structure of the stochastic formulation of the problems in order to derive algorithms and strong formulations for these and related problems. These results appear to be the first of their kind for structured stochastic MIP models. In addition, we have engaged in successful research to apply concepts such as these to health care logistics [48]. We considered train timetabling problems and their re-optimization after a perturbation in the network [55], [54]. The question of formulation is central. Models of the literature are not satisfactory: continuous time formulations have poor quality due to the presence of discrete decision (re-sequencing or re-routing); arc flow in time-space graph blow-up in size (they can only handle a single line timetabling problem). We have developed a discrete time formulation that strikes a compromise between these two previous models. Based on various time and network aggregation strategies, we develop a 2-stage approach, solving the contiguous time model having fixed the precedence based on a solution to the discrete time model.

Currently, we are conducting investigations on a real-world planning problem in the domain of energy production, in the context of a collaboration with EDF. The problem consists in scheduling maintenance periods of nuclear power plants as well as production levels of both nuclear and conventional power plants in order to meet a power demand, so as to minimize the total production cost. For this application, we used a Dantzig-Wolfe reformulation which allows us to solve realistic instances of the deterministic version of the problem [31]. In practice, the input data comprises a number of uncertain parameters. We deal with a scenario-based stochastic demand with help of a Benders decomposition method. We are working on Multistage Robust Optimization approaches to take into account other uncertain parameters like the duration of each maintenance period, in a dynamic optimization framework. The main challenge adressed in this work is the joint management of different reformulations and solving techniques coming from the deterministic (Dantzig-Wolfe decomposition, due to the large scale nature of the problem), stochastic (Benders decomposition, due to the number of demand scenarios) and robust (reformulations based on duality and/or column and/or row generation due to maintenance extension scenarios) components of the problem [28].

5. New Software and Platforms

5.1. BaPCod – a generic Branch-and-Price Code

Participants: Issam Tahiri [Software Engineer], François Clautiaux, Boris Detienne, Pierre Pesneau, Ruslan Sadykov, François Vanderbeck [correspondant].

BaPCod is a prototype code that solves Mixed Integer Programs (MIP) by application of decomposition and reformulation approach (relying mostly on Dantzig-Wolfe reformulation techniques). The reformulated problem is solved using a branch-and-price-and-cut (column and cut generation) algorithm. This software platform, made of C++ classes, offers a "*black-box*" implementation that does not require user input and is not application specific. The features are
(i) A modeling language to express a compact integer linear programming model of the application on hand.
(ii) the automation of the Dantzig-Wolfe reformulation process. The user can provide subproblem solvers if available, but he does not need to explicitly define the reformulation, the explicit form of the columns, their reduced cost, or the Lagrangian bounds.

(iii) a default column generation procedure with standard initialization and stabilization [1], [56] [88] [87] [77] and
(iv) a default branching scheme that is generic to all applications [7],
(v) default primal heuristics specially developed for use in a decomposition framework [61], [76], [89].
The prototype software was/is used as background solver in our application studies and local PhD thesis. It also serves as the framework for our comparative study in a Inria assocaited team project and our transfert projects (the prototype enables us to be very responsive in our industrial contact).

See also the web page https://wiki.bordeaux.inria.fr/realopt/pmwiki.php/Project/BaPCod.

6. New Results

6.1. Highlights of the Year

- Olivier Beaumont and Lionel Eyraud-Dubois have received the HiPC best paper award for their work on resource allocation for large scale virtualized platforms with reliability guarantees. They provided a formulation based on a thorough analysis of a real life usage trace, and a very efficient two-step allocation algorithm.
- The team organized the annual conference of the French Operations Research Society ROADEF14 in Feb 2014.
- An Inria Innovation Lab has been created between Realopt and Ertus Consulting.
- The SAMBA associated team project with Brazil was renewed for 3 years including new collaborators from Chili.
- François Vanderbeck was invited as a plenary speaker at the conference OPTIMIZATION 2014, in Portugal [19].

6.2. Automation and combination of linear-programming based stabilization techniques in column generation

We reviewed in [88] stabilization techniques that can improve in practice the convergence of a column generation algorithm. Proximal methods based on penalising the deviation from the incumbent dual solution have become standards of the domain. However, the analysis of such methods is important to understand the mechanism on which they rely, to appreciate the difference between methods, and to derive intelligent schemes to adjust their parameters. As stabilization procedures for column generation can be viewed as cutting plane strategies in the dual problem, the link with cutting plane separation strategies can be exploited to enlarge the scope of methods and to refine their analysis. In [24], [40], we focus on stabilization schemes that rely solely on a linear programming (LP) solver for the column generation master program. This restrictive scope captures the most common implementations where one uses an LP solver to handle the master program. For dual price smoothing techniques, we analyse the link with the in-out separation strategy and we derive generic convergence properties. For penalty function methods as well as for smoothing, we describe proposals for parameter self-adjusting schemes. Such schemes make initial parameter tuning less of an issue as corrections are made. Also, the dynamic adjustments, compared to a static setting, allows to adapt the parameters to the phase of the algorithm. We provide extensive test reports that highlight the comparative performances of such scheme and validate our self-adjusting parameter scheme. Furthermore, our results show that using smoothing in combination with penalty function yields a cumulative effect on convergence speed-ups [35]. We have also consider other stabilization strategies inspired form algorithmic strategies have been designed to accelerate convergence of cutting plane algorithms in mixed integer programming. In [37], we show that the "Multi-Point Separation" strategy translates into a column generation stabilization technique that consists in restricting the dual solution to be in the convex hull of the selected multi-point set. We have also considered other stabilization strategies inspired from algorithmic strategies that have been designed to accelerate convergence of cutting plane algorithms in mixed integer programming. In [37], we show that the "Multi-Point Separation" strategy translates into a column generation stabilization technique that consists in restricting the dual solution to be in the convex hull of the selected multi-point set.

6.3. Multi-Stage Column generation strategies

In [39], we propose another mechanism to improve the performance of column generation algorithms. We study the application of branch-and-price approaches to the automatic version of the Software Clustering Problem. To tackle this problem, we apply the Dantzig-Wolfe decomposition to a formulation from literature. Given this, we present two Column Generation (CG) approaches to solve the linear programming relaxation of the resulting reformulation: the standard CG approach, and a new approach, which we call Staged Column Generation (SCG). Also, we propose a modification to the pricing subproblem that allows to add multiple columns at each iteration of the CG. We test our algorithms in a set of 45 instances from the literature. The proposed approaches were able to improve the literature results solving all these instances to optimality. Furthermore, the SCG approach presented a considerable performance improvement regarding computational time, number of iterations and generated columns when compared with the standard CG as the size of the instances grows.

6.4. Aggregation techniques to reduce the size of column generation models

We proposed an aggregation method to reduce the size of column generation (CG) models for a class of set-covering problems in which the feasible subsets depend on a resource constraint. The aggregation relies on a correlation between the resource consumption of the elements and the corresponding optimal dual values. The aggregated model obtained allows to find good quality lower bounds more rapidly than the original CG algorithm. The speedup is due to less primal and dual variables in the master, and to an aggregated pricing sub-problem. To guarantee optimaly, we designed an algorithm that iteratively refines the aggregation until the CG optimum is reached. Computational results prove the usefulness of our methods.

6.5. Dual-feasible functions

Dual-feasible functions have been used in the past to compute fast lower bounds and valid inequalities for different combinatorial optimization and integer programming problems. Until now, all the dual-feasible functions proposed in the literature were 1-dimensional functions, and were defined only for positive arguments. In [12] we extended the principles of dual-feasible functions to the m-dimensional case by introducing the concept of vector packing dual-feasible function. We explored the theoretical properties of these functions in depth, and we proposed general schemes for generating some instances of these functions. Additionally, we proposed and analyzed different new families of vector packing dual-feasible functions. All the proposed approaches were tested extensively using benchmark instances of the 2-dimensional vector packing problem. Our computational results showed that these functions can approximate very efficiently the best lower bounds for this problem. In a second paper, currently submitted to a journal, we show that extending these functions to negative arguments raises many issues. Additionally, we describe different construction principles to obtain dual-feasible functions with domain and range $\mathbb{R}$. Specific instances obtained from these principles are proposed and analyzed.

6.6. Resource Allocation and Scheduling in Large Scale Distributed Platforms.

We have considered several problems arising in the context of large scale platforms, that are characterized by their heterogeneity, the difficulty of predicting performance and the risk failures. In [13], we concentrate on heterogeneity issues in collective communication schemes where the goal is to broadcast a message to a set of nodes. In particular, we consider a realistic model in the context of large scale distributed platforms where some nodes may lie behind NATs or firewalls and may be therefore unable to forward the message between them. In [21], [20], we consider resource allocation problems that arise in large scale data centers. In [20], we analyze the main characteristics of the services in a huge trace corresponding to an actual data center and that has been released recently by google. In the same context, in [21], we concentrate on issues related to fault tolerance by over subscribing services in order to guarantee quality of service in a failure prone environment. At last, the difficulty to predict the actual performance of resources made it very popular to rely on dynamic scheduling algorithms where scheduling decisions are made at runtime. In [22], we analyze the performance of such a dynamic scheduling algorithm in terms on number of induced communications for outer product and matrix multiplication kernels.

6.7. Employee timetabling with time varying demand

We addressed a multi-activity tour scheduling problem with time varying demand. The objective is to compute a schedule for a fixed roster in order to minimize the over-coverage and the under-coverage of different parallel activity demands along a planning horizon. Numerous complicating constraints are present in our problem: all employees are different and can perform several different activities during the same day-shift, lunch breaks and pauses are flexible, demand is given for 15 minutes periods. To the best of our knowledge, the work in [29] is the first attempt to combine days-off scheduling, shift scheduling, shift assignment, activity assignment, pause and lunch break assignment. To solve this problem, we developed several methods: a compact linear Mixed Integer Programming model, a branch-and-price like approach with a nested dynamic program to solve heuristically the subproblems, a diving heuristic, and a greedy heuristic based on our subproblem solver. The computational results, based on both real cases and instances derived from real cases, demonstrate that our methods are able to provide good quality solutions in a short computing time. Our algorithms are now embedded in a commercial software, which is already in use in a mini-mart company.

6.8. Time-dependent formulations for routing problems

The paper [16] presents a new formulation for the Time-Dependent Travelling Salesman Problem (TDTSP). We start by reviewing well known natural formulations with some emphasis on the formulation by Picard and Queyranne (1978). The main feature of this formulation is that it uses, as a subproblem, an exact description of the n-circuit problem. Then, we present a new formulation that uses more variables and is based on using, for each node, a stronger subproblem, namely a n-circuit subproblem with the additional constraint that the corresponding node is not repeated in the circuit. Although the new model has more variables and constraints than the original PQ model, the results given from our computational experiments show that the linear programming relaxation of the new model gives, for many of the instances tested, gaps that are close to zero. Thus, the new model is worth investigating for solving TDTSP instances. We have also provided a complete characterization of the feasible set of the corresponding linear programming relaxation in the space of the variables of the PQ model. This characterization permits us to suggest alternative methods of using the proposed formulations.

A well-known formulation for the unit-demand capacitated vehicle routing problem uses a single commodity flow system to represent the delivery of the items. The vehicle capacity is modeled by imposing a maximum capacity on the arcs used by the flow. In [30], we used a time-dependent formulation for the problem to derive, by projection, tighter bounding inequalities on the arcs. The first experiments show that these new inequalities permit to improve significantly the linear relaxation bound of the single commodity flow formulation. We are currently studying separation algorithms in order to generate dynamically these new inequalities.

6.9. Vehicle routing for dial-a-ride problems

Static and deterministic vehicle routing problems cannot be used in many real-life systems, as input data are not reliable and revealed over time. In [11], we study a pickup and delivery problem with time windows accounting for maximum ride time constraints – the so-called dial-a-ride problem – in its static and dynamic variant, and we make specific proposal on robust optimization models for this problem. To solve the static model, we develop a branch-and-price approach that handles ride time constraints in the process of generating feasible vehicle routes in the course of the optimization procedure. The work is focussed on the pricing problem solver and acceleration techniques for the branch-and-price approach. Our numerical results show that the method is competitive compared to existing approaches that are based on branch-and-cut. In the dynamic context, where some input data are revealed or modified over time, we apply our branch-and-price algorithm for re-optimization in a rolling horizon approach.

6.10. A MILP approach to minimize the number of late jobs with and without machine availability constraints

The study in [14] investigates scheduling problems that occur when the weighted number of late jobs that are subject to deterministic machine availability constraints have to be minimized. These problems can be modeled as a more general job selection problem. Cases with resumable, non-resumable, and semi-resumable jobs as well as cases without availability constraints are investigated. The proposed efficient mixed integer linear programming approach includes possible improvements to the model, notably specialized lifted knapsack cover cuts. The method proves to be competitive compared with existing dedicated methods: numerical experiments on randomly generated instances show that all 350-job instances of the test bed are closed for the well-known problem $1|r_i|\sum w_i U_i$. For all investigated problem types, 98.4% of 500-job instances can be solved to optimality within one hour.

6.11. Two phase solution for an intelligent moving target search problem based on a 0–1 linear model

We developed a generic discrete model for the moving, intelligent target problem. Our objective is to maximise the probability of detection of the moving target with respect to target and searcher's constraints. The solution method proposed in [15] is composed of two stages. The first one aims at providing a large-scale strategy based on an Integer Linear Program approach. As a direct solution of this problem is not practically possible, we use a decomposition of the problem into a searcher's strategy on one side, and the target's strategy on the other side. A good strategy for the searcher is determined using a sliding window procedure. Concerning the target, our approach consists in simulating some of the target's possible strategies and considering each of these possibilities as an independent and deterministic entity. The second stage is dedicated to adjusting the large-scale strategy provided by stage 1. Numerical results are presented so as to assess the impact of our approach.

6.12. Computing the Chromatic index and clique numberof special graphs

In our paper [17] on the strong chromatic index of planar graphs with large girth, we prove that every planar graph with maximum degree Δ (let Δ be an integer) and girth at least $10\Delta + 46$ is strong $(2\Delta - 1)$-edge-colorable, that is best possible (in terms of number of colors) as soon as G contains two adjacent vertices of degree Δ. This improves the best previous result when $\Delta \geq 6$. In [18] we show how one can compute the clique number of a-perfect graphs in polynomial time. A main result of combinatorial optimization is that clique and chromatic number of a perfect graph are computable in polynomial time (Grötschel, Lovasz and Schrijver 1981). This result relies on polyhedral characterizations of perfect graphs involving the stable set polytope of the graph, a linear relaxation defined by clique constraints, and a semi-definite relaxation, the Theta-body of the graph. A natural question is whether the algorithmic results for perfect graphs can be extended to graph classes with similar polyhedral properties. In [18] we consider a superclass of perfect graphs, the a-perfect graphs, whose stable set polytope is given by constraints associated with generalized cliques. We show that for such graphs the clique number can be computed in polynomial time as well. The result strongly relies upon Fulkersons's antiblocking theory for polyhedra and Lovasz's Theta function.

7. Bilateral Contracts and Grants with Industry

7.1. Contract with EDF on robust maintenance planning

We are currently working on a project aiming to plan the energy production and the maintenance breaks for a set of nuclear power plants generating electricity. We consider the large-scale power plant maintenance scheduling and production planning problem submitted by EDF to the 2010 Euro/Roadef Challenge. Two types of power plants are used to satisfy a customer demand over a specific time horizon. Type 1 plants can operate continuously while Type 2 plants have to be shut down regularly for refuelling and maintenance, and cannot produce during outage periods. The decision to be made consists of the dates of outages, the amount of refuel for Type 2 plants, and production level for both types of plants. The objective is to minimize the average cost of refuelling and production on various demand scenarios. We previously developed a column generation approach based on extended formulation which enables to solve within a few minutes a deterministic instance of the problem, which is within the time frame of the operational tools currently used by EDF. We now investigate stochastic and robust versions of the problem, where the duration of maintenance operations and the power demand are uncertain. Our approach is tested on real life instances within a rolling horizon framework.

7.2. Collaboration with ERTUS on phytosanitary treatment planning

In planning winary operations (most importantly phytosanitary treatments on the wine tree) under wheather forcast uncertainty, one searches for solutions that remain feasible and “cheap” in case of perturbation in the data. We consider the planning and scheduling of the operations that arise over a one-year horizon. More precisely, the operations to be sheduled include tasks related to soil care, or grape tree care: cutting, line building, thinning out leaves, ..., and chemical treatments. The latter are a main focus of our study since one of the principal goals of better planning is to reduce the amount of chemical treatments by selecting the appropriate products and schemes, but also by spacing out treatements while guarantying a desease free vineyard with some confidence. Each of the scheduled tasks requires its own resource, so the planning also triggers equipement and raw products selection decisions. The objective is to minimize both equipment and product costs augmented by an evaluation of the hazard of chemical product use. The planning should be “robust” to seasonal variations on the proper time frame for scheduling tasks.

7.3. Collaboration with Exeo-Solutions on dimensionning a vehicle fleet for waste collection

Through the internships of Damien Trut and Youcef Magnouche in Exeo, and the current work of Pierre Pesneau, we study the optimization of partitionning a urban area into zones that shall be assigned to vehicles for waste collection. The goal is to minimize the distance traversed by the vehicles in each zone. This can be modeled as a clustering problem with side constraints: zones assigned to a same cluster must be contiguous and satisfy capacity and time constraints.

7.4. Collaboration with B-Travel on a yield management problem

Through the PhD thesis of Martin Bué (in collaboration with inria team Dolphin), we are now working with society B-Travel on pricing and yield management. The goal is to find the best prices and incentives in the context of professional travel. The techniques used are based on network-flow formulations and mathematical programming.

7.5. Collaboration with Vekia on an employee-scheduling problem

Through the PhD thesis of Matthieu Gérard (in collaboration with inria team Dolphin), we are now investigating a very rich version of employee-scheduling problem. We have designed an efficient algorithm for computing the best shift for each employee, based on dynamic programming. This method is used in a greedy algorithm to find solutions in a faster manner, and in a branch-and-price method to prove the optimality of the solution.

7.6. Collaboration with Renault S.A. on truck loading problem

The goal of this one year industrial contrat was to analyze the algorithmic solutions used by Renault S.A. for packing items into trucks. The outcome of the contract was a report on their approach and how hints to improve it.

7.7. Collaboration with St-Gobain Recherche on glass cutting

Through the internships of Quentin Viaud, we have studied a hard glass-cutting problem. The objective is to minimize the quantity of trim loss when rectangular pieces are cut from large rectangles. This first study has shown that our methodologies are able to cope with this problem for medium-sized instances. Solving the problem with large instances is a scientific challenge that we will address in the a follow-up contract. Quentin Viaud has begun a PhD thesis (CIFRE) in 2015 on this topic.

8. Partnerships and Cooperations

8.1. International Initiatives

8.1.1. Inria Associate Teams

8.1.1.1. SAMBA

Title: Combinatorial optimization problems

International Partner (Institution - Laboratory - Researcher):

Pontifícia Universidade Católica do Rio de Janeiro, Brazil

Universidade Federal Fluminense (UFF), Brazil

Universidad Adolfo Ibañez, Chile

Duration: 2014 - 2017

See also: https://wiki.bordeaux.inria.fr/realopt/pmwiki.php/Project/Samba

The renewed project builds on our previous SAMBA output with new emphasis on 4 axis:

1. **Algorithmic Performance Enhancements:** In the line of the considerable algorithmic speed-up that we obtained recently in SAMBA by developping stabilization techniques, warm-starting techniques (with memorized basis to initialize the node of the enumeration tree), and strong branching techniques (that limit the size of the enumeration tree), we aim to develop intensive preprocessing techniques building on contraint propagation. Further contibutions shall consist in integrating dynamic aggregation-disagregation techniques.
2. **Extending the Dantzig-Wolfe reformulation paradigm**. The current SAMBA project has lead to finalizing a technique called “column generation for extended formulations” which can be understood as a generalization of Dantzig-Wolfe reformulation: To favour early convergence, the Dantzig-Wolfe reformulation is lifted into an extended variable space where the recombination of solutions arises. Further extension is built in the proposal of Goycoolea et al.
3. **Combining Dantzig-Wolfe decomposition with Benders':** In a stochastic environement, a numerically realistic approach in to build solutions that resists to worst case perturbations drawn within a contrained uncertainty set. In such context, bilevel optimization naturally arises: the second level models the worst case reaction of the system, along with our recourse, considering as fixed, the decisions of the first level of optimization. The model constraints are therefore decomposed into first level and second level, suited for Benders approach. When the first stage is a multiple resource planning applications, a strong model leading to good continuous approximation can be obtained by reformulating the problem in terms of variables that encode a work allocation for an individual resource (this is known as the Dantzig-Wolfe decomposition approach).
4. **Build-up our BAPCOD software platform for new benchmarks and industrial transfer:** the aim is to translate our research output into efficient code, to develop high level interface that free the end users from the expert knowledge normally required for complex decomposition based solution.

8.2. International Research Visitors

8.2.1. Visits of International Scientists

- B. Stevens, Carleton University (Canada), has visited the University of Bordeaux for one year.
- Shunji Tanaka, Associate professor at Kyoto University, has visited the University of Bordeaux for one week in September 2014.
- Marcos Goycoolea visited us in Bordeaux on the first week of September 2014.

8.2.2. Visits to International Teams

8.2.2.1. Research stays abroad

- Ruslan Sadykov visited Alexander Lazarev of Institute of Control Sciences of Russian Academy of Sciences, Moscow, Russia, for one week in february 2014.
- Arnaud Pêcher has visited the University of Rosario, Rosario, Argentina, for two weeks in December 2014.
- Pierre Pesneau visited Luis Gouveia of the University of Lisbon, Portugal, for one week in July 2014.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. General chair, scientific chair

Our team's organized the annual meeting of the French Operations Research Society (ROADEF) in February 2014. http://roadef2014.sciencesconf.orgRoadef 2014 gathered more than 400 attendees, with plenary talks by Pierre Bonami (IBM ILOG CPLEX), Michel Balinski (Ecole polytechnique - CNRS), Andrea Lodi (University of Bologna), Pascal Van Hentenryck (NICTA), and Jean-Francois Cordeau (HEC Montréal); and 12 clusters having each organized a one-hour tutorial.

9.1.1.2. Chair of conference program committee

Arnaud Pêcher is co-chair of the programm committee of the international conference BGW2014.

9.1.1.3. Member of the conference program committee

- Arnaud Pêcher is member of the program committee of ICGT2014
- Arnaud Pêcher is member of the program committee of Journées Graphes et Algorithmes 2014
- Pierre Pesneau is member of the program committee of INOC 2015, International Network Optimization Conference, May 18-20, 2015

9.1.2. Journal

9.1.2.1. Member of the editorial board

- O. Beaumont is editor for IEEE Transactions on Parallel and Distributed Systems (TPDS)
- F. Vanderbeck is Associate Editor for the EURO Journal on Computational Optimization

9.1.2.2. Reviewer

The team members are regular referees for the best journals of the field.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence : Arnaud Pêcher, Programmation objet et impérative, 200h, DUT, Université de Bordeaux, France

Licence : Arnaud Pêcher, Théorie des graphes, 16h, DUT, Université de Bordeaux, France

Licence : Pierre Pesneau, Système et Programmation, 59h, L2, Université de Bordeaux, France

Master : Olivier Beaumont, Optimisation en Cloud Computing & Big Data, 15h Cours, M2, Université de Bordeaux, France

Master : Olivier Beaumont, Fouille de données, 3h TD, M2, Institut Polytechnique de Bordeaux, France

Master : Olivier Beaumont, Fonctionnement des moteurs de recherche, 4h TD, M1, Institut Polytechnique de Bordeaux, France

Master : François Clautiaux, Programmation linéaire 1, 15h TD, M1, Université Bordeaux 1, France

Master : François Clautiaux, Introduction à l'optimisation en nombres entiers, 30h TD, M1, Université Bordeaux 1, France

Master : François Clautiaux, Gestion des opérations et planification de production, 60h TD, M2, Université Bordeaux 1, France

Master : François Clautiaux, Combinatoire et routage, 30h TD, M2, Institut Polytechnique de Bordeaux, France

Master : Boris Detienne, Optimisation stochastique, 60h cours/TD, M2, Université de Bordeaux, France

Master : Boris Detienne, Recherche opérationnelle, 16h TD, M1, Institut Polytechnique de Bordeaux, France

Master : Lionel Eyraud-Dubois, Optimisation en Cloud Computing & Big Data, 15h Cours, M2, Université de Bordeaux, France

Master : Pierre Pesneau, Programmation Linéaire 2, 14h, M1, Université de Bordeaux, France

Master : Pierre Pesneau, Modèles de flot, 22h Cours, M1, Université de Bordeaux, France

Master : Pierre Pesneau, Algorithmique et Programmation Objet (C++), 30h Cours Intégré, M1, Université de Bordeaux, France

Master : Ruslan Sadykov, Introduction à la Programmation par Contraintes, 30 HETD, M2, Université de Bordeaux, France

Master : Ruslan Sadykov, Modélisation, Optimisation, Complexité et Algorithmes, 50 HETD, M2, CNAM Aquitaine, France

Master : François Vanderbeck, Recherche opérationnelle, 15h cours, M1, Institut Polytechnique de Bordeaux, France

Master : François Vanderbeck, Programmation entière, 50h cours/TD, M2, Université de Bordeaux, France

9.2.2. Supervision

PhD : Nastaran Rahmani, Planning and routing via decomposition approaches [11], Université de Bordeaux, june 26th 2014, François Vanderbeck, Ruslan Sadykov, Boris Detienne

PhD : Sagnik Sen, A contribution to the theory of graph homomorphisms and colorings, Université de Bordeaux, february 3rd 2014, Arnaud Pêcher, E. Sopena, A. Raspaud

PhD in progress : Martin Bué, Gestion du revenu dans le cadre du voyage professionnel, 01/09/2012, François Clautiaux, Luce Brotcorne

PhD in progress : Matthieu Gérard, Résolution de problèmes d'optimisation dans le commerce de détail, 01/09/2012, François Clautiaux

PhD in progress : Jérémy Guillot, Optimisation de problèmes de partionnement, 01/09/2014, François Clautiaux, Pierre Pesneau

PhD in progress : Suraj Kumar (Runtime project team), 01/11/2013, Emmanuel Agullo, Lionel Eyraud-Dubois, Samuel Thibault, Oliver Beaumont

PhD in progress : Thomas Lambert, 01/09/2014, Lionel Eyraud-Dubois, Abdou Guermouche, Olivier Beaumont

PhD in progress : Philippe Moustrou, Le codage aléatoire de réseau, 01/09/2014, Arnaud Pêcher, Pr. Bachoc

9.2.3. Juries

- Olivier Beaumont : Inria CR2 recruitment, Inria Bordeaux-Sud Ouest
- Olivier Beaumont : Inria CR1 recruitment, national
- Olivier Beaumont : Evaluation (rapporteur) of the PhD thesis of Dounia Zaidouni (ENS Lyon)
- François Clautiaux : Evaluation (examinateur) of the Habilitation à Diriger des Recherches d'Alice Yalaoui (Université de Technologie de Troyes)
- François Clautiaux : Evaluation (rapporteur) of the PhD thesis of Michaël Gabay (Université de Grenoble)
- François Clautiaux : Evaluation (examinateur) of the PhD thesis of Mohand Lounes Bentaha (Ecole Nationale des Mines de Saint-Etienne)
- François Clautiaux : Evaluation (examinateur) of the PhD thesis of Nastaran Rahmani (Université de Bordeaux)
- François Clautiaux : Evaluation (examinateur) of the PhD thesis of Rodrigue Tchapnga (Université de Bordeaux)
- Arnaud Pêcher : Evaluation (rapporteur) of the PhD thesis of Djelloul Mameri (Université de Clermont-Ferrand 2)
- Arnaud Pêcher : Evaluation (examinateur) of the PhD thesis of Clément Charpentier (Université de Bordeaux)
- Francois Vanderbeck : Evaluation (rapporteur) of the PhD thesis of Sofia Zaourar (U Grenoble, 11/2014).
- Francois Vanderbeck : Evaluation (rapporteur) of the PhD thesis of Stephen J Maher (University of New South Wales, Sydney, Australia, 01/2014).

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Major publications by the team in recent years

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Doctoral Dissertations and Habilitation Theses

[10] D. PAJAK. *Algorithms for Deterministic Parallel Graph Exploration*, Université Sciences et Technologies - Bordeaux I, June 2014, https://tel.archives-ouvertes.fr/tel-01064992

[11] N. RAHMANI. *Planning and routing via decomposition approaches*, Université de Bordeaux, June 2014, https://hal.inria.fr/tel-01104752

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