View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Online Research Database In Technology

Technical University of Denmark

A Comprehensive Study of Educational Timetabling - a Survey

Kristiansen, Simon; Stidsen, Thomas Jacob Riis

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Kristiansen, S., & Stidsen, T. R. (2013). A Comprehensive Study of Educational Timetabling - a Survey. Department of Management Engineering, Technical University of Denmark. (DTU Management Engineering Report; No. 8.2013).

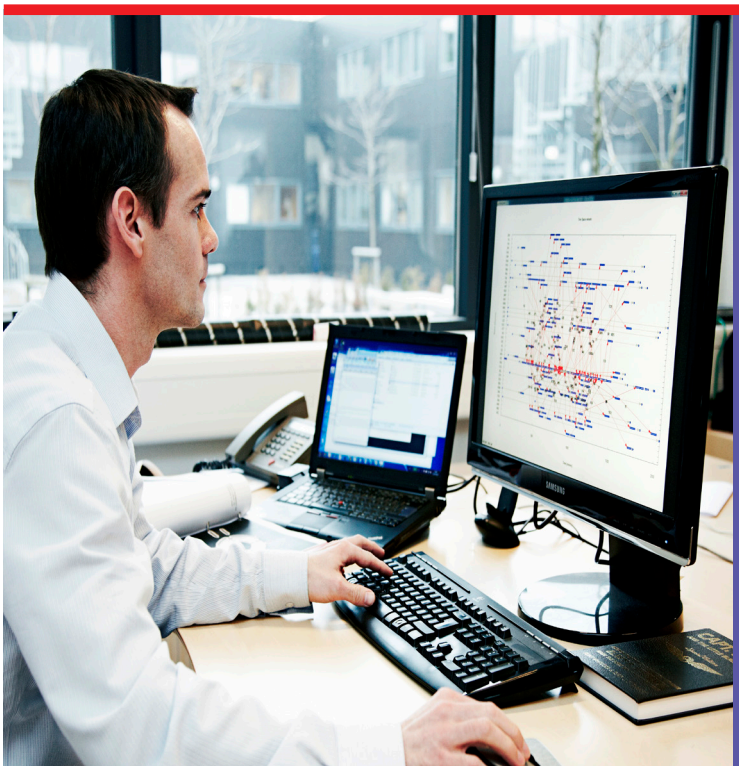
DTU Library
Technical Information Center of Denmark

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

A Comprehensive Study of Educational Timetabling, a Survey



Report 8.2013

DTU Management Engineering

Simon Kristiansen
Thomas Riis Stidsen

November 2013

DTU Management Engineering
Department of Management Engineering

A Comprehensive Study of Educational Timetabling - a survey

Simon Kristiansen[a,b,*], Thomas R. Stidsen[a]

[a] *Section of Operations Research, Department of Management Engineering, Technical University of Denmark, Building 426, Produktionstorvet, DK-2800 Kgs. Lyngby, Denmark*

[b] *MaCom A/S, Vesterbrogade 48, 1., DK-1620 Copenhagen V, Denmark*

Abstract

Educational timetabling is one of the most researched subjects within the range of timetabling problems. There has been a significant increase in efficient planning problems within educational timetabling the last couple of decades. In this paper we will highlight some of the main trends and research achievements within educational planning problems. Furthermore it is an aim to make a differentiation between the different planning problems. This survey is concentrated on the four main education planning problems; *University Course Timetabling*, *High School Timetabling*, *Examination Timetabling* and *Student Sectioning*. Firstly a presentation of educational timetabling and the main components is given. For each problem a description is given with appertaining benchmark data and recent research. The literature presented is mainly solution tested on real-life data or better yet implemented. Summarizing tables for each section are presented to give an overall view of all the literature of this survey.

Keywords: Educational Timetabling, University Course Timetabling, High School Timetabling, Examination Timetabling, Student Sectioning, Benchmark datasets, Search methodologies

*Please address correspondence to Simon Kristiansen

Email addresses: sikr@dtu.dk (Simon Kristiansen), thst@dtu.dk (Thomas R. Stidsen)

1. Introduction

Timetabling has been a challenging and important problem within operations research for several decades and it still is. In Wren (1996) timetabling is defined as:

"*Timetabling is the allocation, subject to constraints, of given resources to objects being placed in space time, in such way as to satisfy as nearly as possible a set of desirable objectives.*"

Due to the broad definition the timetabling problems covers various forms of real-world problems, including *Employee Timetabling* (e.g. Balakrishnan and Wong (1990) and Meisels and Schaerf (2003)), *Rostering Problems* (e.g. Cheang et al. (2003) and Burke et al. (2004b)), *Sports Timetabling* (e.g. Easton et al. (2003) and Kendall et al. (2010)) and *Educational Timetabling* (e.g. Burke and Newall (1999), Melício et al. (2005) and Kristiansen et al. (2011)).

This survey will be concentrated on *Educational Timetabling* and the different problems within this area. Educational timetabling encompasses problems such as *University Course Timetabling*, *High School Timetabling*, *Examination Timetabling* and *Student Sectioning*, and is encountered in all institutions in the educational system throughout the world and it is one of the mostly studied timetabling problems from a practical viewpoint. The problems are very difficult and important for the institutions, and several approaches have been used to create good and feasible solutions. The purpose of this paper is to give a comprehensive overview of the different planning problems within education timetabling with the recent developments and trends. Table 1 lists the educational timetabling problem which we are going to discuss in this paper.

It should be mentioned that it is not attempted to perform any experimental comparison on the different methods used, only to give and overview of the methods.

Furthermore, in the effort of producing an exhaustive review of all the planning problems in the education system, we are conscious that some references have been left out and we will therefore apologize in advance. However the goal is not to list all scientific papers on this subject, but to create an overview which illustrates the different types of planning problems within the educational system and the diversity of solution methods used on these problems.

1.1. Previous Surveys and Competitions

The literature on educational timetable includes several surveys on educational timetables. A briefly discussion of the scope of the surveys is given here sorted into chronological order:

Table 1: Educational timetabling problems

Problem	Short description	Newest survey
University Course Timetabling	Aims to break university courses into sections, and assign times, students and rooms. Either Curriculum-based or Enrollment-based Course Timetabling	McCollum (2006) motivates in bridging the gap between theory and practice within University Course Timetabling
High School Timetabling	Allocating classes to time slots, teachers and rooms to satisfy the restrictions.	Pillay (2013) gives a definition and an overview of the High School Timetabling problem.
Examination Timetabling	Scheduling exams for students under the limited resources.	Qu et al. (2009) is a comprehensive study of Examination Timetabling.
Student Sectioning	Assigning student to sections of courses while respecting the requests of the individual students.	There is no recent survey on Student Sectioning.

Some of the earliest surveys include **Schmidt and Ströhlein (1980)**, **de Werra (1985)** and **Junginger (1986)**. **Schmidt and Ströhlein (1980)** provide an annotated bibliography containing more than 200 papers, and hence listing all the papers on the field up to 1979. **de Werra (1985)** introduces the various problems within education timetabling and provides with different models to the *Class-Teacher Timetabling* and *Course Timetabling* based on graph theory, while **Junginger (1986)** describes the various software products implemented for solving school timetabling in Germany.

The first survey on *Examination Timetabling* was presented in **Carter (1986)**. None of the approaches mentioned in this survey was implemented in more than one institute. The survey was updated in **Carter and Laporte (1996)** where the approaches used on Examination Timetabling between 1986 and 1996 is summarized. The criteria for discussion of this paper, was that the solution methods should either have been implemented in a real world application or tested on real life data.

Bardadym (1996) considers computer-aided timetabling for high schools and universities from 1960 to 1995. The paper discusses the core items in

the different problems and gives a small discussion on open issues for future research within timetabling.

In **Carter and Laporte (1998)** the authors has changed their focus from Examination Timetabling to Course Timetabling. The major components of the University Course Timetabling problem are described in details as well as a discussion of the primary solution methods used. The paper summarize by listing up papers which contains approaches which are either implemented or tested on real data.

In **Schaerf (1999a)** the difference between Course Timetabling and Examination Timetabling is observed as being relatively small and that the problems could be modeled using the same model. Various formulations of School Timetabling, Course Timetabling and Examination Timetabling is surveyed along with the techniques used for solving the problems.

Burke and Petrovic (2002) give an overview of some of the recent developments that have been carried out in the Automated Scheduling, Optimization and Planning Research Group (ASAP) at the University of Nottingham.

Burke et al. (2004c) gives an introduction to the field of Educational and Sport Timetabling. The paper discusses the application of graph coloring methods to the timetabling problems and thereby highlights the fact that graph coloring have been an important part of timetabling problems in several decades.

McCollum (2006) provides information regarding research on University Course Timetabling up to 2006. The aim is to motivate researchers to bridge the gap between research and practice within University Course Timetabling. The paper rounds up by listing the major challenges working within Examination Timetabling and University Course Timetabling.

Qu et al. (2009) is the far newest survey on Examination Timetabling. The basis of the paper is **Carter and Laporte (1996)** and it is therefore concentrated on papers published between 1996 and 2009. The different algorithm approaches are classified and discussed. Furthermore the paper renames the existing problem datasets to avoid a significant amount of confusion which have been a problem for many years. The paper rounds off with an estimate on future research direction within examination timetabling.

Pillay (2013) is the latest survey and the first survey concentrated only on school timetabling. The survey gives a definition of the school timetabling, the different hard and soft constraints and it gives a detailed overview on the solution methods used.

The book *Automated Scheduling and Planning From Theory to Practice* contains a chapter on Educational Timetabling (**Kingston (2013a)**). The chapter gives a brief introduction to the different educational planning problems.

Some conferences are dedicated to the art of timetabling, such as the

International Conference on the Practice and Theory of Automated Timetabling (PATAT) and the *Multidisciplinary International Scheduling Conference: Theory & Application* (MISTA) Both conferences are held every second year.

Besides the mentioned surveys and conferences there has been three ***International Timetabling Competitions*** (ITC) on educational timetabling problems. These competitions have contributed to an increased focus on educational timetabling problems and thus the research within.

The First International Timetabling Competition was held in 2003 (ITC2003) and was regarding University Course Timetabling. The description of the problem can be found on the website of the competition (Paechter et al. (2002)). The results were presented at PATAT in 2004.

The Second International Timetabling Competition of 2007 had three tracks; Enrollment-based University Course Timetabling, Curriculum-based University Course Timetabling and Examination Timetabling (Gaspero et al. (2007), McCollum et al. (2010)) The winner of each track were announced at PATAT in 2008. Problem description can be found at the competition website (McCollum (2007)).

The third and most resent is the ITC2011 with focus on High School Timetabling (Post et al. (2012c)) and the results were presented at PATAT in 2012. The problem description and competition rules can be found at the website of the competition (Post et al. (2011)).

The results of the different competitions are described later in this paper.

From the above listing, it is seen that there exist several excellent surveys on educational timetabling. This paper concentrates on articles tested on real data or better yet implemented. I.e. it tries to follow the approach introduced in Carter and Laporte (1996) and Carter and Laporte (1998). We try to restrict the paper to only contain newly published papers, i.e. papers published since 2003, however we are aware that some of the educational problems are so sparse represented in the literature that earlier papers might be considers for these problems.

The surveys and competitions described above are listed in Table A.2 and Table A.3 in Appendix A.

1.2. Outline of the paper

The educational timetabling problems are in this survey divided into four main categories: *University Course Timetabling*, *High School Timetabling*, *Examination Timetabling* and *Student Sectioning*. However, as aforementioned, other surveys have a different view and it can be discussed whether some of the categories could be combined.

The article is organized as follows. In Section 2 a description of the general timetabling problem in the education system is given. In the following four sections, each section treats their own planning problem. Univer-

sity Course Timetabling problem is described in Section 3 and High School Timetabling in Section 4. Section 5 elaborates on Examination Timetabling. Finally Section 6 describes the Student Sectioning. The conclusion of this paper follows in Section 7 and in Appendix A all the literature for each problem are listed with appertaining comments.

2. Planning Problems and the Components

The definition *timetabling* is often used when solving problems with some form of personnel allocation, such as University Course Timetabling. Due to the personnel allocations, many people are affected by the timetables created. For the combined planning problems in the educational system four main stakeholders are identified. Each with their own set of aims and wants.

- *The administration*: Solves the planning problems and sets the minimum standards that the timetables must conform to. The capacity of the room, consecutive exams, etc.
- *The students*: This is by far the largest in volume of the four stakeholders. The students seldom have much influence on the outcome of the different planning problems. And due to the number of students involved it is difficult to declare what is the best timetable for the students as they all might have different wants and needs.
- *The teachers*: The teachers have a little more influence on the outcome than the students and they do also requests a compressed timetables. Furthermore they might have some restrictions on which day and time they want to give lessons or exams.
- *The departments/sections*: Often only relevant for universities as the high schools rarely are organized with departments or sections. The department can have some restrictions or requests for the exam and course timetabling.

For all the various planning problems some restrictions always apply, these are the so-called *"first-order conflicts"*. E.g. no person can be at more than one place at any time. These first-order constrains are always present in some form. Besides these constraints, there is a great variation between the problems, but also within a given problem there is great variation due to different universities, high schools and/or the Ministries of Education of the respective countries. Hence the other constraints within educational timetabling are many and varied. In the following some of the most common types are listed.

- **Resource assignment:** Resources are rarely preassigned to lectures and in these cases the assigning of resources is a part of the decision

problem. The most common resources to assign are rooms. Some lectures prefer or require to be held in a particular class. Furthermore the number of students in a given room must not exceed the capacity of the room.

- **Continuity:** Constraints that ensure that certain features of the timetables are constant or predictable. E.g. lectures of the same course should be scheduled in the same room or at the same time of days.

- **Compactness:** These constraints are designed to produce a more compact timetable for both students and teachers. For the students a compact timetable is one with a low number of idle time slots in between lectures. A teacher might prefer to have all his lectures in fewer days and thereby have some days of.

- **Spreading:** Often used as contrary to compactness. Meetings should be spread out in time. However it is also used on single meeting. If the same meeting should be repeated twice or more times in the timetable it is often preferable if these similar meetings a spread out.

- **Time assignment:** These constraints are used for assigning meeting to a time. This can be used to specify days on which teachers are unavailable or if one particular meeting must take place after another one, e.g. exercises should be placed right after the corresponding lectures. It is also used for meetings that should be held simultaneous.

These types of constraints are somewhat presented in educational timetabling as we will see in the following sections.

2.1. Annual Cycle of Educational Timetabling Problems

Whether it applies to high schools or universities, all the planning problems at an educational institute are recurring annual administrative tasks. There are differences in the planning problems that the various institutions have in their annual cycle, but in general the annual cycle of educational planning problems contains three main subjects; *Student Sectioning* followed by *University Course Timetabling* or *High School Timetabling* and finally the *Examination Timetabling*. Figure 1 illustrates the annual cycle of planning problems of a typical educational institute.

For some institutes some of the planning problems might be combined or swap positions in the cycle, or additional planning problems might be added to the cycle. At some universities Student Sectioning is used before and after the course timetabling.

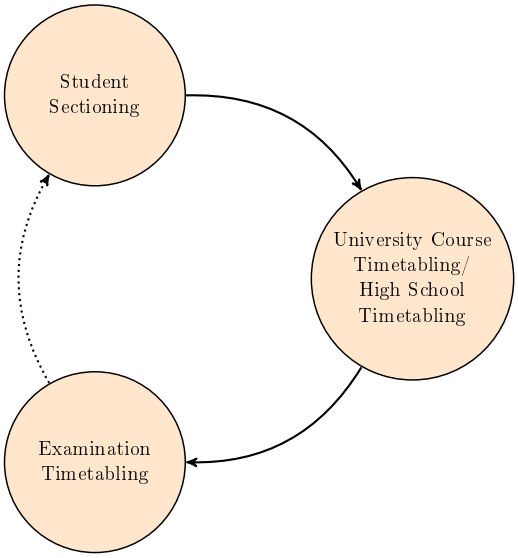


Figure 1: A typical annual cycle of planning problems at an educational institute. Each year starting with Student Sectioning, then Timetabling (either University Course Timetabling or High School Timetabling) and finally the Examination Timetabling before repeating for the next school year.

3. University Course Timetabling

University Course Timetabling problem is the task of assigning lectures of courses to time slots, rooms and other resources, subject to constraints applied for the single student. The large size and structure of universities often makes the problem of solving the course timetabling so complicated that it is solved by several experts scattered across different faculties and departments. Due to the complexity of the problem, it is quite common that the universities re-use the solution from previous years when solving the problem.

The University Course Timetabling is often divided into two general approaches; the *Curriculum-based University Course Timetabling* and the *Enrollment-based University Course Timetabling*.

Courses which can be taken in combination, because they are needed to satisfy the degree rules of the given study, are called curricula. And assigning courses to time slots based on this is called Curriculum-based Course Timetabling. The problem consists of creating the weekly schedules of lectures where conflicts between the courses are set accordingly to the curriculum specified by the university. Gaspero et al. (2007) gives a short description of the Curriculum-based Course Timetabling Problem applied for Track 2 of ITC2007. Several research papers have been working on this university course approach. (Eg. Lach and Lübbecke (2012); Lü et al. (2011); Burke et al. (2012); Cacchiani et al. (2013))

The second approach is the Post Enrollment-based Course Timetabling. Based on the enrollment data of each individual student, it is determined where courses are placed in the timetable such that all students can attend the events on which they are enrolled. This approach has been given various names in the literature including the Class Timetabling Problem and Event Timetabling. Lewis et al. (2007) gives a description of the Post Enrollment-based Course Timetabling Problem applied for Track 3 of ITC2007. Papers working on the Post Enrollment-based Course Timetabling include Cambazard et al. (2008); Ceschia et al. (2012) and Nothegger et al. (2012).

The two approached are not necessary mutually exclusive. The universities can use the curriculum based approach in an early state to get the basic structure of the timetable, and then later on use the enrollment-based approach to improve the timetable.

Though the literature often is divided into the two approaches, many of the constraints remain the same. Below some of the most common constraints for University Course Timetabling are listed.

- Primary hard constraints
  - No 1st-order conflicts for students and teachers.
  - Only one event is put into each room in any time slot.

  - Rooms should satisfy all of the features required by the event.

- Primary soft constraints
  - The capacity of the room should be respected.
  - Compact timetable of each student or curricula.
  - Room stability. Lectures of same course should be assigned the same room.
  - Time and/or room preferences.

3.1. International Timetabling Competition

In the First International Timetabling Competition in 2003 (ITC2003), the focus was Post Enrollment-based University Course Timetabling. The winner became Kostuch (2004) with a Simulated Annealing based heuristic.

The most recent competition on University Course Timetabling is the Second International Timetabling Competition in 2007 (ITC2007) (McCollum et al. (2010)). The competition consisted of three tracks where two were upon University Course Timetabling, with enrollment-based in Track 2 and curriculum-based in Track 3. Track 1 treated the Examination Timetabling problem.

The winner of Track 2 was a team from Ireland solving the Enrollment-based University Course Timetabling using a hybridized local search algorithm with a Constraint Programming approach in a Large Neighborhood Search scheme to address the hardness of finding feasible solutions (Cambazard et al. (2008)).

Track 3 was won by Tomáš Müller using a hybrid heuristic using three phases (Müller (2009)). Firstly a feasible initial solution is found using an Iterative Forward Search algorithm. In phase two the local optimum is found using a Hill Climbing algorithm and third phase is using Great Deluge techniques. This heuristic solver was among the finalist for all three tracks, and won Track 1 and 3.

3.2. Benchmark Data

There is a major lack of benchmark data for University Course Timetabling. ITC2007 contains datasets for both the Enrollment-based Course Timetabling and the Curriculum-based Course Timetabling. The datasets are available at the website of the competition McCollum (2007).

- **ITC2007 Track2 - Enrollment-based Course Timetabling**
  Twenty-four datasets are available; all were created using an automated problem generator designed by the competition organizers, and all are known to feature at least one perfect solution - that is, a solution with no hard or soft constraint violations. The drawback of this benchmark is that it is generated data and not real-life.

- **ITC2007 Track3 - Curriculum-based Course Timetabling**
  Twenty-one instances were released for this track. All instances are real data and come from the University of Udine and for all instances there exists at least one feasible solution.

Bonutti et al. (2012) collects the twenty-one instances of ITC2007 and four instances from Gaspero and Schaerf (2003) together with seven new instances mainly from Italian universities. The datasets are all real cases from various universities, mainly from University of Udine. In the following these datasets are denoted as one benchmark called **The Udine benchmark data**UdineBenchmark .

- **The Purdue benchmark data**
  On the website of the educational scheduling system UniTime, there is access to real data from the University of Purdue, United States. The benchmark consists of data sets for each department and one for the combined problem of three years (PurdueBenchmark).

3.3. Recent Research

University Course Timetabling is one of the most researched subjects within educational timetabling. The last decade many of the used methodologies represent some sort of hybridization of a number of techniques. In the following the scientific papers on University Course Timetabling of the last decade are categorized into the main methodologies used.

3.3.1. Swarm Intelligence Algorithms

Swarm intelligence algorithms belong to the family of population based techniques. Based on some sort of agents interacting locally with one another and with their environment. E.g. in Ant Colony algorithms, the ants search the shortest path to food by laying pheromones on the way. The shortest path is the path with the strongest level of pheromones.

In Socha et al. (2003) two different Ant Colony methods is used to solve the University Course Timetabling; Ant Colony System and MAX-MIN Ant System. In each step of both algorithms, every ant constructs a complete assignment of events to time slots using heuristics and pheromone information. The timetables are then improved using a local search procedure.

Ant Colony is also the method used in Nothegger et al. (2012) to solve the Post Enrollment-based Course Timetabling problem. The algorithm uses two distinct but relatively compact pheromone matrices in combination with an effective procedure to exploit their information in the heuristic solution construction. The algorithm was tested on the benchmark datasets from ITC2007 with the same terms as the competition. It had the best solution for 11 out of the 24 instances compared to the 5 finalists, including ties, which would have given a fourth place. However the algorithm did show a

large variation in the solution quality as it produced both the best and worst solution for several instances.

In Turabieh et al. (2010) a simulation of a fish swarm is applied to the same University Course Timetabling definition used in Socha et al. (2003). The idea of Fish Swarm Intelligent is to simulate the behavior of fishes while searching for food. The movements of the fishes are based on a Nelder-Mead simplex algorithm. Two types of local search were applied to enhance the quality of the solution. A multi decay rate Great Deluge and a steepest descent algorithm. The same method was later used to solve the Examination Timetabling problem (Turabieh and Abdullah (2011b)).

Another Swarm Intelligence is the Particle Swarm optimization, which is used on University Course Timetabling in Shiau (2011) and in Chen and Shih (2013). The Particle Swarm Intelligence algorithm consists of a swarm of particles in the space. The position of a particle is indicated by a vector which presents a solution and the movements of the particles are guided by their own best known position in the search-space as well as the entire swarm's best known position. Shiau (2011) solves the course timetabling problems for a typical university in Taiwan by applying a hybrid particle swarm optimization. Each particle is updated on the basis of continuous particle swarm optimization formulas and local search. Chen and Shih (2013) evaluates on two different kind of particle swarm heuristics used on the problem, an inertia weight version and a constriction version. An interchange heuristic was applied to enhance the quality of the solution. The algorithms were tested on a single dataset where the Constriction Particle Swarm with interchange heuristic performed best.

3.3.2. Evolutionary Algorithms

Evolutionary algorithms do also belong to the family of population based techniques. The most common evolutionary algorithm is the Genetic Algorithm. Genetic algorithms are search heuristic that mimics the process of natural selection.

In Nurmi and Kyngas (2008) the Curriculum-based Course Timetabling problem is solved using an evolutionary algorithm. Firstly the Curriculum-based Course Timetabling is turned into the School Timetabling problem using a conversion scheme. The problem is then solved using a genetic algorithm (Nurmi and Kyngas (2007)). The algorithm consists of one mutation operator and no recombination operators. The most important features of the algorithm are a greedy hill-climbing mutation operator and a adaptive genetic penalty method.

Suyanto (2010) describes an informed generic algorithm for the University Course Timetabling and Student Sectioning. Firstly a greedy heuristic creates some feasible solution were all the hard constraints are satisfied. Then a directed mutation scheme is used to reduce the violations of the soft constraints while keeping the solution feasible.

3.3.3. Local Search Algorithms

Local search based techniques are classified as meta-heuristics and the algorithms move from solution to solution in the search space by applying local changes. Local search algorithms include methods such as Tabu Search, Simulated Annealing (SA) and Greedy Randomized Adaptive Search Procedures (GRASP). Within educational timetabling local search has been widely used and in the following some of the local search based techniques used on University Course Timetabling in the last decade are presented.

Gaspero and Schaerf (2003) propose a set of multi-neighborhood search strategies to improve local search capabilities. It is showed how different neighborhoods operators can be combined. The operators chosen are Tabu Search and Hill-Climber. The combinations used are neighborhood-union, neighborhood-composition and token-ring search. A perturbation operator called "kicker" is used to help improve the search and hence avoid local optima. The algorithm is tested on four real instances from the School of Engineering at Udine University.

Another neighborhood analysis is made in Lü et al. (2011). Four neighborhoods are investigated based on three evaluation criteria: percentage of improving neighbors, improvement strength and search steps. The neighborhoods in this paper is SimpleMove, SimpleSwap and two kinds of KempeMove. To understand the behavior of the neighborhoods and the combinations, they are tested using a steepest descent algorithm. To further evaluate the impact, a series of experiments are conducted using three algorithms: Tabu Search, Iterate Local Search and Adaptive Tabu Search.

Simulated Annealing is another local search algorithm. The idea is to search a wider area of the search space by allowing the algorithm to accept worse moves with a higher probability in the beginning of the search. The acceptance criterion is controlled with a temperature which decades based on a cooling schedule. Kostuch (2004) participated in ITC2003 and won using a heuristic based on Simulated Annealing. Firstly a feasible timetable is constructed, and the timetable is then improved using SA.

Murray et al. (2007) transforms the University Course Timetabling problem at the Purdue University into a constraint satisfaction and optimization problem (CSOP). CSOP consists of a set of variables having finite domain, a set of hard constraints and an objective function. The solver used an iterative forward search algorithm. The paper is a part of the research embedded in the system UniTime.

In Ceschia et al. (2012) the Post Enrollment-based Course Timetabling problem is solved using SA. The SA used is with probabilistic acceptance and a geometric cooling scheme. The algorithm is tested on the benchmark of ITC2003, ITC2007 and the data used in Lewis and Paechter (2005).

Variable Neighborhood Search (VNS) algorithms are used to solve the

Curriculum-Based Course Timetabling in Nguyen et al. (2011). Eight Variable Neighborhood Search algorithms with different implementing strategies were created. A basic VNS and seven popular variants, where the Fleszar-Hindi extension of the basic VNS in general was the most effective in solving the 14 instances from University of Science in Vietnam.

Chiarandini et al. (2006) uses a hyper-heuristic which combines various construction heuristics, Tabu Search, Variable Neighborhood Descent and Simulated Annealing. The algorithm is divided in two parts. In the first part construction heuristics are used to solve the hard constraints of the problem. In the second phase the penalty of soft constraints are improved by first using Variable Neighborhood Search, and then using Simulated Annealing. The authors make use of the racing procedure, the *F-race* method, to automatically tune the parameters of the algorithm. The algorithm is tested on the benchmark of ITC2003.

3.3.4. Graph Coloring Algorithms

In Burke et al. (2007) a graph-based hyper heuristic is developed for University Course Timetabling and Examination Timetabling. A Tabu Search approach is employed to search for permutations of graph heuristics which are used for constructing timetables. For the University Course Timetabling the approach is tested on the datasets from ITC2007 and the results were competitive with the previous approaches reported in the literature.

Many papers work with a two-phase approach for solving University Course Timetabling. A construction phase and an improvement phase. Where most papers are concentrated on the improvement phase, Azlan and Hussin (2013) focus on creating as good initial solutions as possible to solve the Curriculum-based Course Timetable. Two different construction heuristics based on Graph Coloring are created; largest degree and largest weighted degree. The two heuristics are tested on the datasets from ITC2007 and both are able to find feasible solutions for most of the cases. Largest weighted degree being the one performing best.

3.3.5. Exact Methods

The drawback of using some sort of heuristic to solve timetabling problems is the lack of capability to issue certificates of optimality or the quality of the solutions found. This is made possible using *Integer Programming* methods such as decomposition techniques.

The University Course Timetabling at Ohio University's College of Business is solved in Martin (2004) using Integer Programming (IP). The problem is solved using CPLEX.

In Daskalaki et al. (2004) an Integer Programming formulation for the University Course Timetabling is developed. The formulation is based on the timetabling problem in Engineering Schools of Greek universities. It

was possible to solve the single real case of the problem with success using CPLEX. Daskalaki and Birbas (2005) use a two stage relaxation procedure to solve the problem. In first stage the relaxation is performed and it concerns the constraints that ensure consecutiveness for the multi-period sessions assigned to a given course. These constraints are recovered during second stage where a subproblem for each day is solved for local optima.

Avella and Vasil'Ev (2005) describes a Branch-and-Cut algorithm for the University Course Timetabling problem and two cutting planes are derived, Clique inequalities and Lifted Odd-Hole inequalities, to tighten the initial formulation.

Qualizza and Serafini (2005) propose an Integer Programming approach based on Column Generation. Each column represents a weekly timetable of a single course. The master problem then contains all the constraints referring to classroom occupancy and non-overlapping in time of courses. Each subproblem contains the constraints related to a single course timetable and hence creates weekly timetable for a single course. A Branch-and-Bound method is used to ensure feasibility of the solution.

Al-Yakoob and Sherali (2007) takes its origin at Kuwait University. The paper formulates a Mixed Integer Programming (MIP) model for the University Course Timetabling problem which is able to design class timetables that have a number of desirables features related to minimizing class conflicts, providing good patterns, and enhancing traffic flow. Moreover, gender policies are considered when creating sections of courses.

Schimmelpfeng and Helber (2007) solves the University Course Timetabling problem at the School of Economics and Management at Hannover University by modeling the problem as an IP model and solved using a state-of-art MIP solver. An anonymous satisfactory survey among the faculty was initiated and in general the response was positive.

In Lach and Lübbecke (2012) the Udine benchmark datasets on Curriculum-based Course Timetabling are solved using a two stage decomposition approach. The theoretical background of the decomposition is given in Lach and Lübbecke (2008). The outline of the two stage decomposition is firstly to assign lectures to time slots (Stage1) and then assign rooms to the lectures (Stage 2). The approach has proven to be an effective method for solving the Curriculum-based Course Timetabling.

Hao and Benlic (2011) generates lower bound for the ITC2007 benchmark data on the Curriculum-based Course Timetabling problem. They present a new partition-based approach based on the divide and conquer principle consisting of three phases. Firstly, courses are partitioned into a fixed number of subproblems using an iterative Tabu Search. In second stage the subproblems are formulated as integer linear problems using the formulation of Lach and Lübbecke (2012). And finally the subproblems are solved using an IP solver. Better lower bounds were found for all instances except two. The found lower bounds can be used to estimate the quality of the solutions

obtained with some of the various heuristic approaches aforementioned.

In Burke et al. (2012) a Branch-and-Cut procedure is suggested for the Udine benchmark datasets. The Integer Programming formulation is the same as for Burke et al. (2010b). The procedure reduces the number of variables necessary to formulate the soft constraints. Using the Branch-and-Cut it is possible to achieve good lower bounds must faster than solving the initial IP model.

Cacchiani et al. (2013) is the latest research paper working on improvements of lower bounds on the University Course Timetabling problem. The bounds are obtained by splitting the objective function into two parts and formulate an integer linear programming models for both. The solution of each is obtained by using a Column Generation procedure. The global bound is then obtained by summing up the corresponding optimal values. By comparing the results with results from previous research on the instances used at ITC2003 and ITC2007, it is proven that this method is able to improve some best-known lower bounds and that for some instances the best known solutions is indeed optimal (or close to).

3.3.6. Software systems

Only few systems which solve the University Course Timetabling have been published in detail.

Carter (2001) solves the Enrollment-based Course Timetabling for the University of Waterloo, Canada, and has been used since 1985. The algorithm behind is a three-phase method. First, the Student Sectioning problem is solved aiming at minimizing the number of pairs of sections with students in common. Secondly, the sections are assigned time slots and finally the timetabling is improved for each student using single student timetabling, where the timetable of each student is improved individually.

Dimopoulou and Miliotis (2001) has created a system to solve the University Course Timetabling and the Examination Timetabling at Athens University of Economics and Business. The course timetabling problem is modeled and solved using a Branch-and-Bound based computer code. In most of the tests performed the optimal solution was found in less than one minute.

Another system is UniTime. UniTime is an open-source comprehensive educational scheduling system for universities. It offers both Curriculum-based and Enrollment-based Course Timetabling, as well as Examination Timetabling and Student Sectioning, and is used at several universities. The website of UniTime features all the papers published for the system (UniTime).

Rudova and Murray (2003) is some of the earliest work of UniTime. Of later research Rudová et al. (2011) solves the Post Enrollment-based Course Timetabling using the Iterative Forward Search (IFS) algorithm described in Müller et al. (2005). In Müller and Rudová (2012) the Curriculum-based

Course Timetable is solved by transforming its model into the enrollment model and using a local search algorithm for generating the corresponding enrollments. The algorithms of both papers are implemented in UniTime.

All the references mentioned in this section are listed in Table A.4 in Appendix A.

4. High School Timetabling

High School Timetabling is the problem of allocating classes to time slots, teachers and rooms to satisfy the hard and soft constraints. At the high schools the students are grouped into classes prior to the timetabling problem. The students of the classes are usually occupied together for all the lectures of their given class.

The most important components of the High School Timetabling problem are quite similar of those of University Course Timetabling. However there are some significant differences. Firstly, Student Sectioning is considered as part of the University Course Timetabling, whereas at the high schools it is considered as a separate problem. Secondly we have the grouping of students. High schools are timetabling classes, whereas at universities the students are often timetabled individually and at high schools clashes are not acceptable for the classes, whereas it can be acceptable if some students have clashes at universities. Another difference is the use of teachers. At the high schools the teachers are teaching full time, whereas the universities the teaching is often a small part of the professors/lectures workload.

Some of primary hard and soft constraints of High School Timetabling are listed below:

- Primary hard constraints
  - No 1-order conflicts. A student cannot attend two courses that are overlapping in time.
  - Classes/events must be scheduled for the required number of times for each subject.
  - Classes/events must be assigned a resource/room.
  - Room capacity. Classes can only be assigned rooms of which the capacity suits the class size
- Primary soft constraints
  - Limit idle periods for student and/or teachers.
  - Lessons spreading.
  - Resource/times preferences

The XHSTT format, which is described in the next section, operates with 16 different constraints, which can either be denoted hard or soft.

4.1. International Timetabling Competition

As mentioned the Third International Timetabling Competition (ITC2011) had the High School Timetabling problem as topic. The concept of the idea

was to increase the focus on High School Timetabling and the XHSTT format. The competition was launched in October 2011 and features three rounds.

1. In the first round of the competition the competitors should construct all-time-best solutions to the instances of the XHSTT-2012 archive.
2. The second round of the competition will work on the instances of the XHSTT-ITC2011 archive and 15 hidden instances. The participant could use any programming language and free third party software (excludes CPLEX, Gurobi etc.). A time limit of 100 seconds is given.
3. Third round consists of constructing all-time-best solutions to the hidden instances.

Deadline for submission of the contribution was May 2012 and the results was announces at PATAT in August 2012.

4.2. Benchmark Data

Access to public datasets of High School Timetabling has been very limited. Previously research was done for new unique problems each time or on artificial instances. The first accessible real life instances are the Beligiannis data sets.

- **Beligiannis data sets - Greek high schools**
  The archive consists of 7 datasets from Greek high schools and is used in Beligiannis et al. (2008). Each datasets contains a requirements matrix specifying the number of times each teacher must teach each class.

Due to the lack of exchangeable benchmarks in a uniform format, a group of researchers agreed on developing an XML-standard for the High School Timetabling problem, this resulted in the *XHSTT* format.

- **XHSTT**
  The project on creating XHSTT is described in the paper of Post et al. (2012a), and the format was as mentioned used for ITC2011. The objective is to minimize the number of violation of hard and soft constraints. The description of the format of XHSTT is available at the homepage (Post (2013)) along with nearly 40 instances. An evaluator for instances is available at at the web-page of Jeffrey Kingston (Kingston (2013b)).

4.3. Recent Research

Research articles on High School Timetabling are mostly limited to a single high school or a single country. In this section we will look at some of the research papers which have been conducted. For the High School Timetabling, the papers are categorized in order of the origin of the problems.

This does not necessary means that the problems at the different countries are not the same, but that the solution methods only have been tested on instances of the given country.

Pillay (2013) is another comprehensive survey which is advised for additional details on publications on High School Timetabling. In Pillay (2013) the literature is categorized by the used methodologies.

4.3.1. Country Specific Research

Australia.

The Australian case is solved in Boland et al. (2008) by creating two integer linear programming models to solve the course blocking and population problem.

Kingston (2005) solves seven instances of Australian high schools using a tilling algorithm with hill-climbing. The problem is of allocating meetings (teachers and classes) to times. Resources are added to the meeting using an alternating path algorithm. The XHSTT archive consists of three instances from Australia and they are the only instances where teachers workload are constrained.

Brazil.

The Brazilian case of School Timetabling is one of the most represented cases in the literature. Filho and Lorena (2001) use a constructive genetic algorithm to solve two Brazilian high schools, whereas Souza et al. (2003) use a greedy algorithm to find a good initial solution and then a Tabu Search for improving this solution.

Santos et al. (2004, 2005) creates a Tabu Search algorithm with two different memory based diversification strategies. The papers show that the diversification strategies improve the robustness of the Tabu Search.

In Bello et al. (2008) the High School Timetabling problem is treated as a Graph Coloring problem and solved using a Modified Tabucol, where Tabucol is a Tabu Search for Graph Vertex Coloring. The method was tested on five Brazilian high schools. Moura and Scaraficci (2010) solves the High School Timetabling for three Brazilian high schools using a basic GRASP heuristic, followed by a path-relinking improvement. Santos et al. (2012) present Column Generation as an approach for establishing bounds for a set of datasets originating from Brazil. It was a Brazilian team that won the ITC2011, Fonseca et al. (2012).

Currently, the XHSTT archive consists of seven datasets from Brazil.

Denmark.

Denmark is one of the new entrants within High School Timetabling. Sørensen and Stidsen (2013) is the first paper working on Danish high school and it describes a complex MIP model of the problem and establishes computational results for 100 real-life instances using Adaptive Large Neighborhood

Search. The solution approach is implemented in cloud-based administrative software and is available for the majority of all Danish high schools.

Sørensen and Dahms (2014) suggest a two-phase decomposition (created by Lach and Lübbecke (2012)) for solving the high schools in Denmark. In the first stage lectures are assigned to time slots and in the second stage rooms are assigned to the lectures. The results show that the approach is more effective than solving the original IP model in terms of both the obtained solutions and the obtained lower bounds.

At present four instances of Danish high schools are available in the XHSTT archive.

Germany.
In Bufé et al. (2001) the German high schools are treated with an evolutionary heuristic. Firstly an evolutionary algorithm searches the space of all permutations of the events from which the high school timetable is created. The solution is then improved using local search with specific mutation operators.

Lohnertz (2002) uses a hybrid approach with a combination of Tabu Search and Graph Vertex Coloring. Whereas Wilke et al. (2002) uses a genetic algorithm for solving the German high school timetabling.

A Tabu Search algorithm for the German timetabling problem is presented in Jacobsen et al. (2006). The initial solution is created using a construction heuristic with a graph coloring algorithm. The solution is then improved with the Tabu Search algorithm.

So far as we know none of the German instances are available in an online archive.

Greece.
The Greek high schools are well researched and the XHSTT archive is presented with seven instances from Greece.

In Valouxis and Housos (2003) constraint programming are used in combination with local search for Greek high schools. Papoutsis et al. (2003) creates an Integer Programming model of the problem and solves it using Column Generation.

In Beligiannis et al. (2008) an evolutionary algorithm has been created for the High School Timetabling problem in Greece and this system has been extended with a user-friendly interface (Moschopoulos et al. (2009)). In later work Beligiannis et al. (2009) implement a genetic algorithm to solve the same case. Both algorithms is inherent adaptive, which means that the user is able to assign weights to the different constraints. Both algorithms have been tested on seven real timetables used at schools in the city of Patras and has been made available online (See Beligiannis benchmark, Section 4.2).

In Raghavjee and Pillay (2009) and Raghavjee and Pillay (2010) a generic algorithm is used to solve the high school timetabling problem in Greece

and South Africa, respectively. The Greek datasets are from the Beligiannis benchmark datasets.

Birbas et al. (2009) uses a hybrid approach to solve the problem at a secondary Hellenic school. The first phase solves the Shift Assignment Problem where teachers are allocated to shifts, and the second phase solves the High School Timetabling. Both phases are solved using Integer Programming.

Zhang et al. (2010) uses a simulated based algorithm for the High School Timetabling problem. The algorithm is tested on two sets of benchmark instances. One randomly created and one real-life from Greece.

Valouxis et al. (2012) describe a two-phase approach based on MIP used to solve the Greek case of the High School Timetabling problem. This includes two instances which are part of the XHSTT project, which were both solved to optimality (solutions were found with an objective value of 0).

Greece is represented in the XHSTT archive with seven instances.

Italy.
Colorni et al. (1998) compares different solution methods for solving two Italian instances of the High School Timetabling problem. The different methods tested are various versions of Simulated Annealing and Tabu Search, and genetic algorithms with and without local search. The genetic algorithm with local search and the Tabu Search based on temporary problem relaxations outperforms the other Simulated Annealing approach and handmade solutions. The genetic algorithm with Tabu Search being the best.

Schaerf (1999b) has implemented a hybrid approach. After the initial timetable is created a randomized non-ascendant search is applied to improve the solution. When no better solution can be found, a Tabu search is applied. The two methods are repeated sequentially until there are no further improvements of the timetable. The solution method is tested on one artificial school and two Italian high schools.

Avella et al. (2007) uses a hybrid algorithm consisting of a Simulated Annealing for the initial solution and Very Large Neighborhood Search for improvements. It is tested on two real life instances from Italy.

Italy is represented with one instance in the XHSTT archive.

Netherlands.
Post and Ruizenaar (2004) use a combination of clustering and Branch-and-Bound algorithms to solve the school timetabling problem for a Netherlands secondary school. The first step is to construct clusterschemes. A clusterscheme contains clusterlines with optional subjects that can be taught in parallel. The second step is the Branch-and-Bound algorithm which constructs the school timetable.

In de Haan et al. (2007) a three-phase approach is use to generate a timetable for a Netherlands high school. The first phase constructs cluster

schemes for optional subjects, in the second phase a feasible schedule is constructing by assigning all lessons to time slots, such that there are no clashes. Finally the third part makes improvements of the timetable.

Post et al. (2012b) presented a cyclic transfer algorithm for the High School Timetabling problem. The methods are tested on four Dutch high schools and one English high school.

In the XHSTT archive the Netherlands are represented with four instances.

Portugal.
In Fernandes et al. (1999) the Portuguese High School Timetabling problem is solved using evolutionary algorithms. The genes which cause hard constraint violations are denoted *bad genes* and by introducing bad genes mutation it is possible to improve the algorithm in both speed and solution. Melício et al. (2006) developed the software tool THOR. THOR consists of a graphical user interface, an automatic scheduler and a relational database. The automatic scheduler is using a greedy algorithm to establish an initial solution and then improving that using Simulated Annealing. The system is used by more than 100 Portuguese high schools.

Other country specific methods.
Besides the mentioned countries, High School Timetabling has been briefly touched in other countries as well.

Wood and Whitaker (1998) solves the timetabling problem for secondary schools in New Zealand where student requests are an important part of the problem formulation. The problem is formulated as a non-linear goal program and solved in several stages using different heuristics such as Simulated Annealing and the Hungarian assignment algorithm.

Yigit (2007) uses a hybrid genetic algorithm for solving the High School Timetabling problem for the Technical and Vocational High Schools in Turkey.

In Ribic and Konjicija (2010) a two-phase approach to modeling the timetable problem is presented. In the first phase, the classes are allocated to days, and during the second phase, each class in a day are allocated into time slots. The approach is tested on a test case from a Croatian secondary school.

Nurmi and Kyngas (2007) use an extension of a hybrid hill-climbing genetic algorithm. The extension of the algorithm is a Simulated Annealing for choosing periods "intelligently". The algorithm is tested on data from Finnish high schools. Finland is represented in the XHSTT archive with six instances.

The timetabling problem for the Vietnamese high schools were solved in Minh et al. (2010) using a greedy algorithm for the initial solution and then improve the solution using Tabu Search.

4.3.2. The XHSTT-format

Most of the studies on High School Timetabling have resulted in successful solvers, however a big drawback is that many of the papers have only been applied to one problem or one country. One of the reasons for this is the lacking of benchmark data. Another reason is the desire of the single school to get its own problem solved and hence the papers are not interested in a more general approach. By the XHSTT format with corresponding benchmark datasets it is now possible to model a single problem in a standard format and to tests the solution approach on several cases.

As mentioned ITC2011 considered the High School Timetabling problem based on instances of the XHSTT format (Post et al. (2012c)). Four teams made it to the final round: The overall winner (Team Goal) used Simulated Annealing and Iterated Local Search to perform local search around a generated initial solution (Fonseca et al. (2012)). Participant from the University of Nottingham (HySTT) used a method based on Hyper-heuristics (Kheiri et al. (2012)). Team Lectio from Denmark used Adaptive Large Neighborhood Search (ALNS) (Sørensen et al. (2012)) and Romrös and Homberger (2012) (Team HFT) from Germany used an Evolutionary Algorithm. The specification of ITC 2011 and the results are described in Post et al. (2013)

Pimmer and Raidl (2013) describe a 'timeslot-filling' heuristic for XHSTT, which iteratively fills selected timeslots with sets of events. Two state-of-the-art solutions were found for instances of the archive XHSTT-2012.

Fonseca et al. (2013) have made some improvements on their work from ITC2011 which exceeds their previous work (Fonseca et al. (2012)). The new algorithm is a stagnation free Late-Acceptance Hill Climping algorithm. By combining the new approach with the Simulated Annealing from Fonseca et al. (2012) it provides the best results for some XHSTT datasets of ITC2011.

Kristiansen et al. (2013b) is the first paper working on an exact method for solving problems of the XHSTT format. The paper shows that the complex XHSTT format can be formulated as a Mixed Integer Programming model and solved using the state-of-the-art MIP solver, Gurobi. It was possible to find two new optimal solutions and prove optimality of four previously known solutions. Furthermore, lower bounds were established for 11 datasets.

All the references mentioned in this section are listed in Table A.5 and in Table A.6 in Appendix A.

5. Examination Timetabling

Examination Timetabling is the problem of scheduling a given number of exams to a limited number of time slots. Each course has one event representing the exam. The main problem is to avoid clashes in each student's examination timetable and to make sure that they have sufficient preparation time for each exam.

It is mainly the university course timetabling which are discussed in the literature and in Schaerf (1999a) the difference between Examination Timetabling and University Course Timetabling is observed to be relatively small, as both is of assigning event/exams to time slots and resources. However, it is broadly accepted to distinguish between the two due to the characteristics of the examination timetabling. University Course Timetabling pursuit a compact timetable whereas Examination Timetabling pursue more spreading between events for each student. The time between two exams is the preparation time the student has for the next exam. Furthermore, there is only one exam per course and there can be more than one exam in a single room. And a student can only attend one exam a day.

Below is listed some of the most common constraints used in Examination Timetabling.

- Primary hard constraints
  - 1-order conflicts cannot be accepted in Examination Timetabling.
  - Resources needs to be sufficient for the examinations (e.g. room capacity, enough rooms).
- Primary soft constraints
  - Spreading versus compact.
  - Time requirements. Exams can/cannot be in certain time slot.
  - Consecutive exams.
  - Resource requirements
  - Limited number of students and/or exams in any time slot
  - Ordering of exams must be satisfied
  - Only exams with same length can be located in the same room in the same time slot
  - Exams required taking place at the same time, on the same day or at the same location
  - As early/late as possible
  - Splitting the exams over similar locations

5.1. International Timetabling Competition

Aforementioned, the International Timetabling Competition in 2007 consisted, as mentioned, of three tracks, where the first track was regarding Examination Timetabling (McCollum et al. (2010)).

Eight datasets were given to the competitors, four were given immediately and four were given two weeks before competition deadline. The solution methods submitted were then tested on four hidden datasets. As mentioned in Section 3 it was the contribution of Müller (2009) that won Track 1 and Track 3 of the competition. The algorithm was a hybrid heuristic consisting of three parts, an Iterative Forward Search, a Hill Climbing and the Great Deluge techniques.

The datasets were provided by the EventMap research group and eight of the datasets are made available as benchmark, at the ITC2007 website (McCollum (2007)).

5.2. Benchmark Data

As Examination Timetabling has a high research interest it had let to some establishment of a variety of different benchmark problems. These benchmarks have made it possible to create scientific comparison between different approaches to the Examination Timetabling and thereby exchange of research achievements. The goal of this section is only to give a brief description of the known benchmark of Examination Timetabling. This paper will use name of the benchmarks as they were renamed in Qu et al. (2009) to prevent further confusion between papers. The majority of the benchmarks are available online (ExamBenchmarks).

- **The Toronto benchmark data**
  Carter et al. (1996) introduced a set of 13 real-world Examination Timetabling problem (3 from high schools and 10 from universities).

  The Toronto benchmark data have two variants of objectives: 1: Minimize the number of used time slots needed for the problem. 2: Minimize the average cost per student.

- **The Nottingham benchmark data**
  In Burke et al. (1996) a modification of the objective on six of the data sets from Carter et al. (1996) were introduced as benchmark along with the Examination Timetabling data from 1994 at the University of Nottingham.
  The objective is to minimize the number of students having two consecutive exams.

- **The Melbourne benchmark data**
  Merlot et al. (2003) introduced two new datasets from the University

of Melbourne at the fourth conference of Practice and Theory of Automated Timetabling (PATAT2003). The benchmark consists of two datasets which have two time slots for each of the five workdays.

The objective is to minimize adjacent exams on the same day or overnight.

- **The Purdue benchmark data**
  The newest benchmark within Examination Timetabling is given by Müller (2013). Nine datasets from Purdue University are introduced, and each dataset have 29 examination periods, all 2 hours long. PurdueExamBenchmark

5.3. Recent Research

Within educational timetabling, Examination Timetabling is a much researched subject. Qu et al. (2009) is an excellent survey of examination papers from 1996 to 2009 and we recommend the reader to read this paper for additional details on the research of Examination Timetabling.

It is noted that one of the current trends in the literature of operations research is the use of some sort of hybridization of different solution techniques. The same is applicable for the Examination Timetabling.

In the following the literatures are divided into the same classification as used for University Course Timetabling in Section 3, i.e. based on the main techniques used.

5.3.1. Swarm Intelligence Algorithms

Ant Colony algorithms has been used to solve Examination Timetabling in Dowsland and Thompson (2005) and Eley (2007). In Dowsland and Thompson (2005) an Ant Colony algorithm based on the ANTCOL algorithm for graph coloring from Costa and Hertz (1997) is developed to solve the Toronto benchmarks. A number of enhancements and modifications to the algorithm are introduced. These include an initialization method, using recursive Largest Degree and Saturation Degree, and trail calculations. Eley (2007) compares the ANTCOL algorithm with the MAX-MIN Ant System for University Course Timetabling from Socha et al. (2003). The algorithms are tested on the Toronto benchmarks and it is showed that the ANTCOL system outperforms the MAX-MIN Ant System.

In Turabieh and Abdullah (2011b) the Examination Timetabling problem is solved using the Fish Swarm algorithm developed in Turabieh et al. (2010) for University Course timetabling. The results show that the algorithm performs well on the Toronto benchmark datasets. In later work of the same authors (Turabieh and Abdullah (2011a)) a Great Deluge algorithm within an electromagnetic-like mechanism is employed for Examination Timetabling. This mechanism method shares the same concepts as the Particle Swarm, where the position is changed based on the total force that

affects the particle in the search space. The algorithm was tested on the Toronto benchmark and ITC2007 competition datasets.

Sabar et al. (2009) uses a honey bee mating algorithm to solve the Toronto Benchmark datasets. The honey bee mating process is a typically swarm-based approach, were the algorithm is inspired by the process of the mating of honey bees. The queen (current best solution) leaves the nest to perform a mating flight during which the drones (new solutions) follows the queen and mate with her. In the beginning of the flight, the queen's speed is high and therefore the probability of mating is also high, which is also the case when the fitness of the drones is as good as the queen's. The queen then moves between different solutions in the solution space, according to her speed, and mates with the drones. After a successful mating, a new brood is generated, the fittest replaces the queen, and the rest become the new drones. Solutions show that the honey bee mating algorithm can produce good quality solutions for the Toronto benchmarks.

5.3.2. Evolutionary Algorithms

Wong et al. (2002) present an exam timetable generator which implemented for Ecole de Technologie Superieure at the University of Quebec. The approach of the generator is a Generic Algorithm to construct the exam timetable. A binary tournament selection is used to produce candidates for the algorithm.

Mansour et al. (2011) developed an evolutionary heuristic based on the scatter search approach. Scatter search operates on maintaining and evolving a population of small candidate solutions. It is then possible to find good suboptimal solutions for the problem. The algorithm is compared with other heuristics (genetic algorithm, Simulated Annealing, and 3-phase Simulated Annealing) on real data of the Lebanese American University and the results shows that the adaptive scatter search approach generates the best timetables.

5.3.3. Local Search Techniques

In Casey and Thompson (2003) a Greedy Randomized Adaptive Search Procedure (GRASP) is used for solving the Examination Timetabling problem for the Toronto benchmark datasets. The GRASP algorithm consists of a construction phase, where feasible timetables are created, and an improvement phase. In the constructing phase a limited form of a Tabu Search and efficient ordering of the exams are used. The improvement phase makes use of a neighborhood based on Kempe chains and a limited form of Simulated Annealing. In order to enhance the solution space the algorithm makes use of memory functions. The GRASP algorithm produced is simple to understand and performs robustly across all the instances.

In Ahmadi et al. (2003) a hyper heuristic is developed with a Variable Neighborhood Search to find good combinations of parameterized heuristics.

Permutations of twelve low level heuristics are employed to create solutions. Seven of the heuristic are exam selection, two time slot selection and three room selection heuristics. The hyper-heuristic is tested on instances from University of Nottingham.

Merlot et al. (2003) employ constraint programming to create a feasible initial solution for the Examination Timetabling problem. To improve the solution Simulated Annealing and Hill Climbing are used. The hybrid method has been tested on the University of Melbourne, two variants of Toronto instances and the Nottingham benchmark.

Burke et al. (2004a) make used of two variants of local search; a time-predefined variant of Simulated Annealing and an adaptation of the Great Deluge method. The Great Deluge has the same advantage as Simulated Annealing by accepted worse moves during its run. The algorithms are tested on the Toronto and Nottingham benchmarks and it is showed that the Great Deluge approach was superior to the Simulated Annealing approach.

White and Xie (2001) developed a four phase Tabu Search called OTTABU. In each phase more constraints are considered. The OTTABU algorithm was tested on the Examination Timetabling problem at the University of Ottawa, Canada. The approach was extended in White et al. (2004) where the Tabu lists are dynamically relaxed after a certain solution time with no improvements. This extended approach was tested on the Toronto benchmark.

Abdullah et al. (2007) developed a Large Neighborhood Search based on the search methodology originally developed in Ahuja et al. (2001). The key features of the approach are the combination of the very large neighborhood tree-based structure with the technique of identifying improvement moves by addressing negative cost partition-disjoint cycles. The approach was able to find some new best solutions for the Toronto benchmarks. In Abdullah et al. (2010) a hybridized approach of tabu-based and memetic algorithms is developed. The construction phase of the algorithm is based on a saturation degree graph coloring heuristic and the improvement phase makes use of the hybrid heuristic. A tabu list is used to penalize neighborhood structures that are unable to generate better solutions after the crossover and mutation operators have been applied to the selected solutions from the population pool.

In Caramia et al. (2008) four variant of a local search based algorithm are tested on the Toronto benchmarks and compared with solution from other papers. The algorithm consists of three building blocks; a greedy scheduler to find timetables with small length, a penalty decreaser to reduce the penalty of a schedule without changing the length and a penalty trader to reduce the penalty of a schedule by increasing the number of used time slots. The four variants are different depending on the type of checkpointing used, and on whether bridging priorities were used. The algorithms perform more robust than those of the comparison. The best variation being a hybridization of

an approach using adaptive checkpointing and bridging priorities with an approach using constant checkpointing but no bridging priorities.

Pillay and Banzhaf (2009) suggest a hyper-heuristic with hierarchal combination of heuristics. A Tabu Search is used to search the heuristic space for a heuristic list that produces the best quality exam timetable. Each list contains two of the six low level heuristics. The algorithm is tested on the Toronto benchmark and provides all instances with feasible timetables.

Gogos et al. (2012) developed a multi-stage algorithmic process to solve the datasets of ITC2007. The top level heuristic is a GRASP and low level methods consist of several optimization algorithms, heuristics and metaheuristics. The approach has a construction phase and an improvement phase. Each phase consists of stages that are consumed in a circular fashion.

5.3.4. Graph Coloring Algorithms

Graph bases methods are widely used on Examination Timetabling problems. The algorithms are often hyper-heuristics where the lower level heuristics are graph coloring heuristics, such as largest degree and saturation degree.

In Asmuni et al. (2005) a Fuzzy Logic algorithm was employed to order exams to be scheduled based on graph coloring heuristics. The fuzzy weight of an exam is used to represent how difficult it is to schedule. The method cannot compete with other solution methods on the Toronto benchmark, but the potential of it is demonstrated. Different or more Fuzzy functions are needed to be able to produce best known solutions. In later work of the same authors, a Fuzzy system was developed to evaluate the quality of the exam timetables (Asmuni et al. (2007)). The quality of exam timetables is measured considering two criteria: the average penalty per student and the highest penalty imposed on any of the students.

Yang and Petrovic (2005) used a hyper-heuristic with a Case-Based Reasoning as high level heuristics to choose graph heuristics to construct a feasible initial solution. A Great Deluge algorithm is then employed to improve the solution. Burke et al. (2005) also make use of a Case-Based Reasoning in a hyper-heuristic. Two different ways of hybridizing the low level graph heuristics were compared for solving the Toronto benchmark data. One were Case-Based Reasoning is used as higher level heuristic and one with a Tabu Search. The Tabu Search approach performed a little better than the Case-Based Reasoning approach, however it was significant slower.

The Tabu Search as higher level heuristic for low level graph coloring heuristics were investigated once more in Burke et al. (2007). It was observed that the more different graph-based heuristics used in the lower level the better the performance might by. The drawback is however the enlargement of the search space which can influence the solving time. The approach was used on both the Examination Timetabling and University

Course Timetabling and in both cases it was competitive with other solution methods from the literature.

The Examination Timetabling problem from Universiti Malaysia Pahang, Malaysia, is presented in Kahar and Kendall (2010). The paper compares the Examination Timetabling problem at the university with known benchmark data, and two new constraint concerning splitting exams into different rooms are introduced. When splitting an exam the rooms must be in the same building (hard constraint) and the distance between the rooms should be as close as possible (soft constraint). The algorithm presented in the paper is based on graph coloring heuristics and produce superior solutions compared to the existing software at the university.

Sabar et al. (2012) developed a graph coloring constructive hyper-heuristic algorithm. At the higher level of the hyper heuristic the difficulty level of examinations is calculated by using hybridizations of four graph coloring heuristics. At the low level four graph coloring algorithms are used; largest degree, saturation degree, largest colored degree and largest enrollment. The results show that the approach is a simple and an efficient tool to produce competitive results for the Toronto and the ITC2007 benchmark data.

Rahman et al. (2014) employ adaptive linear combinations of graph coloring heuristics with a heuristic modifier to address the Examination Timetabling problem for the Toronto and the ITC2007 benchmark data. The approach makes use of two graph coloring heuristics, largest descent and saturation degree.

5.3.5. Other Heuristic Methods

This section contains literature which application method does not fit in the previous heuristic categories.

In Petrovic and Bykov (2003) the multi-criteria called compromised programming is used. The method requires the user to specify a reference solution. To improve the values of the reference objectives a trajectory is drawn in the criteria space and a Great Deluge is conducted using the specified trajectory. The criteria weights can be dynamically changed to guide the search, starting from random points, towards the reference point.

Duong and Lam (2004) present a two phase heuristic for the Examination Timetabling problem. In the first phase constraint programming is used to generate a feasible initial solution and in the second phase a Simulated Annealing with Kempe chain neighborhood improves that solution. The algorithm is tested on real data of Ho Chi Minh City University of Technology.

Ozcan et al. (2009) uses a late acceptance hyper-heuristic to solve the Toronto benchmark data. Late acceptance strategy is a memory based technique that maintains the history of objective values from the last $\mathcal{L}$ previous solutions. The new solution is compared to a previous solution obtained at the $\mathcal{L}$'th step and the acceptance decision is made accordingly. The results show that Simple Random performs the best when combined with late

acceptance as compared with the other heuristic of the paper.

Abdullah et al. (2009) present a hyper-heuristic of an electromagnetic-like mechanism and the Great Deluge algorithm. Electromagnetic-like mechanism is implemented to calculate the force for each solution. The force value later will be used in the Great Deluge algorithm to calculate the force decay rate.

Another hyper-heuristic for Examination Timetabling is the Monte Carlo based hyper heuristic developed in Burke et al. (2010a). A number of new and previous suggested Monte Carlo based selection hyper-heuristics are investigated on the Toronto benchmark data. As heuristic selection methods a simple random algorithm, a greedy algorithm, a Choice Function algorithm and a learning scheme are utilized. The hyper-heuristic make use of four low level heuristics.

In Demeester et al. (2012) a tournament based hyper-heuristic is presented. The hyper-heuristic framework of Özcan et al. (2008) is extended using a *tournament factor*. At each iteration, the selected heuristic generates a predefined number, namely the tournament factor, of random moves. The low level heuristics are Simulated Annealing, Great Deluge and steepest descent. The hyper heuristic is tested on the Toronto benchmark, the instances from ITC2007 and datasets from KAHO Sint-Lieven, Belgium.

Anwar et al. (2013) propose a harmony search based hyper-heuristic method for the Examination Timetabling. The harmony search algorithm is a fairly new meta-heuristic method inspired by musical improvisation process. The algorithm of this paper employed harmony search algorithm at the high level to evolve a sequence of improvement low-level heuristics. At the low level, two different neighborhood structures are used. Swap and move. The algorithm is tested on the ITC2007 benchmark

5.3.6. Exact Methods

The amount of research using some sort of exact methods, such as decomposition, is quite sparse for Examination Timetabling.

In Qu and Burke (2007) a new decomposition technique is developed for the Examination Timetabling. The idea is to decompose the problem into two sub-sets of events; a difficult and an easy sub-set. In the first step the exams of the difficult set is ordered to find the best feasible solution. In second step the solution from step one is fixed and the easy events are ordered. The two steps are then repeated in a cycle. The approach was tested on the Toronto benchmark data.

Al-Yakoob et al. (2010) considers two exam related problems at Kuwait University; the Examination Timetabling problem and the proctor assignment problem. A Mixed Integer Programming model has been created for both problem and solved using the State-of-art MIP solver CPLEX. The

results obtained by solving the MIP models are of significant improvements compared to the existing manual approach at the given university.

5.3.7. Software Systems

Many of the systems mentioned in Section 3.3.6 are for both University Course Timetabling and Examination Timetabling. In Dimopoulou and Miliotis (2001) the initial solution for the Examination Timetabling is based on the University Course Timetabling. This is then adjusted repeatedly by a heuristic approach.

The newest paper from the system UniTime on Examination Timetabling is Müller (2013). The algorithm presented consists of several phases. A construction phase where a complete solution is found using an Iterative Forward Search (Müller et al. (2005)). The next phase uses a Hill Climber to find a local optimum. Once a solution cannot be improved further a Great Deluge technique is used.

Other systems which only solves the Examination Timetabling problem includes Hansen and Vidal (1995) and Thompson and Dowsland (1998).

Hansen and Vidal (1995) is a system for timetabling oral and written examinations at more than 200 high schools in Denmark. The system uses a four phase process dealing with different objectives using different techniques. Phase one is the subject draft which determine which exams a student is assigned. Examination chains are generated in phase two. Phase three creates the examination timetables and finally phase four assigns censorships to the exams.

Thompson and Dowsland (1998) create an Examination Timetabling system at Swansea University in Wales. The problem is divided in two phases both solved using Simulated Annealing. The first phase seeks out a feasible solution and the second finds an improvement in terms of meeting the secondary objectives and soft constraints.

All the references mentioned in this section are listed in Table A.7 in Appendix A.

6. Student Sectioning

The previous mentioned educational timetabling problems are all considering the problem of assigning some events to times. *Student Sectioning* usually resides outside this categorization as it involves assigning students to sections and not times.

A course might be split into sections/classes, i.e. copies of the same course, each with its own time, room and teachers. Student Sectioning is the problem of assigning students to sections of courses while respecting the requests of the individual student. Some of primary hard and soft constraints of Student Sectioning problems are listed below:

- Primary hard constraints
  - No 1-order conflicts. A student cannot attend two courses that are overlapping in time.
  - Limitations on class sizes.
  - Resource limitation. E.g. only two Physic classes in each cluster.
- Primary soft constraints
  - Equally distribution between sections of same course (spreading)
  - Minimize the number of sections used.

6.1. Recent Research

Literature concerning Student Sectioning is very sparse, none of the previous surveys listed in Section 1.1 use much effort on this research subject and in many papers where Student Sectioning is mentioned the papers are on University Course Timetabling or High School Timetabling and not specific on Student Sectioning.

The surveys of Carter and Laporte (1998) and Schaerf (1999a) provides a good overview of previous work within practical course timetabling and automated timetabling problems. Both papers give a short description of student sectioning problem and some of the earliest work on the subject. Kingston (2013a) makes a short description on the subject, however the book chapter only reefers to few articles. Other surveys only briefly mentioned that many articles on timetabling problems have a preprocessing problem of assigning students to classes.

Student Sectioning arises at both universities and high schools. In both cases it is often a preprocessing problem for the timetabling problem.

Of the two cases, Student Sectioning at high schools is the least studied and are in general smaller in size compared to university student sectioning. In de Haan et al. (2007) *optional subject* for the students is used when constructing timetables at high schools in Netherlands, and *cluster schemes*

are created to maintain the students' optional courses. Due to a new educational system at the test case high school the program in the paper is only used operational for the Student Sectioning (constructing the cluster schemes) and not on the timetabling.

Kristiansen and Stidsen (2013) use the comparative term *electives*. The problem is to assign 2nd and 3rd year students to electives given their requests while minimizing the number of classes created and producing a fair distribution. An Adaptive Large Neighbor Search algorithm has been created to solve the problem and the results are in average 0.5% from the best known lower bound. The algorithm developed in Kristiansen and Stidsen (2013) is implemented in the cloud-based high school administration software *Lectio*.

In Kristiansen et al. (2013a) the problem is concerned the first year students at Danish high schools and is bipartite. First the students are grouped into cohorts in which they are going to attend the same mandatory courses, secondly the cohorts are assigned time slots to satisfy the students requests for two electives. The problem is solved using the MIP solver Gurobi.

There exist more papers on Student Sectioning at universities, however in many cases you must search in papers on University Course Timetabling to find discussion on the subject, e.g Rudova and Murray (2003) and Suyanto (2010).

Carter (2001) and Rudova and Murray (2003) describe a *demand-driven timetabling* where student selections of courses are utilized to create a timetable that satisfy as many requests as possible. In Carter (2001) the University Course Timetabling is created first by assigning time slots to sections and the students is then assigned individually to the sections that maximizes timetable satisfaction and balance section sizes. Rudova and Murray (2003) uses student course selections to construct timetables that attempt to maximize the number of satisfied course requests.

In Sönmez and Ünver (2010) they make use of a bidding system. The students make bids on which courses they want to participate in, and based on these bids the courses are placed in class rooms which size reflects the number of bids for the given course. This paper looks on the mechanisms within the course bidding.

The approach of using "bidding/requests" and solving Student Sectioning as a subproblem to the university course timetabling is the most common method. (Aubin and Ferland (1989); Sampson et al. (1995); Robert and Hertz (1996))

In other papers the students are clustered to avoid conflicts between the students' choices of courses. Banks et al. (1998) formulates the timetabling problem as a *Constraint Satisfaction Problem* (CSP) where the algorithm iteratively adds subset constraints to the CSP formulation. Amintoosi and Haddadnia (2005) proposed a fuzzy clustering algorithm to create an initial sectioning prior to timetabling a set of classes. The same approach is used in Alvarez-Valdes et al. (2000). The students select course in an interactive

process in the first phase and in the second phase a Tabu search algorithm is used for constructing the timetable.

In Müller and Murray (2010) Student Sectioning is solved as a part of the University Course Timetabling where it is considered during and after the creation of the timetabling. In Suyanto (2010) used a two stage approach for solving the university course timetabling, where batch student sectioning is done by allowing the first stage timetable to change.

All the references mentioned in this section are listed in Table A.8 in Appendix A.

7. Conclusion

This paper has been provided in in-depth survey on educational timetabling literature in the last decade. The survey provides a comprehensive overview of methodologies used for each of the four main subjects within educational timetabling problems; University Course Timetabling, High School Timetabling, Examination Timetabling and Student Sectioning. For each planning problem a description is given along with benchmarks and recent research.

It is possible to draw a few conclusions for the complete educational timetabling problems. Firstly, within the last decade the amount of successful literature on this subject has been increasingly and many of the used solution approach is of some kind of hybridization of multiple heuristics.

Secondly, in many cases the quality of a solution is only compared to previous solutions and not on the optimal or lower bound. The main approach is some sort of heuristic, it could be advantage to research in the use of more exact methods to create some good lower bounds or better yet, optimal solutions to the benchmark data.

Finally, there is still a problem of closing the gap between theory and practice. The different planning problems are still in need of some generalized format and description and more benchmark data from the real world. The XHSTT format for High School Timetabling is an excellent example on a generalized description on a educational planning problem with corresponding benchmark consisting of real world data from a range of countries.

Appendix A. Summary Tables

This section contains summarization tables on the literature mentioned in each section, listed in order of appearance in this survey. For each section, the references are sorted according to the year of publication. Some of the mentioned papers in the tables might cover more than one subject and these papers are therefore listed in all the corresponding tables.

Each table consists of the description of author(s), research area and comments.

First we have the tables related to previous surveys and competitions within educational timetabling in Table A.2 and Table A.3, respectively.

Table A.8 lists all the papers related to Student Sectioning.

Table A.2: Surveys on educational timetabling

References	Title	Research area	Comments
Schmidt and Ströhlein (1980)	Timetable construction – an annotated bibliography	Timetabling	Provide an annotated bibliography including more than 200 entries.
de Werra (1985)	An introduction to timetabling	Class-teacher and course timetabling	Graph coloring and network flows methods.
Junginger (1986)	Timetabling in Germany–A Survey	School timetabling	Various software products implemented in Germany .
Carter (1986)	A Survey of Practical Applications of Examination Timetabling Algorithms	Examination timetabling	Algorithms tested on real data or implemented.
Carter and Laporte (1996)	Recent developments in practical examination timetabling	Examination timetabling	Algorithms tested on real data or implemented from 1986 to 1996.
Bardadym (1996)	Computer-aided school and university timetabling: The new wave	Educational timetabling	Computer-aided management systems for timetabling.
Wren (1996)	Scheduling, timetabling and rostering — A special relationship?	Scheduling and timetabling	Links scheduling, timetabling and rostering.
Carter and Laporte (1998)	Recent developments in practical course timetabling	Course timetabling	Algorithms tested on real data or implemented.
Schaerf (1999a)	A Survey of Automated Timetabling	School, course and exam timetabling	Classification of solution techniques particularly from artificial intelligence.
Burke and Petrovic (2002)	Recent research directions in automated timetabling	University timetabling (course and exam)	Tries to explore approaches that can operate at a higher level of generality.
Burke et al. (2004c)	Application to timetabling	Class-teacher, course, exam and sport timetabling	Application of graph coloring methods to timetabling.

Continued on next page

Table A.2 – continued from previous page

References	Title	Research area	Comments
McCollum (2006)	University Timetabling: Bridging the Gap between Research and Practice	Latest survey on University Course Timetabling.	
Qu et al. (2009)	A Survey of Search Methodologies and Automated System Development for Examination Timetabling	Examination timetabling	Algorithms from 1996 to 2009. Presenting a definitive renaming of different benchmark problem datasets.
Pillay (2013)	An Overview of School Timetabling Research	School timetabling	A standardized definition of the problem in terms of problem requirements, hard constraints and soft constraints.
Kingston (2013a)	Educational Timetabling	-	Book chapter introducing the problems of timetabling educational institutions.

Table A.3: Competitions within Educational Timetabling

References	Research area	Comments
Kostuch (2004)	University Timetabling	Winner of the 1st International Timetabling Competition 2002
Gaspero et al. (2007)	University Timetabling and Exam Timetabling	Overview of the competitions and the competitors of the 2nd International Timetabling Competition 2007
McCollum et al. (2010)	Setting the Research Agenda in Automated Timetabling: The Second International Timetabling Competition	
Post et al. (2012c)	High School Timetabling	Overview of the competitions and the competitors of the 3rd International Timetabling Competition 2011

Table A.4: University Course Timetabling

Authors	Problem	Comments
Carter (2001)	A comprehensive course timetabling and student scheduling system at the university of waterloo	Implemented at University of Waterloo and in 2001 it has been used successfully for 15 years.
Dimopoulou and Miliotis (2001)	Implementation of a university course and examination timetabling system	A system for University Course Timetabling and Examination Timetabling at Athens University of Economics and Business.
Socha et al. (2003)	Ant Algorithms for the University Course Timetabling Problem with Regard to the State-of-the-Art	-
Rudova and Murray (2003)	University Course Timetabling with Soft Constraints	A part of the UniTime systems publications. Using constraint logic programming.
Gaspero and Schaerf (2003)	Multi-neighbourhood Local Search with Application to Course Timetabling	Tested on the School of Engineering at Udine University.

Continued on next page

Table A.4 – continued from previous page

Authors	Problem	Comments
Martin (2004)	Ohio University's College of Business Uses Integer Programming to Schedule Classes	Solves the University Course Timetabling at College of Business, Ohio University.
Daskalaki et al. (2004)	An integer programming formulation for a case study in university timetabling	Engineering School of Greek universities.
Kostuch (2004)	Timetabling Competition - SA-based Heuristic	Winner of ITC2002
Müller et al. (2005)	Minimal Perturbation Problem in Course Timetabling	Iterative Forward Search. Part of UniTime system.
Avella and Vasil'Ev (2005)	A Computational Study of a Cutting Plane Algorithm for University Course Timetabling	Branch-and-Cut method with two cutting planes.
Daskalaki and Birbas (2005)	Efficient solutions for a university timetabling problem through integer programming	A two stage relaxation procedure.
Qualizza and Serafini (2005)	A Column Generation Scheme for Faculty Timetabling	Column Generation with a Branch-and-Bound method to ensure feasibility.
Chiarandini et al. (2006)	An effective hybrid algorithm for university course timetabling	Tested on the benchmark of ITC2003.
Lewis et al. (2007)	Post Enrolment based Course Timetabling: A Description of the Problem Model used for Track Two of the Second International Timetabling Competition	Explanation of Post enrollment-based course timetabling used for ITC2007 Track 3.
Al-Yakoob and Sherali (2007)	A mixed-integer programming approach to a class timetabling problem: A case study with gender policies and traffic considerations	Incorporates gender policies in the University Course Timetabling at Kuwait University.
Burke et al. (2007)	A graph-based hyper-heuristic for educational timetabling problems	Tested on the benchmark of ITC2007.
Murray et al. (2007)	Modeling and Solution of a Complex University Course Timetabling Problem	Transform the University Course Timetabling problem at Purdue University into a constraint satisfaction and optimization problem. Part of the UniTime system.

Continued on next page

Table A.4 – continued from previous page

Authors	Problem	Comments
Schimmelpfeng and Helber (2007)	Application of a real-world university-course timetabling model solved by integer programming	Solves the problem at School of Economics and Management at Hannover University.
Lach and Lübbecke (2008)	Optimal University Course Timetables and the Partial Transversal Polytope	Theoretical background for a two stage decomposition method for the University Course Timetabling.
Nurmi and Kyngas (2008)	A Conversion Scheme for Turning a Curriculum-Based Timetabling Problem into a School Timetabling Problem	Transform the problem description of Curriculum-Based Timetabling Problem from ITC2007 to a school timetabling problem and solves it using a genetic algorithm.
Cambazard et al. (2008)	Local Search and Constraint Programming for the Post Enrolment-based Course Timetabling Problem	Winner of ITC2007 Track 2.
Müller (2009)	ITC2007 solver description: a hybrid approach	Winner of ITC2007 Track 1 and 3.
Suyanto (2010)	An informed genetic algorithm for university course and student timetabling problems	-
Turabieh et al. (2010)	Fish Swarm Intelligent Algorithm for the Course Timetabling Problem	Applied to the definition of Socha et al. (2003).
Lü et al. (2011)	Neighborhood analysis: a case study on curriculum-based course timetabling	-
Rudová et al. (2011)	Complex university course timetabling	Newest research paper from UniTime on Post Enrollment-based Course Timetabling.
Nguyen et al. (2011)	Variable Neighborhood Search for a Real-World Curriculum-Based University Timetabling Problem	Solves 14 instances from University of Science in Vietnam.
Shiau (2011)	A hybrid particle swarm optimization for a university course scheduling problem with flexible preferences	Solves the course timetabling at a university in Taiwan.
Hao and Benlic (2011)	Lower bounds for the ITC-2007 curriculum-based course timetabling problem	Generates lower bounds for the ITC2007 instances.

Continued on next page

Table A.4 – continued from previous page

Authors	Problem	Comments
Bonutti et al. (2012)	Benchmarking curriculum-based course timetabling: formulations, data formats, instances, validation, visualization, and results	Formulations and collection of the Udine benchmark.
Lach and Lübbecke (2012)	Curriculum based course timetabling: new solutions to Udine benchmark instances	Uses the two stage decomposition of Lach and Lübbecke (2008) to solve the Udine Benchmark.
Müller and Rudová (2012)	Real-life curriculum-based timetabling	Newest research paper from UniTime on Curriculum-based Course Timetabling.
Burke et al. (2012)	A branch-and-cut procedure for the Udine Course Timetabling problem	Generates good lower bounds fast.
Ceschia et al. (2012)	Design, engineering, and experimental analysis of a simulated annealing approach to the post-enrolment course timetabling problem	Tested on the ITC2003 and ITC2007 benchmark data.
Nothegger et al. (2012)	Solving the post enrolment course timetabling problem by ant colony optimization	Tested on the ITC2007 benchmark with mixed results.
Chen and Shih (2013)	Solving University Course Timetabling Problems Using Constriction Particle Swarm Optimization with Local Search	-
Cacchiani et al. (2013)	A new lower bound for curriculum-based course timetabling	Lower bounds on the benchmark sets of ITC2003 and ITC2007.
Azlan and Hussin (2013)	Implementing graph coloring heuristic in construction phase of curriculum-based course timetabling problem	Tested on the benchmark of ITC2007.

Table A.5: High School timetabling - XHSTT

Authors	Problem	Comments
Post et al. (2012a)	An XML format for benchmarks in High School Timetabling	The XHSTT format description.

Continued on next page

Table A.5 – continued from previous page

Authors	Problem	Comments
Fonseca et al. (2012)	A SA-ILS approach for the High School Timetabling Problem	1st place at ITC2011.
Kheiri et al. (2012)	HySST: Hyper-heuristic Search Strategies and Timetabling	2nd place at ITC2011.
Sørensen et al. (2012).	International Timetabling Competition 2011: An Adaptive Large Neighborhood Search algorithm	3rd place at ITC2011.
Romrös and Homberger (2012)	An Evolutionary Algorithm for High School Timetabling	4th place at ITC2011.
Post et al. (2013)	The Third International Timetabling Competition	Description and results of ITC2011.
Pimmer and Raidl (2013)	A Timeslot-Filling Heuristic Approach to Construct High-School Timetables	
Fonseca et al. (2013)	Late Acceptance-Hill Climbing Applied to the High School Timetabling Problem	Improvements of Fonseca et al. (2012).
Kristiansen et al. (2013b)	Integer Programming for the Generalized (High) School Timetabling Problem	IP model for the XHSTT format and creation of lower bounds.

Table A.6: High School timetabling - country based

Studies	Subject	Comments
Wood and Whitaker (1998)	Student Centred School Timetabling	Solves the problem at Secondary schools in New Zealand using Hill Climber and Hungarian Assignment.
Colorni et al. (1998)	Metaheuristics for High School Timetabling	Solves two Italian high school instances. A genetic algorithm with Tabu Search being the best.
Schaerf (1999b)	Local search techniques for large high school timetabling problems	Solves one artificial and two Italian high schools using a hybrid heuristic with Tabu Search.
Fernandes et al. (1999)	High school weekly timetabling by evolutionary algorithms	High schools in Portugal.

Continued on next page

Table A.6 – continued from previous page

Studies	Subject	Comments
Bufé et al. (2001)	Automated Solution of a Highly Constrained School Timetabling Problem - Preliminary Results	Using Tabu Search to solve the German high school timetabling problem.
Filho and Lorena (2001)	A Constructive Evolutionary Approach to School Timetabling	Solves two Brazilian high schools.
Lohnertz (2002)	A timetabling system for the German gymnasium	Combines Tabu Search and Graph Vertex Coloring for German high school.
Wilke et al. (2002)	A Hybrid Genetic Algorithm for School Timetabling	German high school.
Souza et al. (2003)	A GRASP-tabu search algorithm for school timetabling problems	Brazilian high schools.
Valouxis and Housos (2003)	Constraint programming approach for school timetabling	Greek high schools.
Papoutsis et al. (2003)	A column generation approach for the timetabling problem of Greek high schools	Greek high schools.
Santos et al. (2004)	An Efficient Tabu Search Heuristic for the School Timetabling Problem	Brazilian high schools.
Post and Ruizenaar (2004)	Clusterschemes in Dutch secondary schools	Clusterschemes are constructed and a Branch-and-Bound approach is then used for Dutch high school timetabling problem.
Kingston (2005)	A Tiling Algorithm for High School Timetabling	Solves seven instances of Australian high schools.
Santos et al. (2005)	A Tabu search heuristic with efficient diversification strategies for the class/teacher timetabling problem	Uses memory based diversifications to improve robustness in a Tabu Search. Brazilian high schools.
Jacobsen et al. (2006)	Timetabling at German Secondary Schools: Tabu Search versus Constraint Programming	German high school.
Melício et al. (2006)	THOR: A Tool for School Timetabling	Describes the system THOR which in use by more than 100 schools in Portugal.

Continued on next page

Table A.6 – continued from previous page

Studies	Subject	Comments
Yigit (2007)	Constraint-Based School Timetabling Using Hybrid Genetic Algorithms	Solves the problem at the Technical and Vocational High Schools in Turkey.
Nurmi and Kyngas (2007)	A framework for school timetabling problem	Finnish high schools.
de Haan et al. (2007)	A Case Study for Timetabling in a Dutch Secondary School	Solves the Dutch case from Post and Ruizenaar (2004) using a three phase approach.
Avella et al. (2007)	A computational study of local search algorithms for Italian high-school timetabling	Using a hybrid heuristic with Variable Neighborhood Search and Simulated Annealing on two Italian high schools.
Bello et al. (2008)	An Approach for the Class/Teacher Timetabling Problem using Graph Coloring	Tested on five Brazilian high schools.
Boland et al. (2008)	New integer linear programming approaches for course timetabling	Australian high schools.
Beligiannis et al. (2008)	Applying evolutionary computation to the school timetabling problem: The Greek case	Greek high schools made available as benchmark data.
Moschopoulos et al. (2009)	A User-Friendly Evolutionary Tool for High-School Timetabling	An user interface for the system created in Beligiannis et al. (2008).
Beligiannis et al. (2009)	A genetic algorithm approach to school timetabling	Solves the Beligiannis benchmark.
Raghavjee and Pillay (2009)	Evolving solutions to the school timetabling problem	Solves the Beligiannis benchmark.
Birbas et al. (2009)	School timetabling for quality student and teacher schedules	Solves a secondary Hellenic school. First by assigning teachers to shifts and then solving the High School Timetabling problem.
Moura and Scaraficci (2010)	A GRASP strategy for a more constrained School Timetabling Problem	Solves the Brazilian high schools Teacher-class assignment problem.
Zhang et al. (2010)	A simulated annealing with a new neighborhood structure based algorithm for high school timetabling problems	Tested on two set of benchmark instances. A randomly generated and instances from Greek high schools in Patras.

Continued on next page

Table A.6 – continued from previous page

Studies	Subject	Comments
Santos et al. (2012)	Strong bounds with cut and column generation for class-teacher timetabling	Brazilian high schools Class-teacher assignment problem.
Raghavjee and Pillay (2010)	An informed genetic algorithm for the high school timetabling problem	High schools in South Africa.
Minh et al. (2010)	Using Tabu Search for Solving a High School Timetabling Problem	High schools in Vietnam solved using Tabu Search.
Post et al. (2012b)	Cyclic transfers in school timetabling	High school timetabling in the Netherlands and England.
Ribic and Konjicija (2010)	A two phase integer linear programming approach to solving the school timetable problem	Croatian secondary school.
Valouxis et al. (2012)	Decomposing the High School Timetable Problem	Greek high schools.
Sørensen and Stidsen (2013)	Integer Programming and Adaptive Large Neighborhood Search for Real-World Instances of High School Timetabling	Implemented at available for more than 200 Danish high schools.
Sørensen and Dahms (2014)	A Two-Stage Decomposition of High School Timetabling applied to cases in Denmark	Using the approach of Lach and Lübbecke (2012) on the Danish high school timetabling problem.

Table A.7: Examination timetabling

References	Problem	Comments
Hansen and Vidal (1995)	Planning of high school examinations in Denmark	System for examination timetabling and censorships assignment at Danish high schools.
Carter et al. (1996)	Examination Timetabling: Algorithmic Strategies and Applications	Created the Toronto benchmark datasets.
Burke et al. (1996)	A Memetic Algorithm for University Exam Timetabling	Extended Carter et al. (1996) with the Nottingham benchmark datasets.

Continued on next page

Table A.7 – continued from previous page

References	Problem	Comments
Thompson and Dowsland (1998)	A robust simulated annealing based examination timetabling system	A system for handling exams at Swansea University, Wales.
White and Xie (2001)	Examination Timetables and Tabu Search with Longer-Term Memory	University of Ottawa, Canada.
Dimopoulou and Miliotis (2001)	Implementation of a university course and examination timetabling system	A system for University Course Timetabling and Examination Timetabling at Athens University of Economics and Business.
Wong et al. (2002)	Final exam timetabling: a practical approach	Solve the examination problem at Ecole de Technologie Superieure, Montreal, Canada, and has been in use since 2001.
Ahmadi et al. (2003)	Perturbation based variable neighbourhood search in heuristic space for examination timetabling problem	Tested on the Nottingham benchmark.
Merlot et al. (2003)	A Hybrid Algorithm for the Examination Timetabling Problem	Created the Melbourne benchmarks.
Petrovic and Bykov (2003)	A Multiobjective Optimisation Technique for Exam Timetabling Based on Trajectories	Tested on the Nottingham and Toronto benchmarks.
Casey and Thompson (2003)	GRASPing the Examination Scheduling Problem	Tested on the Toronto benchmarks.
Burke et al. (2004a)	A time-predefined local search approach to exam timetabling problems	Tested on the Nottingham and Toronto benchmarks.
Duong and Lam (2004)	Combining Constraint Programming and Simulated Annealing on University Exam Timetabling	HoChiMinh City University of Technology, Vietnam.
White et al. (2004)	Using tabu search with longer-term memory and relaxation to create examination timetables	University of Ottawa, Canada.
Burke et al. (2005)	Hybrid Graph Heuristics within a Hyper-Heuristic Approach to Exam Timetabling Problems	Tested on the Toronto benchmarks.
Asmuni et al. (2005)	Fuzzy Multiple Heuristic Orderings for Examination Timetabling	Tested on the Toronto benchmarks.

Continued on next page

Table A.7 – continued from previous page

References	Problem	Comments
Yang and Petrovic (2005)	A Novel Similarity Measure for Heuristic Selection in Examination Timetabling	Tested on the Toronto benchmarks.
Dowsland and Thompson (2005)	Ant colony optimization for the examination scheduling problem	Tested on the Toronto benchmarks.
Abdullah et al. (2007)	Investigating Ahuja–Orlin's large neighbourhood search approach for examination timetabling	Tested on the Toronto benchmarks.
Asmuni et al. (2007)	A Novel Fuzzy Approach to Evaluate the Quality of Examination Timetabling	Tested on the Toronto benchmarks.
Burke et al. (2007)	A graph-based hyper-heuristic for educational timetabling problems	Tested on the Toronto benchmarks.
Eley (2007)	Ant Algorithms for the Exam Timetabling Problem	Tested on the Toronto benchmarks.
Qu and Burke (2007)	Adaptive decomposition and construction for examination timetabling problems	Tested on the Toronto benchmarks.
Caramia et al. (2008)	Novel Local-Search-Based Approaches to University Examination Timetabling	Tested on the Toronto benchmarks.
Pillay and Banzhaf (2009)	A study of heuristic combinations for hyper-heuristic systems for the uncapacitated examination timetabling problem	Tested on the Toronto benchmarks.
Ozcan et al. (2009)	Examination timetabling using late acceptance hyper-heuristics	Tested on the Toronto benchmarks.
Abdullah et al. (2009)	A Hybridization of Electromagnetic-Like Mechanism and Great Deluge for Examination Timetabling Problems	Tested on the Toronto benchmarks.
Müller (2009)	ITC2007 solver description: a hybrid approach	Winner of ITC2007 Track 1 and 3.
Sabar et al. (2009)	Solving Examination Timetabling Problems using Honey-bee Mating Optimization	Tested on the Toronto benchmarks.
Burke et al. (2010a)	Monte Carlo hyper-heuristics for examination timetabling	Tested on the Toronto benchmarks.

Continued on next page

Table A.7 – continued from previous page

References	Problem	Comments
Abdullah et al. (2010)	A Tabu-Based Memetic Approach for Examination Timetabling Problems	Tested on the Toronto benchmarks.
Kahar and Kendall (2010)	The examination timetabling problem at Universiti Malaysia Pahang: Comparison of a constructive heuristic with an existing software solution	Universiti Malaysia Pahang, Malaysia.
Al-Yakoob et al. (2010)	A mixed-integer mathematical modeling approach to exam timetabling	Kuwait University.
Mansour et al. (2011)	Scatter search technique for exam timetabling	Lebanese American University, Lebanon.
Turabieh and Abdullah (2011a)	An integrated hybrid approach to the examination timetabling problem	Tested on Toronto benchmarks and the datasets from ITC2007.
Turabieh and Abdullah (2011b)	A Hybrid Fish Swarm Optimisation Algorithm for Solving Examination Timetabling Problems	Tested on the Toronto benchmarks.
Sabar et al. (2012)	A graph coloring constructive hyper-heuristic for examination timetabling problems	Tested on Toronto benchmarks and the datasets from ITC2007.
McCollum et al. (2012)	A new model for automated examination timetabling	Tested on the datasets from ITC2007.
Gogos et al. (2012)	An improved multi-staged algorithmic process for the solution of the examination timetabling problem	Tested on Toronto benchmarks and the datasets from ITC2007.
Demeester et al. (2012)	A hyperheuristic approach to examination timetabling problems: benchmarks and a new problem from practice	Tested on the Toronto benchmark, the ITC 2007 benchmarks and the examination timetabling problem at KAHO Sint-Lieven (Ghent, Belgium).
Müller (2013)	Real-life Examination Timetabling	Purdue University datasets.
Anwar et al. (2013)	Harmony Search-based Hyper-heuristic for examination timetabling	ITC2007 benchmark.
Rahman et al. (2014)	Adaptive linear combination of heuristic orderings in constructing examination timetables	Tested on Toronto benchmarks and the datasets from ITC2007.

Table A.8: Student sectioning

Author(s)	Problem	Comments
Aubin and Ferland (1989)	A large scale timetabling problem	Tested on data from a High School in Montreal, Canada.
Sampson et al. (1995)	Class scheduling to maximize participant satisfaction	Using a local search heuristic and is able to meet 94% of the requirements at the Graduate School of Business Administration at the University of Virginia, USA.
Robert and Hertz (1996)	How to decompose constrained course scheduling problems into easier assignment type subproblems	Course timetabling with student requests.
Banks et al. (1998)	A heuristic incremental modeling approach to course timetabling	Constraints are added to the timetabling model to avoid student conflicts. The students are individually scheduled after complete timetabling.
Alvarez-Valdes et al. (2000)	Assigning students to course sections using tabu search	Used at the Faculty of Mathematics, University of Valencia, Spain of the academic year 96/97.
Carter (2001)	A comprehensive course timetabling and student scheduling system at the university of waterloo	Implemented at University of Waterloo and in 2001 it has been used successfully for 15 years.
Rudova and Murray (2003)	University course timetabling with soft Constraints	Tested on a data for the fall semester 2001 at Purdue University, USA.
Amintoosi and Haddadnia (2005)	Feature selection in a fuzzy student sectioning algorithm	Tested on the Mathematical department of Sabzevar University, Iran.
de Haan et al. (2007)	A case study for timetabling in a Dutch secondary school	Is used operationally only for constructing the cluster schemes.
Sönmez and Ünver (2010)	Course bidding at business schools	Mechanisms within course bidding.

Continued on next page

Table A.8 – continued from previous page

Author(s)	Problem	Comments
Müller and Murray (2010)	Comprehensive approach to student sectioning for Purdue University, USA	Student sectioning during course timetabling and batch sectioning after a complete timetable. Implemented in the open source software UniTime.
Suyanto (2010)	An informed genetic algorithm for university course and student timetabling problems	Batch student sectioning within a sparse timetabling model.
Kristiansen and Stidsen (2013)	Elective course student sectioning	Implemented and used for the majority of the Danish high schools from 2012 and forward.
Kristiansen et al. (2013a)	High school student sectioning at Danish high schools	Tested on 25 real life instances from Danish high schools.

References

S. Abdullah, S. Ahmadi, E.K. Burke, and M. Dror. Investigating ahuja–orlin's large neighbourhood search approach for examination timetabling. *OR Spectrum*, 29:351–372, 2007. ISSN 0171-6468. 10.1007/s00291-006-0034-7.

S. Abdullah, H. Turabieh, B. McCollum, and P. McMullan. A tabu-based memetic approach for examination timetabling problems. In Jian Yu, Salvatore Greco, Pawan Lingras, Guoyin Wang, and Andrzej Skowron, editors, *Rough Set and Knowledge Technology*, volume 6401 of *Lecture Notes in Computer Science*, pages 574–581. Springer Berlin / Heidelberg, 2010.

Salwani Abdullah, Hamza Turabieh, and Barry McCollum. A hybridization of electromagnetic-like mechanism and great deluge for examination timetabling problems. In María J. Blesa, Christian Blum, Luca Gaspero, Andrea Roli, Michael Sampels, and Andrea Schaerf, editors, *Hybrid Metaheuristics*, volume 5818 of *Lecture Notes in Computer Science*, pages 60–72. Springer Berlin Heidelberg, 2009. ISBN 978-3-642-04917-0.

S. Ahmadi, R. Barrone, P. Cheng, P. Cowling, and B. McCollum. Perturbation based variable neighbourhood search in heuristic space for examination timetabling problem. In *Multidisciplinary International Scheduling: Theory and Application (MISTA 2003)*, pages 155–171, August 2003.

Ravindra K. Ahuja, James B. Orlin, and Dushyant Sharma. Multi-exchange neighborhood structures for the capacitated minimum spanning tree problem. *Mathematical Programming*, 91(1):71–97, 2001. ISSN 0025-5610.

Salem M. Al-Yakoob and Hanif D. Sherali. A mixed-integer programming approach to a class timetabling problem: A case study with gender policies and traffic considerations. *European Journal of Operational Research*, 180 (3):1028 – 1044, 2007. ISSN 0377-2217.

SalemM. Al-Yakoob, Hanif D. Sherali, and Mona Al-Jazzaf. A mixed-integer mathematical modeling approach to exam timetabling. *Computational Management Science*, 7(1):19–46, 2010. ISSN 1619-697X.

Ramon Alvarez-Valdes, Enric Crespo, and Jose M. Tamarit. Assigning students to course sections using tabu search. *Annals of Operations Research*, 96(1-4):1–16, 2000. ISSN 0254-5330.

Mahmood Amintoosi and Javad Haddadnia. Feature selection in a fuzzy student sectioning algorithm. In Edmund Burke and Michael Trick, editors, *Practice and Theory of Automated Timetabling V*, volume 3616 of *Lecture Notes in Computer Science*, pages 147–160. Springer Berlin Heidelberg, 2005. ISBN 978-3-540-30705-1.

K. Anwar, A.T. Khader, M.A. Al-Betar, and M.A. Awadallah. Harmony search-based hyper-heuristic for examination timetabling. In *IEEE 9th International Colloquium on Signal Processing and its Applications (CSPA), 2013*, pages 176–181, 2013.

H. Asmuni, E.K. Burke, J. Garibaldi, and B. McCollum. Fuzzy multiple heuristic orderings for examination timetabling. In Edmund Burke and Michael Trick, editors, *Practice and Theory of Automated Timetabling V*, volume 3616 of *Lecture Notes in Computer Science*, pages 334–353. Springer Berlin / Heidelberg, 2005.

Hishammuddin Asmuni, Edmund K. Burke, Jonathan M. Garibaldi, and Barry McCollum. A novel fuzzy approach to evaluate the quality of examination timetabling. In EdmundK. Burke and Hana RudovÃ¡, editors, *Practice and Theory of Automated Timetabling VI*, volume 3867 of *Lecture Notes in Computer Science*, pages 327–346. Springer Berlin Heidelberg, 2007. ISBN 978-3-540-77344-3.

J. Aubin and J.A. Ferland. A large scale timetabling problem. *Computers & Operations Research*, 16(1):67 – 77, 1989. ISSN 0305-0548.

P. Avella, B. D'Auria, S. Salerno, and I. Vasilâev. A computational study of local search algorithms for italian high-school timetabling. *Journal of Heuristics*, 13:543–556, 2007. ISSN 1381-1231.

Pasquale Avella and Igor Vasil'Ev. A computational study of a cutting plane algorithm for university course timetabling. *Journal of Scheduling*, 8:497–514, 2005. ISSN 1094-6136.

Ammar Azlan and Naimah Mohd. Hussin. Implementing graph coloring heuristic in construction phase of curriculum-based course timetabling problem. In *Computers Informatics (ISCI), 2013 IEEE Symposium on*, pages 25–29, 2013. doi: 10.1109/ISCI.2013.6612369.

N. Balakrishnan and R.T. Wong. A network model for the rotating workforce scheduling problem. *Networks*, 20:25–42, 1990.

Don Banks, Peter Beek, and Amnon Meisels. A heuristic incremental modeling approach to course timetabling. In RobertE. Mercer and Eric Neufeld, editors, *Advances in Artificial Intelligence*, volume 1418 of *Lecture Notes in Computer Science*, pages 16–29. Springer Berlin Heidelberg, 1998. ISBN 978-3-540-64575-7.

V. Bardadym. Computer-aided school and university timetabling: The new wave. In Edmund Burke and Peter Ross, editors, *Practice and Theory of Automated Timetabling*, volume 1153 of *Lecture Notes in Computer Science*, pages 22–45. Springer Berlin / Heidelberg, 1996.

G.N. Beligiannis, C.N. Moschopoulos, G.P. Kaperonis, and S.D. Likothanassis. Applying evolutionary computation to the school timetabling problem: The greek case. *Computers & Operations Research*, 35(4):1265 – 1280, 2008. ISSN 0305-0548.

G.N. Beligiannis, C.N. Moschopoulos, and S.D. Likothanassis. A genetic algorithm approach to school timetabling. *Journal of the Operatio*, 60: 23–42, 2009.

G.S. Bello, M.C. Rangel, and M.C.S. Boeres. An approach for the class/teacher timetabling problem using graph coloring. In *In the proceedings of the 7th International Conference on the Practice and Theory of Automated Timetabling*. PATAT2008, 2008.

T. Birbas, S. Daskalaki, and E. Housos. School timetabling for quality student and teacher schedules. *J. of Scheduling*, 12:177–197, April 2009. ISSN 1094-6136.

N. Boland, B.D. Hughes, L.T.G. Merlot, and P.J. Stuckey. New integer linear programming approaches for course timetabling. *Computers & Operations Research*, 35(7):2209 – 2233, 2008. ISSN 0305-0548. Part Special Issue: Includes selected papers presented at the ECCO'04 European Conference on combinatorial Optimization.

A. Bonutti, F. De Cesco, L. Di Gaspero, and A. Schaerf. Benchmarking curriculum-based course timetabling: formulations, data formats, instances, validation, visualization, and results. *Annals of Operations Research*, 194(1):59–70, April 2012. ISSN 0254-5330.

M. Bufé, T. Fischer, H. Gubbels, C. Häcker, O. Hasprich, C. Scheibel, K. Weicker, N. Weicker, M. Wenig, and C. Wolfangel. Automated solution of a highly constrained school timetabling problem - preliminary results. In Egbert Boers, editor, *Applications of Evolutionary Computing*, volume 2037 of *Lecture Notes in Computer Science*, pages 431–440. Springer Berlin / Heidelberg, 2001.

Edmund K. Burke, Jakub Marec, Andrew J. Parkes, and Hana Rudova. A branch-and-cut procedure for the udine course timetabling problem. *Annals of Operations Research*, 194(1):71–87, 2012. ISSN 0254-5330.

E.K. Burke and J.P. Newall. A multistage evolutionary algorithm for the timetable problem. *Evolutionary Computation, IEEE Transactions on*, 3 (1):63 –74, apr 1999. ISSN 1089-778X.

E.K. Burke and S. Petrovic. Recent research directions in automated timetabling. *European Journal of Operational Research*, 140(2):266 – 280, 2002. ISSN 0377-2217.

E.K. Burke, J.P. Newall, and R.F. Weare. A memetic algorithm for university exam timetabling. In *Selected papers from the First International Conference on Practice and Theory of Automated Timetabling*, pages 241–250, London, UK, 1996. Springer-Verlag. ISBN 3-540-61794-9.

E.K. Burke, Y. Bykov, J.P. Newall, and S. Petrovic. A time-predefined local search approach to exam timetabling problems. *IIE Transactions*, 36(6): 509–528, 2004a.

E.K. Burke, P. De Causmaecker, G.V. Berghe, and H. Van Landeghem. The state of the art of nurse rostering. *Journal of Scheduling*, 7:441–499, 2004b. ISSN 1094-6136. 10.1023/B:JOSH.0000046076.75950.0b.

E.K. Burke, J. Kingston, and D. Werra. Application to timetabling. In J. Gross and J. Yellen, editors, *The Handbook of Graph Theory*, chapter 5, pages 445–474. Chapman Hall/CRC Press, 2004c.

E.K. Burke, M. Dror, S. Petrovic, and R. Qu. Hybrid graph heuristics within a hyper-heuristic approach to exam timetabling problems. In Ramesh Sharda, Stefan Voß, Bruce Golden, S. Raghavan, and Edward Wasil, editors, *The Next Wave in Computing, Optimization, and Decision Technologies*, volume 29 of *Operations Research/Computer Science Interfaces Series*, pages 79–91. Springer US, 2005. ISBN 978-0-387-23529-5.

E.K. Burke, B.McCollum, A. Meisels, S. Petrovic, and R. Qu. A graph-based hyper-heuristic for educational timetabling problems. *European Journal of Operational Research*, 176(1):177 – 192, 2007. ISSN 0377-2217.

E.K. Burke, G. Kendall, M. Mısır, and E. Özcan. Monte carlo hyper-heuristics for examination timetabling. *Annals of Operations Research*, pages 1–18, 2010a. ISSN 0254-5330.

E.K. Burke, J. Marecek, A.J. Parkes, and H. Rudová. Decomposition, reformulation, and diving in university course timetabling. *Computers & Operations Research*, 37(3):582–597, 2010b.

V. Cacchiani, A. Caprara, R. Roberti, and P. Toth. A new lower bound for curriculum-based course timetabling. *Computers & Operations Research*, 40(10):2466 – 2477, 2013. ISSN 0305-0548.

Hadrien Cambazard, Emmanuel Hebrard, Barry O'Sullivan, and Alexandre Papadopoulos. Local search and constraint programming for the post enrolment-based course timetabling problem. In *PATAT2008: Proceedings of the 7th International Conference on the Practice and Theory of Automated Timetabling*, 2008.

M. Caramia, P. Dell'Olmo, and G.F. Italiano. Novel local-search-based approaches to university examination timetabling. *INFORMS JOURNAL ON COMPUTING*, 20(1):86–99, 2008.

Michael W. Carter. A comprehensive course timetabling and student scheduling system at the university of waterloo. In Edmund Burke and Wilhelm Erben, editors, *Practice and Theory of Automated Timetabling III*, volume 2079 of *Lecture Notes in Computer Science*, pages 64–82. Springer Berlin Heidelberg, 2001. ISBN 978-3-540-42421-5.

M.W. Carter. A survey of practical applications of examination timetabling algorithms. *Operations Research*, 34(2):193 – 202, 1986. ISSN 0030364X.

M.W. Carter and G. Laporte. Recent developments in practical examination timetabling. In Edmund Burke and Peter Ross, editors, *Practice and Theory of Automated Timetabling*, volume 1153 of *Lecture Notes in Computer Science*, pages 1–21. Springer Berlin / Heidelberg, 1996.

M.W. Carter and G. Laporte. Recent developments in practical course timetabling. In Edmund Burke and Michael Carter, editors, *Practice and Theory of Automated Timetabling II*, volume 1408 of *Lecture Notes in Computer Science*, pages 3–19. Springer Berlin / Heidelberg, 1998.

M.W. Carter, G. Laporte, and S.Y. Lee. Examination timetabling: Algorithmic strategies and applications. *The Journal of the Operational Research Society*, 47(3):373–383, March 1996.

S. Casey and J. Thompson. Grasping the examination scheduling problem. In Edmund Burke and Patrick De Causmaecker, editors, *Practice and Theory of Automated Timetabling IV*, volume 2740 of *Lecture Notes in Computer Science*, pages 232–244. Springer Berlin / Heidelberg, 2003.

Sara Ceschia, Luca Di Gaspero, and Andrea Schaerf. Design, engineering, and experimental analysis of a simulated annealing approach to the post-enrolment course timetabling problem. *Computers & Operations Research*, 39(7):1615 – 1624, 2012. ISSN 0305-0548.

B. Cheang, H. Li, A. Lim, and B. Rodrigues. Nurse rostering problems–a bibliographic survey. *European Journal of Operational Research*, 151(3): 447 – 460, 2003. ISSN 0377-2217.

Ruey-Maw Chen and Hsiao-Fang Shih. Solving university course timetabling problems using constriction particle swarm optimization with local search. *Algorithms*, 6(2):227–244, 2013. ISSN 1999-4893.

M. Chiarandini, M. Birattari, K. Socha, and O. Rossi-Doria. An effective hybrid algorithm for university course timetabling. *Journal of Scheduling*, 9:403–432, 2006. ISSN 1094-6136.

A. Colorni, M. Dorigo, and V. Maniezzo. Metaheuristics for high school timetabling. *Comput. Optim. Appl.*, 9:275–298, March 1998. ISSN 0926-6003.

D. Costa and A. Hertz. Ants can colour graphs. *Journal of the Operational Research Society*, 48(3):295–305, 1997.

Sophia Daskalaki and Theodore Birbas. Efficient solutions for a university timetabling problem through integer programming. *European Journal of Operational Research*, 160(1):106 – 120, 2005. ISSN 0377-2217.

Sophia Daskalaki, Theodore Birbas, and Efthymios Housos. An integer programming formulation for a case study in university timetabling. *European Journal of Operational Research*, 153:117–135, 2004.

P. de Haan, R. Landman, G. Post, and H. Ruizenaar. A case study for timetabling in a dutch secondary school. In Edmund Burke and Hana Rudova, editors, *Practice and Theory of Automated Timetabling VI*, volume 3867 of *Lecture Notes in Computer Science*, pages 267–279. Springer Berlin / Heidelberg, 2007.

D. de Werra. An introduction to timetabling. *European Journal of Operational Research*, 19(2):151 – 162, 1985. ISSN 0377-2217.

Peter Demeester, Burak Bilgin, Patrick Causmaecker, and Greet Berghe. A hyperheuristic approach to examination timetabling problems: benchmarks and a new problem from practice. *Journal of Scheduling*, 15(1): 83–103, 2012. ISSN 1094-6136.

M. Dimopoulou and P. Miliotis. Implementation of a university course and examination timetabling system. *European Journal of Operational Research*, 130(1):202 – 213, 2001. ISSN 0377-2217.

K. A. Dowsland and J. M. Thompson. Ant colony optimization for the examination scheduling problem. *Journal of the Operational Research Society*, 56:456–438, 2005. doi: doi:10.1057/palgrave.jors.2601830.

Tuan-Anh Duong and Kim-Hoa Lam. Combining constraint programming and simulated annealing on university exam timetabling, 2004.

K. Easton, G. Nemhauser, and M. Trick. Solving the travelling tournament problem: A combined integer programming and constraint programming approach. In E.K Burke and P. De Causmaecker, editors, *Practice and Theory of Automated Timetabling IV*, volume 2740 of *Lecture Notes in Computer Science*, pages 100–109. Springer Berlin / Heidelberg, 2003.

Michael Eley. Ant algorithms for the exam timetabling problem. In Edmund K. Burke and Hana Rudová, editors, *Practice and Theory of Automated Timetabling VI*, volume 3867 of *Lecture Notes in Computer Science*, pages 364–382. Springer Berlin Heidelberg, 2007. ISBN 978-3-540-77344-3.

ExamBenchmarks. Benchmark data sets in exam timetabling. `http://www.cs.nott.ac.uk/~rxq/data.htm`[Retrieved 08/11-2013].

C. Fernandes, J.P. Caldeira, F. Melicio, and A. Rosa. High school weekly timetabling by evolutionary algorithms. In *Proceedings of the 1999 ACM symposium on Applied computing*, SAC '99, pages 344–350, New York, NY, USA, 1999. ACM. ISBN 1-58113-086-4.

G. Filho and L. Lorena. A constructive evolutionary approach to school timetabling. In Egbert Boers, editor, *Applications of Evolutionary Computing*, volume 2037 of *Lecture Notes in Computer Science*, pages 130–139. Springer Berlin / Heidelberg, 2001.

G.H.G Fonseca, H.G. Santos, T.A.M Toffolo, S.S. Brito, and M.J.F. Souza. A sa-ils approach for the high school timetabling problem. In *Proceedings of the Ninth International Conference on the Practice and Theory of Automated Timetabling (PATAT 2012)*, 2012.

G.H.G Fonseca, H.G. Santos, and T.A.M Toffolo. Late acceptance-hill climbing applied to the high school timetabling problem,. In *Multidisciplinary International Scheduling Conference VI*, 2013.

L. Di Gaspero, A. Schaerf, and B. McCollum. The second international timetabling competition (itc-2007): Curriculum-based course timetabling (track 3). Technical report, School of Electronics, Electrical Engineering and Computer Science, Queen's University SARC Building, Belfast, United Kingdom, 2007.

Luca Gaspero and Andrea Schaerf. Multi-neighbourhood local search with application to course timetabling. In Edmund Burke and Patrick Causmaecker, editors, *Practice and Theory of Automated Timetabling IV*, volume 2740 of *Lecture Notes in Computer Science*, pages 262–275. Springer Berlin Heidelberg, 2003. ISBN 978-3-540-40699-0.

Christos Gogos, Panayiotis Alefragis, and Efthymios Housos. An improved multi-staged algorithmic process for the solution of the examination timetabling problem. *Annals of Operations Research*, 194(1):203–221, 2012. ISSN 0254-5330.

M.P. Hansen and R.V.V. Vidal. Planning of high school examinations in denmark. *European Journal of Operational Research*, 87(3):519 – 534, 1995. ISSN 0377-2217. doi: DOI:10.1016/0377-2217(95)00227-8. Operational Research in Europe.

Jin-Kao Hao and Una Benlic. Lower bounds for the itc-2007 curriculum-based course timetabling problem. *European Journal of Operational Research*, 212(3):464 – 472, 2011. ISSN 0377-2217.

F. Jacobsen, A. Bortfeldt, and H. Gehring. Timetabling at german secondary schools: Tabu search versus constraint programming. In E. K. Burke and H. Rudova, editors, *Proceedings of the International Conference on the Practice and Theory of Automated Timetabling (PATAT 2006)*, pages 439–442, 2006. ISBN 80-210-3726-1.

W. Junginger. Timetabling in germany–a survey. *Interfaces*, 16(4):66–74, 1986. doi: 10.1287/inte.16.4.66.

M.N.M. Kahar and G. Kendall. The examination timetabling problem at universiti malaysia pahang: Comparison of a constructive heuristic with an existing software solution. *European Journal of Operational Research*, 207(2):557 – 565, 2010. ISSN 0377-2217.

G. Kendall, S. Knust, C.C. Ribeiro, and S. Urrutia. Scheduling in sports: An annotated bibliography. *Computers & Operations Research*, 37(1):1 – 19, 2010. ISSN 0305-0548.

Ahmed Kheiri, Ender Ozcan, and Andrew J. Parkes. Hysst: Hyper-heuristic search strategies and timetabling. In *Proceedings of the Ninth International Conference on the Practice and Theory of Automated Timetabling (PATAT 2012)*, pages 497–499, 2012.

J. Kingston. A tiling algorithm for high school timetabling. In Edmund Burke and Michael Trick, editors, *Practice and Theory of Automated Timetabling V*, volume 3616 of *Lecture Notes in Computer Science*, pages 208–225. Springer Berlin / Heidelberg, 2005.

Jeffrey H. Kingston. Educational timetabling. In A. Sima Uyar, Ender Ozcan, and Neil Urquhart, editors, *Automated Scheduling and Planning*, volume 505 of *Studies in Computational Intelligence*, pages 91–108. Springer Berlin Heidelberg, 2013a. ISBN 978-3-642-39303-7.

Jeffrey H. Kingston. The hseval high school timetable evaluator. `http://sydney.edu.au/engineering/it/~jeff/hseval.cgi` [Retrieved 12/8-2013], Aug. 2013b.

Philipp Kostuch. Timetabling competition - sa-based heuristic. In *PATAT 2004: Proceedings of the 5th International Conference on the Practice and Theory of Automated Timetabling*, 2004.

Simon Kristiansen and Thomas R. Stidsen. Elective course student sectioning at danish high schools. *Annals of Operations Research*, PATAT 2012 SI:To appear, 2013.

Simon Kristiansen, Matias Sørensen, and Thomas R. Stidsen. Elective course planning. *European Journal of Operational Research*, 215(3):713 – 720, 2011. ISSN 0377-2217. doi: 10.1016/j.ejor.2011.06.039.

Simon Kristiansen, Andrew Mason, and Thomas R. Stidsen. High school student sectioning at danish high schools. *European Journal of Operational Research*, MISTA 2013:To appear, 2013a.

Simon Kristiansen, Matias Sørensen, and Thomas R. Stidsen. Integer programming for the generalized (high) school timetabling problem. *Journal of Scheduling*, Submitted 5/9-2013, 2013b.

Zhipeng Lü, Jin-Kao Hao, and Fred Glover. Neighborhood analysis: a case study on curriculum-based course timetabling. *Journal of Heuristics*, 17 (2):97–118, 2011. ISSN 1381-1231.

G. Lach and M. Lübbecke. Optimal university course timetables and the partial transversal polytope. In Catherine McGeoch, editor, *Experimental Algorithms*, volume 5038 of *Lecture Notes in Computer Science*, pages 235–248. Springer Berlin / Heidelberg, 2008.

G. Lach and M. Lübbecke. Curriculum based course timetabling: new solutions to udine benchmark instances. *Annals of Operations Research*, 194: 255–272, 2012. ISSN 0254-5330.

R. Lewis, B. Paechter, and B. McCollum. Post enrolment based course timetabling: A description of the problem model used for track two of the second international timetabling competition. Cardiff Accounting and Finance Working Papers A2007/3, Cardiff University, Cardiff Business School, Accounting and Finance Section, 2007.

Rhydian Lewis and Ben Paechter. Application of the grouping genetic algorithm to university course timetabling. In Günther R. Raidl and Jens Gottlieb, editors, *Evolutionary Computation in Combinatorial Optimization*, volume 3448 of *Lecture Notes in Computer Science*, pages 144–153. Springer Berlin Heidelberg, 2005. ISBN 978-3-540-25337-2.

Martin Lohnertz. A timetabling system for the german gymnasium. In *Proceedings of the fourth international conference on the practice and theory of automated timetabling.*, 2002.

Nashat Mansour, Vatche Isahakian, and Iman Ghalayini. Scatter search technique for exam timetabling. *Applied Intelligence*, 34(2):299–310, 2011. ISSN 0924-669X.

Clarence H. Martin. Ohio university's college of business uses integer programming to schedule classes. *Interfaces*, 34(6):460–465, November 2004.

B. McCollum. University timetabling: Bridging the gap between research and practice. In *in Proceedings of the 5th International Conference on the Practice and Theory of Automated Timetabling*, pages 15–35. Springer, 2006.

Barry McCollum. International timetabling competition 2007. `http://www.cs.qub.ac.uk/itc2007/index.htm`[Retrieved 08/11-2013], 2007.

Barry McCollum, Andrea Schaerf, Ben Paechter, Paul McMullan, Rhyd Lewis, Andrew J. Parkes, Luca Di Gaspero, Rong Qu, and Edmund K. Burke. Setting the research agenda in automated timetabling: The second international timetabling competition. *INFORMS Journal on Computing*, 22(1):120–130, 2010.

Barry McCollum, Paul McMullan, Andrew Parkes, Edmund Burke, and Rong Qu. A new model for automated examination timetabling. *Annals of Operations Research*, 194:291–315, 2012. ISSN 0254-5330. 10.1007/s10479-011-0997-x.

Amnon Meisels and Andrea Schaerf. Modelling and solving employee timetabling problems. *Annals of Mathematics and Artificial Intelligence*, 39 (1-2):41–59, 2003. ISSN 1012-2443.

F. Melício, P. Caldeira, and A. Rosa. Solving real school timetabling problems with meta-heuristics. In *Proceedings of the 4th WSEAS International Conference on Applied Mathematics and Computer Science*, pages 4:1–4:8, Stevens Point, Wisconsin, USA, 2005. World Scientific and Engineering Academy and Society (WSEAS). ISBN 960-8457-17-3.

F. Melício, J. P. Calderia, and A. Rosa. Thor: A tool for school timetabling. In E. K. Burke and H. Rudova, editors, *Proceedings of the 6th International Conference on the Practice and Teaching of Automated Timetabling (PATAT 2006)*, pages 532–535, 2006. ISBN 80-210-3726-1.

L. Merlot, N. Boland, and P. Hughes, B.and Stuckey. A hybrid algorithm for the examination timetabling problem. In Edmund Burke and Patrick De Causmaecker, editors, *Practice and Theory of Automated Timetabling IV*, volume 2740 of *Lecture Notes in Computer Science*, pages 207–231. Springer Berlin / Heidelberg, 2003.

K. Minh, N. Thanh, K. Trang, and N. Hue. Using tabu search for solving a high school timetabling problem. In Ngoc Nguyen, Radoslaw Katarzyniak, and Shyi-Ming Chen, editors, *Advances in Intelligent Information and Database Systems*, volume 283 of *Studies in Computational Intelligence*, pages 305–313. Springer Berlin / Heidelberg, 2010.

MISTA. Multidisciplinary international scheduling conference: Theory & application. `http://www.schedulingconference.org/`.

T. Müller. Itc2007 solver description: a hybrid approach. *Annals of Operations Research*, 172:429–446, 2009. ISSN 0254-5330.

T. Müller. Real-life examination timetabling. In *Proceedings of the tenth Multidisciplinary International Scheduling Conference (MISTA2013)*, 2013.

T. Müller and K. Murray. Comprehensive approach to student sectioning. *Annals of Operations Research*, 181:249–269, 2010. ISSN 0254-5330.

Tomáš Müller and Hana Rudová. Real-life curriculum-based timetabling. In *Proceedings of the 9th International Conference on the Practice and Theory of Automated Timetabling, PATAT2012*, 2012.

Tomáš Müller, Hana Rudová, and Roman Barták. Minimal perturbation problem in course timetabling. In Edmund Burke and Michael Trick, editors, *Practice and Theory of Automated Timetabling V*, volume 3616 of *Lecture Notes in Computer Science*, pages 126–146. Springer Berlin Heidelberg, 2005. ISBN 978-3-540-30705-1.

Charalampos N. Moschopoulos, Christos E. Alexakos, Christina Dosi, Grigorios N. Beligiannis, and Spiridon D. Likothanassis. A user-friendly evolutionary tool for high-school timetabling. In Constantinos Koutsojannis and Spiros Sirmakessis, editors, *Tools and Applications with Artificial Intelligence*, volume 166 of *Studies in Computational Intelligence*, pages 149–162. Springer Berlin Heidelberg, 2009. ISBN 978-3-540-88068-4.

A.V. Moura and R.A. Scaraficci. A grasp strategy for a more constrained school timetabling problem. *International Journal of Operational Research*, 7:152–170(19), 2010.

Keith Murray, Tomáš Müller, and Hana Rudová. Modeling and solution of a complex university course timetabling problem. In Edmund Burke and Hana Rudová, editors, *Practice and Theory of Automated Timetabling VI*, volume 3867 of *Lecture Notes in Computer Science*, pages 189–209. Springer Berlin Heidelberg, 2007. ISBN 978-3-540-77344-3.

Khang Nguyen, Quang Nguyen, Hien Tran, Phuc Nguyen, and Nuong Tran. Variable neighborhood search for a real-world curriculum-based university timetabling problem. In *Knowledge and Systems Engineering (KSE), 2011 Third International Conference on*, pages 157 –162, oct. 2011.

Clemens Nothegger, Alfred Mayer, Andreas Chwatal, and Günther R. Raidl. Solving the post enrolment course timetabling problem by ant colony optimization. *Annals of Operations Research*, 194(1):325–339, 2012. ISSN 0254-5330.

K. Nurmi and J. Kyngas. A framework for school timetabling problem. In *Proceedings of the 3rd multidisciplinary international scheduling conference: theory and applications*, pages 386–393, 2007.

K. Nurmi and J. Kyngas. A conversion scheme for turning a curriculum-based timetabling problem into a school timetabling problem. In *Proceedings of the 7th International Conference on the Practice and Theory of Automated Timetabling (PATAT 2008)*, 2008.

E. Ozcan, Y. Bykov, M. Birben, and E.K. Burke. Examination timetabling using late acceptance hyper-heuristics. In *Evolutionary Computation, 2009. CEC '09. IEEE Congress on*, pages 997 –1004, may 2009.

Ben Paechter, Luca Maria Gambardella, and Olivia Rossi-Doria. International timetabling competition 2003. `http://www.idsia.ch/Files/ttcomp2002/oldindex.html`[Retrieved 08/11-2013], 2002.

K. Papoutsis, C. Valouxis, and E. Housos. A column generation approach for the timetabling problem of greek high schools. *The Journal of the Operational Research Society*, 54(3):230–238, 2003.

PATAT. International conference on the practice and theory of automated timetabling. `http://www.patatconference.org/`.

S. Petrovic and Y. Bykov. A multiobjective optimisation technique for exam timetabling based on trajectories. In Edmund Burke and Patrick De Causmaecker, editors, *Practice and Theory of Automated Timetabling IV*, volume 2740 of *Lecture Notes in Computer Science*, pages 181–194. Springer Berlin / Heidelberg, 2003.

N. Pillay and W. Banzhaf. A study of heuristic combinations for hyper-heuristic systems for the uncapacitated examination timetabling problem. *European Journal of Operational Research*, 197(2):482 – 491, 2009. ISSN 0377-2217.

Nelishia Pillay. A survey of school timetabling research. *Annals of Operations Research*, February 2013. ISSN 0254-5330.

Michael Pimmer and Günther R. Raidl. A timeslot-filling heuristic approach to construct high-school timetables. In Luca Di Gaspero, Andrea Schaerf, and Thomas Stützle, editors, *Advances in Metaheuristics*, volume 53 of *Operations Research/Computer Science Interfaces Series*, pages 143–157. Springer New York, 2013. ISBN 978-1-4614-6321-4.

G. Post, S. Ahmadi, S. Daskalaki, J. Kingston, J. Kyngas, C. Nurmi, and D. Ranson. An xml format for benchmarks in high school timetabling. *Annals of Operations Research*, 194:385–397, 2012a. ISSN 0254-5330.

G. Post, S. Ahmadi, and F. Geertsema. Cyclic transfers in school timetabling. *OR Spectrum*, 34(1):133–154, 2012b. ISSN 0171-6468.

G. F. Post and H. W. A. Ruizenaar. Clusterschemes in dutch secondary schools. Memorandum 1707, Department of Applied Mathematics, University of Twente, Enschede, 2004.

Gerhard Post. Benchmarking project for (high) school timetabling. `http://www.utwente.nl/ctit/hstt/` [Retrieved 12/8-2013], Aug. 2013.

Gerhard Post, Jeff Kingston, Andea Schaerf, Luca Di Gaspero, and Barry McCollum. International timetabling competition 2011. `http://www.utwente.nl/ctit/hstt/itc2011/`[Retrieved 08/11-2013], 2011.

Gerhard Post, Luca Di Gaspero, Jeffrey H. Kingston, Barry McCollum, and Andrea Schaerf. The third international timetabling competition. In *Proceedings of the Ninth International Conference on the Practice and Theory of Automated Timetabling (PATAT 2012)*, Son, Norway, August 2012c.

Gerhard Post, Luca Gaspero, JeffreyH. Kingston, Barry McCollum, and Andrea Schaerf. The third international timetabling competition. *Annals of Operations Research*, February 2013. ISSN 0254-5330.

PurdueBenchmark. The purdue benchmark data. `http://www.unitime.org/uct_datasets.php`.

PurdueExamBenchmark. The purdue benchmark data. `http://www.unitime.org/exam_datasets.php`.

R. Qu, E.K. Burke, B. McCollum, L.T.G. Merlot, and S.Y. Lee. A survey of search methodologies and automated system development for examination timetabling. *Journal of Scheduling*, 12(1):55–89, 2009. ISSN 1094-6136.

Rong Qu and Edmund K. Burke. Adaptive decomposition and construction for examination timetabling problems. In *Proceedings of the 3rd multidisciplinary international scheduling conference: theory and applications*, 2007.

Andrea Qualizza and Paolo Serafini. A column generation scheme for faculty timetabling. In Edmund Burke and Michael Trick, editors, *Practice and Theory of Automated Timetabling V*, volume 3616 of *Lecture Notes in Computer Science*, pages 161–173. Springer Berlin Heidelberg, 2005. ISBN 978-3-540-30705-1.

R. Raghavjee and N. Pillay. Evolving solutions to the school timetabling problem. In *Nature Biologically Inspired Computing, 2009. NaBIC 2009. World Congress on*, pages 1524–1527, 2009.

R. Raghavjee and N. Pillay. An informed genetic algorithm for the high school timetabling problem. In *Proceedings of the 2010 Annual Research Conference of the South African Institute of Computer Scientists and Information Technologists*, SAICSIT '10, pages 408–412, New York, NY, USA, 2010. ACM. ISBN 978-1-60558-950-3.

Syariza Abdul Rahman, Andrzej Bargiela, Edmund K. Burke, Ender Özcan, Barry McCollum, and Paul McMullan. Adaptive linear combination of heuristic orderings in constructing examination timetables. *European Journal of Operational Research*, 232(2):287 – 297, 2014. ISSN 0377-2217.

S. Ribic and S. Konjicija. A two phase integer linear programming approach to solving the school timetable problem. In *Information Technology Interfaces (ITI), 2010 32nd International Conference on*, pages 651–656, 2010.

Vincent Robert and Alain Hertz. How to decompose constrained course scheduling problems into easier assignment type subproblems. In Edmund Burke and Peter Ross, editors, *Practice and Theory of Automated Timetabling*, volume 1153 of *Lecture Notes in Computer Science*, pages 364–373. Springer Berlin Heidelberg, 1996. ISBN 978-3-540-61794-5.

Jonathan Romrös and Jörg Homberger. An evolutionary algorithm for high school timetabling. In *Proceedings of the Ninth International Conference on the Practice and Theory of Automated Timetabling (PATAT 2012)*, pages 485–488. SINTEF, 2012.

H. Rudova and K. Murray. University course timetabling with soft constraints. In *Practice And Theory of Automated Timetabling IV.*, pages 310–328, 2003.

Hana Rudová, Tomáš Müller, and Keith Murray. Complex university course timetabling. *Journal of Scheduling*, 14(2):187–207, 2011. ISSN 1094-6136.

Nasser R. Sabar, Masri Ayob, and Graham Kendall. Solving examination timetabling problems using honey-bee mating optimization (etp-hbmo). In *Proceedings of the 4rd multidisciplinary international scheduling conference: theory and applications*, 2009.

Nasser R. Sabar, Masri Ayob, Rong Qu, and Graham Kendall. A graph coloring constructive hyper-heuristic for examination timetabling problems. *Applied Intelligence*, 37(1):1–11, 2012. ISSN 0924-669X.

Scott E. Sampson, James R. Freeland, and Elliott N. Weiss. Class scheduling to maximize participant satisfaction. *Interfaces*, 25(3):30–41, 1995.

H. Santos, L. Ochi, and M. Souza. An efficient tabu search heuristic for the school timetabling problem. In Celso Ribeiro and Simone Martins, editors,

Experimental and Efficient Algorithms, volume 3059 of *Lecture Notes in Computer Science*, pages 468–481. Springer Berlin / Heidelberg, 2004.

H. Santos, E. Uchoa, L. Ochi, and N. Maculan. Strong bounds with cut and column generation for class-teacher timetabling. *Annals of Operations Research*, 194(1):399–412, April 2012. ISSN 0254-5330.

H.G. Santos, L.S. Ochi, and M.J.F. Souza. A tabu search heuristic with efficient diversification strategies for the class/teacher timetabling problem. *J. Exp. Algorithmics*, 10, December 2005. ISSN 1084-6654.

A. Schaerf. A survey of automated timetabling. *Artificial Intelligence Review*, 13:87–127, 1999a. ISSN 0269-2821.

A. Schaerf. Local search techniques for large high school timetabling problems. *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, 29(4):368 –377, jul 1999b. ISSN 1083-4427.

Katja Schimmelpfeng and Stefan Helber. Application of a real-world university-course timetabling model solved by integer programming. *OR Spectrum*, 29:783–803, 2007. ISSN 0171-6468.

G. Schmidt and T. Ströhlein. Timetable construction – an annotated bibliography. *The Computer Journal*, 23(4):307–316, 1980.

Der-Fang Shiau. A hybrid particle swarm optimization for a university course scheduling problem with flexible preferences. *Expert Systems with Applications*, 38(1):235 – 248, 2011. ISSN 0957-4174.

Tayfun Sönmez and M. Utku Ünver. Course bidding at business schools*. *International Economic Review*, 51(1):99–123, 2010. ISSN 1468-2354.

Krzysztof Socha, Michael Sampels, and Max Manfrin. Ant algorithms for the university course timetabling problem with regard to the state-of-the-art. In Stefano Cagnoni, Colin G. Johnson, Juan J. Romero Cardalda, Elena Marchiori, David W. Corne, Jean-Arcady Meyer, Jens Gottlieb, Martin Middendorf, Agnès Guillot, GüntherR. Raidl, and Emma Hart, editors, *Applications of Evolutionary Computing*, volume 2611 of *Lecture Notes in Computer Science*, pages 334–345. Springer Berlin Heidelberg, 2003. ISBN 978-3-540-00976-4.

M.J.F. Souza, N. Maculan, and L.S. Ochi. A grasp-tabu search algorithm for school timetabling problems. In M.G.C. Resende and J.P. de Sousa, editors, *Metaheuristics: Computer decision-making*, pages 659–672. Kluwer Academic Publishers, 2003.

Matias Sørensen and Florian H. W. Dahms. A two-stage decomposition of high school timetabling applied to cases in denmark. *Computers & Operations Research*, 43:36–49, March 2014.

Matias Sørensen and Thomas R. Stidsen. Integer programming and adaptive large neighborhood search for real-world instances of high school timetabling. *Annals of Operations Research*, PATAT 2012 SI:Submitted Jan 21. 2013, 2013.

Matias Sørensen, Simon Kristiansen, and Thomas R. Stidsen. International timetabling competition 2011: An adaptive large neighborhood search algorithm. In *Proceedings of the Ninth International Conference on the Practice and Theory of Automated Timetabling (PATAT 2012)*, pages 489–492. SINTEF, 2012.

Suyanto Suyanto. An informed genetic algorithm for university course and student timetabling problems. In *Proceedings of the 10th international conference on Artifical intelligence and soft computing: Part II*, ICAISC'10, pages 229–236, Berlin, Heidelberg, 2010. Springer-Verlag. ISBN 3-642-13231-6, 978-3-642-13231-5.

J.M. Thompson and K.A. Dowsland. A robust simulated annealing based examination timetabling system. *Computers & Operations Research*, 25 (7-8):637 – 648, 1998. ISSN 0305-0548.

H. Turabieh and S. Abdullah. An integrated hybrid approach to the examination timetabling problem. *Omega*, 39(6):598 – 607, 2011a. ISSN 0305-0483.

Hamza Turabieh and Salwani Abdullah. A hybrid fish swarm optimisation algorithm for solving examination timetabling problems. In CarlosA.Coello Coello, editor, *Learning and Intelligent Optimization*, volume 6683 of *Lecture Notes in Computer Science*, pages 539–551. Springer Berlin Heidelberg, 2011b. ISBN 978-3-642-25565-6.

Hamza Turabieh, Salwani Abdullah, Barry McCollum, and Paul McMullan. Fish swarm intelligent algorithm for the course timetabling problem. In Jian Yu, Salvatore Greco, Pawan Lingras, Guoyin Wang, and Andrzej Skowron, editors, *Rough Set and Knowledge Technology*, volume 6401 of *Lecture Notes in Computer Science*, pages 588–595. Springer Berlin Heidelberg, 2010. ISBN 978-3-642-16247-3.

UdineBenchmark. The udine benchmark data. `http://satt.diegm.uniud.it/ctt`.

UniTime. Unitime publications. `http://www.unitime.org/publications.php`[Retrieved 08/11-2013].

C. Valouxis and E. Housos. Constraint programming approach for school timetabling. *Computers & Operations Research*, 30(10):1555 – 1572, 2003. ISSN 0305-0548. Part Special Issue: Analytic Hierarchy Process.

Christos Valouxis, Christos Gogos, Panayiotis Alefragis, and Efthymios Housos. Decomposing the high school timetable problem. In *Practice and Theory of Automated Timetabling (PATAT 2012)*, Son, Norway, August 2012.

G. White and B. Xie. Examination timetables and tabu search with longer-term memory. In Edmund Burke and Wilhelm Erben, editors, *Practice and Theory of Automated Timetabling III*, volume 2079 of *Lecture Notes in Computer Science*, pages 85–103. Springer Berlin / Heidelberg, 2001.

G.M. White, B.S. Xie, and S. Zonjic. Using tabu search with longer-term memory and relaxation to create examination timetables. *European Journal of Operational Research*, 153(1):80 – 91, 2004. ISSN 0377-2217. Timetabling and Rostering.

P. Wilke, M. Gröbner, and N. Oster. A hybrid genetic algorithm for school timetabling. In Bob McKay and John Slaney, editors, *AI 2002: Advances in Artificial Intelligence*, volume 2557 of *Lecture Notes in Computer Science*, pages 455–464. Springer Berlin / Heidelberg, 2002.

T. Wong, P. Cote, and P. Gely. Final exam timetabling: a practical approach. In *Electrical and Computer Engineering, 2002. IEEE CCECE 2002. Canadian Conference on*, volume 2, pages 726 – 731 vol.2, 2002. doi: 10.1109/CCECE.2002.1013031.

J. Wood and D. Whitaker. Student centred school timetabling. *The Journal of the Operational Research Society*, 49(11):1146–1152, Nov. 1998.

A. Wren. Scheduling, timetabling and rostering — a special relationship? In Edmund Burke and Peter Ross, editors, *Practice and Theory of Automated Timetabling*, volume 1153 of *Lecture Notes in Computer Science*, pages 46–75. Springer Berlin / Heidelberg, 1996.

Y. Yang and S. Petrovic. A novel similarity measure for heuristic selection in examination timetabling. In Edmund Burke and Michael Trick, editors, *Practice and Theory of Automated Timetabling V*, volume 3616 of *Lecture Notes in Computer Science*, pages 247–269. Springer Berlin / Heidelberg, 2005.

Tuncay Yigit. Constraint-based school timetabling using hybrid genetic algorithms. In Roberto Basili and MariaTeresa Pazienza, editors, *AI*IA 2007: Artificial Intelligence and Human-Oriented Computing*, volume 4733 of *Lecture Notes in Computer Science*, pages 848–855. Springer Berlin Heidelberg, 2007. ISBN 978-3-540-74781-9.

Ender Özcan, Burak Bilgin, and Emin Erkan Korkmaz. A comprehensive analysis of hyper-heuristics. *Intelligent Data Analysis*, 12:3–23, 2008.

D. Zhang, Y. Liu, R. M'Hallah, and S.C.H. Leung. A simulated annealing with a new neighborhood structure based algorithm for high school timetabling problems. *European Journal of Operational Research*, 203(3):550 – 558, 2010. ISSN 0377-2217.

Educational timetabling is one of the most researched subjects within the range of timetabling problems.
This report contains a comprehensive survey of the research in Educational Timetabling problems. The paper highlights some of the main trends and research achievements within this research subject.
Educational Timetabling is often divided into four main categories; University Course Timetabling, High School Timetabling, Examination Timetabling and Student Sectioning. For each planning problem a description is given with appertaining benchmark and the recent research.

978-87-93130-02-9

DTU Management Engineering
Department of Management Engineering
The Technical University of Denmark

Produktionstorvet
Building 424
2800 Kongens Lyngby
Tlf. 45 25 48 00
Fax 45 93 34 35

www.man.dtu.dk