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Integration of AI and OR Techniques in Constraint Programming

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Preface

The 12th International Conference on Integration of Artificial Intelligence (AI) and Operations Research (OR) techniques in Constraint Programming (CPAIOR 2015) was held during May 18–22, 2015 in Barcelona, Spain. The purpose of the conference series is to bring together researchers in the fields of Constraint Programming, Artificial Intelligence, and Operations Research to explore ways of solving hard and large-scale combinatorial optimization problems that emerge in various industrial domains. Pooling the skills and strengths of this diverse group of researchers has proved extremely effective and valuable during the past decade leading to improvements and cross-fertilization between the three fields as well as breakthrough for actual applications.

This year, the call for papers was opened to both long (15 pages) and short (8 pages) papers. A dedicated Program Committee of 29 members reviewed both types of submissions with the same stringent criteria. The conference received 90 submissions in total and the field narrowed down to 80 papers contending for publication. In the end, we accepted 35 papers for presentation and publication. This year, CPAIOR also featured a Journal Fast Track dedicated to the publication of selected papers with a level of maturity and details that warrants their immediate archival publication. Five papers among the 35 were identified for this process and are published in a special issue of the Journal.

In addition to the papers, the conference attendees enjoyed three invited talks. The speakers were Nikolaos Sahinidis, who is the John E. Swearingen Professor of Chemical Engineering at Carnegie Mellon University, Robert Nieuwenhuis who is a Professor in the Computer Science Department at the Technical University of Catalonia, and Jeffrey T. Linderoth who is a Professor in the Department of Industrial and Systems Engineering at the University of Wisconsin-Madison.

The traditional CPAIOR Master Class was delivered on the afternoon of May 18 and the entire day on the 19th. Pascal Van Hentenryck, who holds the Vice-Chancellor Chair in Data-Intensive Computing at the Australian National University and leads the NICTA Optimization Research Group organized the event whose theme was "Constraint Programming and Verification." The event featured no less than nine speakers all focused on verification. The morning of May 18 was devoted to three workshops titled "CPAIOR Meets CAV" organized by Justin Pearson and Michel Rueher, ISA: "Innovative Scheduling and Scheduling Applications using CPAIOR" organized by Pierre's Schaus and "Smart Cities" organized by Michele Lombardi.

I wish to extend my deepest gratitude to all the organizers. Carlos Ansotegui from Universitat de Lleida carried the torch as Conference Chair and was supported by a team consisting of Maria Bonet (UPC), Jordi Levy (IIIA-CSIC), and Mateu Villaret (UDG). David Bergman (UConn) was at the helm of the publicity effort and cannot be thanked enough. Pascal's enthusiasm delivered a stellar cast for this year's Master Class and I'm truly thankful for his energy and involvement. Finally, I wish to extend my thanks to the entire Program Committee for their efforts and participation throughout the entire process despite the tight schedule.

Naturally, I would be remiss if I did not express my gratitude to the sponsors of the conference which include, at the time of this writing, the ACP, Google Inc., National ICT Australia, The Catalan Association for Artificial Intelligence (ACIA), AIMMS, AMPL, ECCAI, Gurobi, and Inspires (The Polytechnic Institute of Research and Innovation in Sustainability). Last but not least, EasyChair deserves accolades for its flawless platform.

March 2015 Laurent Michel

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Invited Talks

Symmetry in Integer Programming

Jeff Linderoth

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We will discuss mechanisms for dealing with integer programs that contain a great deal of symmetry [1,2]. The methods use information encoded in the symmetry group of the integer program to guide the branching decision and prune nodes of the search tree. These methods are adaptations of similar methods used in the constraint programming community, and they have been adapted into commercial integer programming software. We will discuss some recent work on using symmetry to augment the cutting plane procedures of branch-and-cut based solvers, and we will conclude with a brief discussion of using large-scale distributed computing platforms to solve difficult symmetric integer programs [3].

Joint work with Jim Ostrowski, Francois Margot, Fabrizio Rossi, Stefano Smriglio, and Greg Thain.

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IntSat: From SAT to Integer Linear Programming

Robert Nieuwenhuis

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One of the most remarkable successes in Artificial Intelligence (AI) and Constraint Programming (CP) is probably the combination of activity-based heuristics and learning that allows Conflict-Driven Clause Learning (CDCL) propositional SAT solvers to solve, fully automatically, large and hard real-world industrial and scientific problems.

On the other hand, extremely powerful tools for Integer Linear Programming (ILP) and Mixed Integer Programming (MIP) exist, based on sophisticated techniques from Operations Research (OR), combining LP relaxations, simplex, branch-and-cut, including specialized cuts, heuristics and presolving methods, an extremely mature technology, with a 475000 times speedup between 1991 and 2012, according to [1].

Since SAT is the particular case of ILP where all variables are binary (0-1) and constraints have the form $x_1 + \ldots + x_m - y_1 \ldots - y_n > -n$, (usually written as *clauses* $x_1 \vee \ldots \vee x_m \vee \overline{y_1} \vee \ldots \vee \overline{y_n}$, i.e., disjunctions of *literals*), some natural questions arise. Why do OR solvers perform so poorly on pure SAT problems? Can CDCL-based techniques also beat OR ones for richer ILP problems than just deciding SAT?

Indeed, an extensive amount of work exists on CDCL-like techniques for Pseudo-Boolean optimization (aka. 0-1 ILP), see [4] for all background and references. IntSat [3] goes another step beyond, introducing a CDCL technique for full ILP (arbitrary integer variables, linear constraints and objective). IntSat extends CDCL by taking decisions on *bounds* (instead of literals), exhaustive *bound propagation*, and at each conflict it attempts to obtain by cuts a new ILP constraint, use it to *backjump*, and to *learn* it. This learning precludes "similar" future conflicts, which are ubiquitous in structured real-world problems (but not in randomly generated ones). IntSat appears to be the first method that is competitive, at least on certain ILP problem classes, with commercial OR tools such as CPLEX and Gurobi.

In this talk we will give an overview of CDCL-based SAT, the difficulties that arise when extending it, the key ideas behind IntSat, and several options between SAT and ILP, including Cutsat [2]. Along the way we will address further questions: How to exploit (and control) learned ILP constraints? Are CDCL-based techniques superior on problems with a combinatorial flavor? Are OR techniques better for the rather numerical ones? We also contribute to the theoretical background: completeness of cut-related inference rules, and infeasibility (or refutation) proof complexity.

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Constraint Programming for Infeasibility Diagnosis with BARON

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Since its inception in the early 1990s, the BARON global optimization solver [1,2] was designed as a system that combined constraint programming and mathematical programming techniques for the global solution of algebraic nonlinear and mixed-integer nonlinear optimization problems (NLPs and MINLPs).

In this paper, we discuss recent developments in BARON, aiming to diagnose infeasibilities in nonconvex optimization models. Early work in the optimization literature to address the cause of infeasibilities has shown that the identification of Irreducible Inconsistent Sets (IIS) in a model can help speed up the process of correcting infeasible models [3]. An Irreducible Inconsistent Set is defined as an infeasible set of constraints with every proper subset being feasible. Identifying an IIS provides the modeler with a set of mutual inconsistencies that need to be diagnosed. Currently, efficient implementations for IIS isolation are only available for linear programs (LPs).

We propose a novel approach for IIS identification that is applicable to NLPs and MINLPs. This approach makes use of constraint programming techniques in a computationally inexpensive preprocessing stage to test for infeasibility in subparts of the infeasible model. This stage allows for rapid elimination of a large number of constraints in the model. Further, this preprocessing step itself could be sufficient to eliminate all constraints not part of an IIS for a large number of problems. The reduced model obtained can be filtered with any standard IIS isolation algorithm to obtain an IIS. The benefits of the approach lie in the efficient reduction in the model obtained by the preprocessing stage which leads to speedups in IIS identification. Extensive computational results are presented with an implementation of the proposed preprocessing algorithm in BARON along with four different filtering algorithms: deletion filter, addition filter, addition-deletion filter and depth-first binary search filter [4].

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Abstracts
of Fast Tracked Journal Papers

Lagrangian Bounds from Decision Diagrams

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Decision diagrams are compact graphical representations of Boolean functions widely applied in circuit design and verification. Recently, *relaxed decision diagrams* were introduced as a new type of relaxation for discrete optimization problems [2]. In the context of constraint programming, relaxed decision diagrams have been successfully applied to improve constraint propagation and optimization reasoning [1,3]. One typically associates a decision diagram with a specific global constraint that is defined on a subset of variables (its scope), and the diagram is subsequently filtered and refined according to the other constraints of the problem. Additionally, if the objective function is evaluated on the same set of variables, the decision diagram can be used to obtain optimization bounds and for applying cost-based filtering.

In this work we propose a technique to strengthen a relaxed decision diagram of a problem by incorporating inference from constraints via a *Lagrangian relaxation* method. Namely, we associate penalties with the constraints that may be potentially violated by the solutions encoded in a relaxed decision diagram. These penalties are incorporated directly into the diagram as arc costs, which are taken into account in the diagram's objective function evaluation. We show that, with this generic approach, the resulting diagram may potentially yield stronger optimization bounds than the one obtained from the original relaxation, while the associated cost-based filtering allows for further refining the diagram and ultimately reducing the search space. If the incorporated constraints are linear, we also demonstrate that the optimal set of penalties are the duals of a shortest-path linear program derived from the decision diagram.

To evaluate our approach, we perform computational experiments on the traveling salesman problem with time windows. Relaxed decision diagrams are used in a global constraint enforcing that city visits must not overlap in time, and tests are performed with a state-of-the-art constraint-based scheduler. Results show that the diagram with improved Lagrangian bounds can drastically reduce solution times in comparison to the original relaxation.

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A Constraint-Based Local Search Backend for MiniZinc (Summary)

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Solving combinatorial problems is a difficult task and no single solver can be universally better than all other solvers. Hence, when facing a problem, it is useful to be able to model it once and run several solvers to find the best one. MiniZinc [3] is a technology-independent modelling language for combinatorial problems, which can then be solved by a solver provided in a backend. There are many backends, based on various solving technologies. However, to the best of our knowledge, there is currently no constraint-based local search (CBLS, see [4]) backend. While most MiniZinc backends are just a parsing interface in front of the underlying solver, things are not as straightforward in the case of CBLS. In [1], we discuss the challenges to develop such a CBLS backend and give an overview of the design of a backend based on the OscaR/CBLS solver [2]. Our backend is called `fzn-oscar-cbls` and is publicly available from https://bitbucket.org/oscarlib/oscar/src/?at=fzn-oscar. The main *contributions* of [1] are:

- a description of a CBLS backend for MiniZinc;
- a heuristic to discover the structure of a model that can be used by a black-box local search procedure;
- a black-box local search procedure using constraint-specific neighbourhoods;

Experimental results show that, for some MiniZinc models, `fzn-oscar-cbls` is able to give good-quality results in competitive time. In [1], we focus on presenting a backend that works with existing MiniZinc models without modification, but we also briefly discuss how one can modify MiniZinc models or add annotations that would help a CBLS backend.

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New Filtering for AtMostNValue and Its Weighted Variant: A Lagrangian Approach

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The AtMostNValue global constraint, which restricts the maximum number of distinct values taken by a set of variables, is a well known NP-Hard global constraint. The weighted version of the constraint, AtMostWValue, where each value is associated with a weight or cost, is a useful and natural extension. Both constraints occur in many industrial applications where the number and the cost of some resources have to be minimized. They have been initially introduced in [1,2]. Filtering these constraints has been proved to be NP-hard [4] but has been widely investigated by the Constraint Programming (CP) community [4] and remains an active topic [5,9,12].

This paper introduces a new filtering algorithm based on a Lagrangian relaxation for both constraints. The role of Lagrangian relaxation in constraint programming is an active area of research [11]. Its use for propagating NP-Hard global constraints is not new but has mostly been performed in very specific and applicative contexts [7,8,14,15] although propators for the Multi-cost-regular and Weighted-circuit global constraints have been designed with Lagrangian relaxation [3,8,10,13]. We believe that many global constraints (and in particuler NP-Hard global constraints involving costs) could be propagated using Lagrangian relaxation in a relatively generic manner [6]. This paper is investigating this idea for AtMostNValue and AtMostWValue .

The main contribution of this paper is a new filtering algorithm, based on Lagrangian relaxation, for both AtMostNValue and AtMostWValue. The algorithm proposed in this paper has several advantages : First, from a software engineering point of view, it is simple to implement and it does not require any connection with a linear solver. Second, it can provide a significantly stronger level of filtering compared to the state of the art algorithm for these constraints. Third, instead of the graph-based algorithm, it can be used directly to propagate the AtMostWValue global constraint for which no simple and efficient filtering algorithm exists. Thus, it is relevant to include it in a CP solver.

Several design options are discussed and empirically evaluated. The contribution is illustrated on problems related to facility location, which is a fundamental class of problems in operations research and management science. Results show that the Lagrangian propagator for both AtMostNValue and AtMostWValue provides significant improvement over a CP approach, up to being competitive with an Integer Linear Programming (ILP) approach. We believe it can help to bridge the gap between CP and ILP for a large class of problems related to facility location.

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A Hybrid Exact Method for a Scheduling Problem with a Continuous Resource and Energy Constraints

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Keywords: Continuous scheduling · Energy constraints · Energetic reasoning · Branching scheme · Mixed integer programming

We are studying a scheduling problem with a continuous resource and energy constraints, the Continuous Energy-Constrained Scheduling Problem (CECSP). In this problem, given a cumulative continuous resource of capacity B and a set of tasks, the goal is to find a schedule such that each task uses a variable resource quantity lying between a minimum and a maximum value, b_i^{min} and b_i^{max} respectively. Furthermore, each task needs to be executed during its time window $[r_i, d_i]$. Finally, each task has an energy requirement W_i and the energy used by a task is obtained by the integration of a function of the resource allocated to it, i.e. $\int f_i(b_i(t))dt \geq W_i$ (where $b_i(t) \leq B,\ \forall t$ is the resource quantity consumed by task i at time t). In this study, we focus on the case where function f_i is non-decreasing, continuous and linear.

For this NP-complete problem, we exhibit structural properties of the feasible solutions and we present a Mixed Integer Linear Program (MILP) based on an event-based formulation.

We also adapt the famous “left-shift/right-shift” satisfiability test (keystone of the so-called energetic reasoning) and the associated time-window adjustments to our specific problem. To achieve this test, we present three different ways for computing the relevant intervals.

Finally, we present a hybrid branch-and-bound method to solve the CECSP, which performs, at each node, the satisfiability test and time-window adjustments and, when the domains of all start and end times are small enough i.e. below a given parameter, the remaining solution space is searched via the event-based MILP.

Computational experiments on randomly generated instances are reported showing the interest of the hybrid method compared to pure MILP.

A Column-Generation Approach for Joint Mobilization and Evacuation Planning

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Large-scale evacuation planning is a critical part of the preparation and response to natural and man-made disasters. Surprisingly, local authorities still primarily rely on expert knowledge and simple heuristics to design and execute evacuation plans, and rarely integrate human behavioral models in the process. This is partly explained by the limited availability of algorithms and decision support systems able to produce evacuation plans that are compatible with operational constraints. Apart from a few exceptions, existing evacuation approaches rely on free-flow models which assume that evacuees can be dynamically routed in the transportation network. However, free-flow models violate a key operational constraint in actual evacuation plans, i.e., the fact that all evacuees in a given residential zone are instructed to follow the same evacuation route. In addition, only few studies have considered behavioral models and the mobilization process, and mainly from a simulation perspective.

This work addresses these issues and introduce the Joint Mobilization and Evacuation Planning Problem (JMEPP) which integrates evacuation planning and mobilization by incorporating the behavioral response of the evacuees. This methodological contribution is implemented through the integration of response curves into a column-generation algorithm that jointly decides the evacuation route, evacuation time, and the resource allocation for each evacuated area in order to maximize the number of evacuees reaching safety and minimize the total duration of the evacuation.

The column-generation algorithm for the JMEPP decomposes the problem as follows. The master problem selects *time-response evacuation plans*, which consists of an evacuation path, a response curve, and an evacuation time. The pricing subproblem generates columns of negative reduced costs, each representing a time-response evacuation plan associated with a single evacuated area. The approach leverages the response curve to solve the pricing subproblem efficiently by finding a shortest path for each evacuated node in a time-expanded graph.

Experimental results based on real instances demonstrate the practicability and benefits of the approach. Indeed, the case study shows that the quality of the resulting evacuation plans remains reasonably close to earlier approaches which assume full control of evacuation timing. In addition, the proposed approach produce evacuation schedules that ensure a continuous evacuation process, while previous approaches can lead to a schedule with numerous interruptions of the flow of vehicles — which would be difficult to enforce in a practical setting.

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Contents