Computers & Operations Research 76 (2016) 195–207

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

An ILP based heuristic for a generalization of the post-enrollment course timetabling problem

Isabel Méndez-Díaz [a], Paula Zabala [a,b], Juan José Miranda-Bront [a,b,*]

[a] Departamento de Computación, FCEyN, Universidad de Buenos Aires, Argentina
[b] Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina

ARTICLE INFO

Article history:
Received 5 August 2014
Received in revised form
30 November 2015
Accepted 25 June 2016
Available online 30 June 2016

Keywords:
Integer programming
Matheuristic
University timetabling

ABSTRACT

We consider a new timetabling problem arising from a real-world application in a private university in Buenos Aires, Argentina. In this paper we describe the problem in detail, which generalizes the Post-Enrollment Course Timetabling Problem (PECTP), propose an ILP model and a heuristic approach based on this formulation. This algorithm has been implemented and tested on instances obtained from real data, showing that the approach is feasible in practice and produces good quality solutions.

1. Introduction and literature review

Timetabling problems within the context of universities represent a very challenging task, where many different restrictions and demands must be satisfied by a feasible solution. During the last decade, this type of timetabling problems has received quite a lot of attention, partly due to the organization of three different competitions: the First International Timetabling Competition (ITC) in 2002, the Second ITC in 2007 and the Third ITC in 2011. As a result, a wide variety of methods and algorithms for different approaches to the problem has been proposed.

The ITC 2007 presented three tracks with different university-related timetabling problems: Examination Timetabling (ETP) [18], where the objective is to schedule exams along a time horizon while satisfying a set of constraints (see, e.g., [3,11]); Post Enrolment based Course Timetabling (PECTP) [18], where the objective is to schedule a set of events into rooms and time-slots (usually, a week) based on the selections made by the students; and Curriculum-based Course Timetabling (CCTP) [18], where the problem consists in scheduling a set of events to rooms and time-slots, but according to the curricula of the university (see, for example, [2,14,16]). Bettinelli et al. [1] provide a good overview on course timetabling problems, and Lübbecke [17] gives some further comments regarding practical and implementation issues.

The PECTP is defined by the following information, as stated in [18]: a set of events to be scheduled into a number of time-slots; a set of rooms with an associated capacity; a set of room-features that may be required by the events and satisfied by the rooms; a set of students who are enrolled in different combinations of events; a set of feasible time-slots for each of the events; and a set of precedence requirements among certain events. The objective is to assign the events to a room and a time-slot while satisfying the following *hard constraints*: every student must attend at most one event per time-slot; the room assigned to each event must have enough capacity and satisfy the features required by the corresponding event; at most one event is assigned to a room in any time-slot; events must be assigned to time-slots which are feasible; and where specified, events must be scheduled in the order established by the precedences. As regards the objective function, a set of *soft constraints* is defined, adding a penalization for each violation within the schedule: students should not be scheduled to attend an event in the last time-slot of a day; students should not attend three or more events in successive time-slots, and should not be required to attend only one event in a given day.

Several approaches have been proposed for the PECTP, mainly considering metaheuristics since in the ITC 2007 a strict time limit was imposed on the running time of the algorithms. Most of them are designed to tackle the problem in two or three stages, focusing first on the feasibility and then on the optimality of the generated timetable. Lewis [15] proposes a three-phase heuristic that uses Simulated Annealing (SA) for the last two in order to improve the generated schedule. Jat and Yang [12] propose a two phase approach using Genetic Algorithms and Tabu Search. Chiarandini et al. [9] propose a heuristic based on stochastic local search. Ceschia et al. [6] perform an extensive study for the PECTP by

* Corresponding author at: Departamento de Computación, Pabellón I, Ciudad Universitaria, C1428EGA, CABA, Argentina.
E-mail addresses: imendez@dc.uba.ar (I. Méndez-Díaz), pzabala@dc.uba.ar (P. Zabala), jmiranda@dc.uba.ar (J.J. Miranda-Bront).

http://dx.doi.org/10.1016/j.cor.2016.06.018
0305-0548/

considering several variations of the problem and propose a metaheuristic based on SA. Nothegger et al. [21] propose an ant colony optimization algorithm. Cambazard et al. [4] study a wide variety of approaches, including Constraint Programming (CP) and a list-coloring relaxation of the PECTP. Finally, van den Broek and Hurkens [23] propose an ILP based heuristic for the problem. They use a column-generation approach in a construction phase and then formulate an ILP model to refine the solution, focusing also on the soft constraints. They report competitive solutions compared to the five finalists in the competition. Due to the definition of the PECTP, many of these approaches apply a preprocessing phase in which conflicts among events are derived. For example, the set of events a particular student is enrolled in cannot be assigned to the same time-slot, since otherwise the schedule violates a hard constraint. In general, all approaches produced good computational results in the instances involved in the competition.

A different perspective of the problem is addressed in van den Broek et al. [24], where the authors study a real timetabling problem at TU Eindhoven. In this case, the weekly timetable is already given and students have a preference list of events and request to be assigned to a certain number of them. The objective is to assign students to events satisfying constraints that are similar to the PECTP (i.e., one event per time-slot, not exceeding capacity of the room, and minimum and maximum quota constraints) among some other constraints. They show that for some combinations of constraints the problem is $\mathcal{NP}$ – Complete and propose an Integer Linear Programming (ILP) formulation for the problem. Computational results show that the approach is effective for real instances considered.

Another problem similar to the PECTP is the so-called *student sectioning problem*, which consists in assigning students to particular sections (i.e., classes) based on their requests and satisfying several traditional constraints such as room and section capacity, and avoiding conflicts in students timetables due to overlapping assignments. Carter [5] describes the characteristics of the problem and provides the details of the scheduling system developed at the University of Waterloo. The timetable construction and the sectioning of students is divided in mainly three stages: a student preregistration for the next semester; the generation of an initial timetabling (involving both an automated and a manual stage); and the student scheduling, including a *drop/add* period. Students are willing to attend to a set of courses, which are composed by multiple sections. In this sense, the problem considers a more complex structure for courses than the PECTP, similarly to our problem. The problem also considers that a student is willing to take all the courses in the list provided. Murray et al. [20] and Muller and Murray [19] build upon this research, mainly using the method proposed by Carter [5] to construct the initial timetable. The former presents a framework for tackling the problem, including several practical considerations. Muller and Murray [19] tackle the overall problem, generating the initial timetable as in Carter [5] and providing further developments, including several new local search operators, for the student sectioning stage. In both cases, the research is motivated by its application in Purdue University.

We further include a comparison with some other problems in the literature regarding timetables in educational institutions. The Balanced Academic Curriculum Problem (see, e.g., Chiarandini et al. [8]) aims to define at a general level the organization of courses for a university degree. The planning horizon is divided in years, where each of them is further divided into teaching terms where the courses can take place. Courses present precedences among them and load constraints are imposed on each teaching period, including both the number of courses assigned and the total credits involved in a teaching period. In a follow up paper, Ceschia et al. [7] consider a generalization of this problem.

Regarding the methodology, we briefly discuss a few approaches concerning the use of ILP techniques within more general frameworks. Sorensen and Dahms [22] propose a two stage decomposition heuristic based on an ILP formulation for a High School Timetabling Problem. Kristiansen et al. [13] consider an ILP for the High School Timetabling Problem, which is solved in two stages by means of a general purpose solver, but in this case resulting in an exact algorithm. The approach produces good results, obtaining 9 new best known solutions for the problem. Finally, Daskalaki and Birbas [10] consider a university timetabling problem where groups of students are enrolled in a set of courses, similarly to the PECTP. Standard operational constraints are considered, and a difference regarding the PECTP and with our problem is that all the requests of a student must be satisfied. The structure of the courses is, however, more general than in the PECTP and may include more than one type of class. The authors propose a two stage approach, where some of the heaviest operational constraints are relaxed in the first stage and then reconsidered in the second one, where smaller ILPs are formulated and solved for each day of the week independently.

Concerning the methodology proposed in Carter [5] for the student sectioning problem, firstly a *conflict matrix* is constructed, where each entry accounts for the number of students that have requested each pair of courses. In addition, due to the size of the problem considered, the students are first clustered based on the similarities among their courses' request and then a preliminary assignment to sections is performed, aiming always to minimize the expected number of conflicts. This step is referred as *homogeneous sectioning*. Using this information, the overall problem, consisting in approximately 3000 course sections and 17 000 students, is decomposed into several subproblems trying to group together sections with high interaction, which are then solved independently one at a time in decreasing order of difficulty. For each of these subproblems, different steps are considered sequentially. Firstly, an *automated course timetabling* step is considered where sections are assigned to time-slots aiming to minimize the total number of student conflicts and considering aggregated information regarding the room capacities by defining *room profiles*. This step is performed using a greedy heuristic and followed by a local search phase consisting of a 2-opt operator. Then, a *classroom assignment* step is performed using the information from the preregistration and including several constraints regarding type, distance and availability of the classrooms. After manual improvements made by the representatives of each university department, the original sectioning is discarded and the students are reassigned using the overall timetable generated in the previous steps. The students are sectioned one at a time in a two-pass fashion, considering in the first pass only some of the choices and in then the remaining ones. The objective is to prevent filling up courses only by students which registered earlier.

In this paper, we focus on a real-world application arising from a private university in Argentina which simultaneously involves timetabling events to time-slots and rooms as well as assigning students to a certain number of events chosen from their preference list. Similarly to the PECTP, the assignment of events to time-slots must satisfy certain constraints, which in turn depends on the assignment of students to events. In addition, courses have a particular hierarchical structure, similar to the student sectioning problem described before, that must be taken into account when performing the different assignments. This problem is named *Generalized Post-Enrollment Course Timetabling Problem* (GPECTP).

The contributions of this paper are threefold. Firstly, we study a problem with a direct and practical application that integrates, combines and tackles jointly two other problems from the related literature, namely the PECTP and the problem defined in van den